A Life Cycle Assessment of Glued Laminated Timber (Glulam) Production in Indonesia

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Abstract

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The building construction sector is one of the most carbon-intensive industries, contributing nearly 40% of global energy-related CO_2 emissions. In tropical countries, rapid urbanization and economic growth amplify this impact, highlighting the need to reduce both operational and embodied carbon. While mass timber is gaining traction as a low-carbon solution in temperate regions, its potential in tropical areas remains underexplored. As the country of this case study, Indonesia offers a unique opportunity to harness the environmental benefits of mass timber due to its abundant wood resources, strong wood industry, and supportive climate policies. However, challenges such as land use change remain a major concern. This research aims to document the mass timber supply chain and perform a cradle-to-gate LCA of glued laminated timber (glulam) produced in Indonesia, with the consideration of land use and land use change (LULUC). The results demonstrate the potential of glulam produced in Indonesia to contribute positively to climate change mitigation. The production of 1 m^3 of glulam in

Indonesia results in 523.26 kg CO2 eq. of fossil emissions, while 914.11 kg CO2 eq. of biogenic carbon is stored. Thus, the overall product’s carbon balance is -390.85 kg CO2 eq. Two land use change scenarios were considered to reflect conditions where logs are harvested from forest lands that have undergone conversion. One scenario was conversion from primary to secondary dryland forest, representing forest degradation, while the other was conversion from dry shrubs to secondary dryland forest, representing forest gains. For the forest gain scenario, the product’s overall climate impact becomes -426.75 kg CO_2 eq. In contrast, forest degradation raises it to 821.48 kg CO_2 eq. The forest degradation scenario takes away the biogenic carbon sequestration credit while still accounting for all the biogenic and fossil emissions throughout the product’s life, resulting in a significantly higher climate impact. This highlights the importance of sourcing wood from sustainably managed forests to claim the carbon benefits of wood products.

Table of Contents

List of Tables, Figures, and Equations

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1. Introduction

1.1. The building industry's impact on climate change

The building construction sector is regarded as one of the most carbon-intensive industrial sectors, responsible for nearly 40% of global energy-related CO2 emissions, 50% of material extraction, and one-third of the world's waste (COP28). In 2023, the building sector gained long-overdue recognition from countries and stakeholders with the launch of the Buildings Breakthrough initiative at COP28. This initiative sets an ambitious goal to achieve near-zero emissions and climate-resilient buildings by 2030 (UN Environment Programme 2023). However, to meet climate targets, reducing operational carbon alone will not be sufficient. Collective efforts must also be made to reduce embodied carbon. Embodied carbon encompasses the GHG emissions associated with the upstream stages of a product's or a system's lifecycle, starting from raw material procurement, transportation, production, construction, use, and end-of-life (EPA).

One of the ways to reduce the embodied carbon in the built environment sector is by exploring alternative building materials with a lower carbon footprint than conventional materials, such as concrete and steel. In this context, mass timber emerges as a potential decarbonization solution. Mass timber represents a category of engineered wood products (EWP) created by layering and bonding wood boards together to create a strong and lightweight building material (Brind'Amour & Bertrand 2023). Glued-laminated timber (glulam) and cross-laminated timber (CLT) are notable examples. Different from lumber, which is commonly used in traditional stick-frame housing construction and low-rise buildings, mass timber is typically used as panels, beams, and columns in larger and taller buildings, replacing concrete and steel. To date, the world's tallest mass timber structure is a 25-story apartment building in Milwaukee, Wisconsin (USDA Forest Service 2022). Mass timber systems offer a potentially appealing alternative to traditional materials where buildings can be constructed using wood as the primary structural material with (i) lower fossil carbon emissions, (ii) reduced material waste, (iii) increased construction efficiency, and (iv) long-term biogenic carbon storage.

Life cycle assessment (LCA) has evolved as an internationally accepted method that enables the quantification of embodied carbon and offers insights into the environmental impacts of various construction materials and systems, including mass timber. The environmental impacts are evaluated based on the resources required (inputs) and emissions generated (outputs) occurring at each life cycle stage, which can include resource extraction, transportation, product manufacturing, usage, and disposal. Over the past two decades, there has been a steady increase in the number of publications on mass timber LCAs, mostly from European and North American countries (Duan et al. 2022). Its environmental impacts have been addressed at various levels, ranging from materials, structures, whole buildings, to urban scales. At the building level, many comparative LCA studies consistently show that mass timber buildings have a lower embodied carbon than functionally equivalent conventional buildings made with concrete and/or steel. The reductions in global warming potential (GWP) typically range from 25% to 50%, depending on the scope of the LCA (Chen et al. 2022; Allan & Phillips 2021; Pierobon et al. 2019; Puettmann et al. 2021; Skullestad et al. 2016; Pittau et al. 2019; Hemmati et al. 2024; Dodoo et al. 2021).

1.2. The popularity of mass timber in temperate regions

Mass timber has emerged as a transformative material in construction, especially in temperate regions like Europe and North America (Anderson et al. 2024). Its history dates to the early 1890s when glulam was first used in Europe. A 1901 Swiss patent marked the formal start of its use in construction. In the United States, one of the earliest glulam structures was a research laboratory at the USDA Forest Products Laboratory in Madison, Wisconsin, built in 1934 and still in use today (APA). Meanwhile, cross-laminated timber (CLT) was introduced in Austria and Germany in the early 1990s. CLT saw a breakthrough in the mid-1990s when Austria launched a collaborative research initiative between academia and industry to develop new markets for sawmill by-products (Espinoza et al. 2016). This led to the development of modern CLT technology. CLT construction eventually gained momentum in the early 2000s, spurred by the green building movement, among others (Gagnon et al. 2013).

Glulam and CLT, while both mass timber products, serve different purposes in construction. Glulam is typically used for beams and columns to support structural loads, often complementing CLT panels. CLT can be used for all major building components like floors, interior and exterior walls, and roofs. Glulam production tends to be smaller scale, with custom-made beams being a common focus. In North America, the annual glulam production has remained steady at around 700,000 m^3 since 2017 (Anderson et al. 2024). Meanwhile, Austria and Germany's top ten glulam producers generated nearly 1.5 million m^3 in 2022 (Timber-Online 2024). On the other hand, CLT production in 2023 had a global output exceeding 2 million m^3 from 97 production lines (Anderson et al. 2024). Central Europe also dominates CLT manufacturing, accounting for over 65% of global production (40 percent by Austria alone). All European manufacturers contributed more than 80% of the global CLT production volume. The North American CLT production contributes 12% in 2023 to the global volume.

The Council on Tall Buildings and Urban Habitat (CTBUH) reported that as of 2022, there were 84 mass timber buildings under construction or completed around the world of at least eight stories. This was a 75% increase from 2017 compared with the previous study conducted by CTBUH (CTBUH 2017). The evolving building codes that allowed tall timber building construction played a role in the adoption of mass timber for high-rise construction. If considering seven stories or higher and proposed projects, the numbers increase by more than four-fold at more than 200 mass timber buildings globally (CTBUH 2022). Europe, the birthplace of mass timber technology, leads the world in high-rise timber buildings, accounting for 71% of the total as of 2022. This dominance is unsurprising, given its mature, well-managed forests and some of the strictest environmental regulations globally. North America follows with 18%, benefiting from its vast managed forests and a long tradition of wood construction.

The mass timber industry is characterized by its diversity in manufacturing processes, levels of automation, and operational scales (Anderson et al. 2024). From small artisanal factories to fully automated, high-capacity facilities, manufacturers offer a wide array of products and services, including custom-designed panels and pre-assembled components. This diversity extends to market strategies and the complex modes of interaction across its supply and value chains. Unlike traditional commodity-oriented forest product industries, the sector's development has followed an unconventional trajectory, making it difficult to find an adequate precedent (Anderson et al. 2024). As a result, the industry remains relatively young and is still largely unknown in many emerging markets (Anderson et al. 2024).

1.3. The status of mass timber in tropical regions

The construction needs in tropical regions are immense, driven by rapid economic growth and urbanization, increasing the demand for housing and infrastructure. Raw resource use is predicted to double by 2060, while construction materials such as concrete and steel are already major contributors to greenhouse gas emissions (United Nations Environment Programme, 2022). Despite the surge in building activities, nations such as India, Brazil, Indonesia, and sub-Saharan African states still face a critical housing shortage, with millions of new homes needed annually. Mass timber offers an innovative solution to meet these demands while mitigating environmental impacts, including greenhouse gas emissions, and reducing reliance on carbon-intensive materials like concrete and steel.

Emerging initiatives and projects demonstrate growing interest in mass timber across tropical regions, beyond the key temperate regions (Climate Smart Forest Economy Program, a). Countries like Indonesia, Brazil, Gabon, Uganda, Mozambique, and Tanzania are exploring and developing their mass timber value chain. In addition, partially tropical nations like India, Bhutan, Kenya, and South Africa are also advancing their mass timber capabilities. Some of these countries, like Kenya, are leveraging locally available timber species, ranging from softwoods such as pine to hardwoods like eucalyptus (ARUP). This contributes to diversifying the wood sources typically associated with mass timber, which are softwoods, and adding hardwoods into the species mix.

The scope of these initiatives varies widely, from building supply chains and construction projects to programs like Climathon, which foster innovation in climate-resilient construction (Climate Smart Forest Economy Program, a). Countries are at different stages of development: Kenya is in the early phase of forming partnerships with currently no production capacity, South Africa and Brazil have small-scale local production capabilities, and Indonesia has progressed to implementing projects using mass timber. Despite their varied stages, these initiatives share a common motivation: addressing housing shortages, promoting affordable and sustainable construction, managing forests responsibly, and meeting climate targets.

In tropical countries, challenges to mass timber adoption are concerning. Bhutan, for instance, faces issues of forest degradation, illegal logging, outdated timber technologies, and weak policy implementation (Wangdi & Norbu 2023a). Gabon faces deforestation rates of approximately 500,000 hectares annually in the Congo Basin, with only 2.5% of its forest land under sustainable management (Climate Smart Forest Economy Program, b). Similarly, Kenya lacks a cohesive value chain for mass timber, faces high production costs, and suffers from public misconceptions about the material (Climate Smart Forest Economy Program, c). South Africa and Brazil also struggle with policy and regulatory gaps, limited government investment, and insufficient local wood production, which hinder mass timber's growth (Climate Smart Forest Economy Program, c).

Despite these obstacles, notable progress is being made in knowledge sharing and planning. India and Bhutan have conducted studies on potential timber sourcing and preliminary carbon emissions reductions (Climate Smart Forest Economy Program, 2022d; Wangdi & Norbu 2023a; Wangdi & Norbu 2023b). Kenya has explored supply-demand projections, sector development pathways, and behavioral change strategies to enhance public acceptance of mass timber (ARUP; Climate Smart Forest Economy Program, c; Busara Center for Behavioral Economics 2022; Climate Smart Forest Economy Program, e; Climate Smart Forest Economy Program, f). Published research and opportunity notes from these countries serve as blueprints for others seeking to develop their mass timber industries. This collaborative approach underscores the potential for tropical nations to address their unique challenges through shared learning and adaptive strategies.

1.4. Indonesia's emerging role in the mass timber industry

Indonesia is one of the few tropical countries advancing the mass timber industry, with strong interest from all the key stakeholders, including the government, private industry, and academia. Recent initiatives on mass timber tall building construction in Indonesia have been led by the Ministry of Public Works and Housing (*Pekerjaan Umum dan Perumahan Rakyat* or PUPR). Beyond the environmental benefits of mass timber construction, the PUPR plans to leverage mass timber construction to help address a housing backlog that currently stands at nearly 10 million units annually (Ministry of Public Works and Housing 2024). Given the reduced construction time offered by mass timber, it presents a potential solution to alleviate Indonesia's housing shortages.

In the context of Indonesia's new capital city development, the PUPR sees this project as an ideal platform, given its scale, attention, and infrastructure, to implement mass timber initiatives and advance the country's production and supply chain system. As a pilot project, the PUPR plans to design and construct a 10-story multi-family residential building in the new capital city to demonstrate the potential of mass timber in Indonesia (Ministry of Public Works and Housing 2024). At this stage, the PUPR is actively consolidating various stakeholders, including the wood and bamboo industries, manufacturers, associations, academia, researchers, service providers, government, and other relevant external parties. This collaboration, which includes both domestic and international participants, is focused on developing residential buildings using engineered wood and bamboo.

Like Brazil and South Africa, prior to the government's initiatives on mass timber construction, the private sector in Indonesia was leading its growth from 2015. To date, four manufacturers in Indonesia produce structurally rated mass timber products on a by-request basis. The market is currently limited to domestic demand, which is still in its infancy. The primary mass timber product in Indonesia is glulam. Other mass timber products like CLT production face challenges due to inconsistent local lumber quality and dimensions, making it difficult to secure the steady, uniform supply needed for structural-scale production. Additionally, the high percentage of log-to-lumber waste further hinders the viability of CLT manufacturing in Indonesia.

1.5. Overview of Indonesia's glulam industry

Species used for glulam production in Indonesia are local hardwood species, namely jabon (*Anthocephalus cadamba*) and red meranti (*Shorea leprosula*). The current practice is to source these species from secondary natural production forests in Indonesia, specifically from the Kalimantan and Sulawesi regions. Different forest cover class in Indonesia is defined in Table 2-6. There has been a growing effort to identify alternative tropical plantation species suitable for structurally rated glulam. These include Sumatran pine (*Pinus merkusii*), mangium (*Acacia mangium*), sengon (*Paraserianthes falcataria*), mahogany (*Switenia mahagoni*), teak (*Tectona grandis*), trembesi (*Albizia saman*), merpauh (*Swintonia floribunda*), jelutong (*Dyera costulata*), and sesendok (*Endospermum spp.*) (Awaludin et al. 2025).

The first production of structurally rated glulam in Indonesia was reported in 1996, using merbau (*Intsia bijuga*) for building applications exported to Australia. In Indonesia, the interest in glulam construction gained traction more recently, when one of the mills established a dedicated glulam production line in 2015. Since then, production has steadily grown, reaching a combined capacity of approximately 10,000 m^3/year today. Indonesian manufacturers have undertaken numerous initiatives to expand further, including investing in modern equipment, aligning with EN 14080 standards, securing national and international sustainability certifications, and exploring opportunities to meet U.S. requirements under ANSI A190.1.

More than 15 glulam buildings exist in major cities across Indonesia, including Jakarta, Bogor, Bandung, Yogyakarta, and Bali. The wood was all locally sourced and produced by Indonesia's glulam manufacturers. Construction is limited to low-rise buildings, typically four stories or lower. This is largely because the current national building code does not accommodate tall timber construction. The building types range from single-family residences, primarily high-end private villas, to mixed-use structures such as commercial spaces, community halls, and restaurants. The tallest glulam building in Indonesia was recently completed in 2024, which is a 4-story mixed-use commercial space in the north of Jakarta. It used a hybrid glulam and steel construction system.

1.6. Opportunities of Indonesia's mass timber industry

The case of Indonesia presents a unique perspective on the potential of mass timber. The abundance of local wood resources in Indonesia positions the nation favorably to harness its benefits. As the world's largest archipelagic country, approximately 120.5 million hectares or 63% of Indonesia's total land area is designated as State Forest Area (Ministry of Environment and Forestry 2022a). Indonesia categorizes its forest area into three types, such as conservation forest, protection forest, and production forest. The production forest is further broken down into permanent, limited, and convertible production forests. Production forests are designated to produce timber and non-timber forest products from natural and plantation forests. From Indonesia's total State Forest Area, 29.1 million hectares are equipped with business licenses for wood resource utilization, including 10.9 million hectares of plantation forests and 18.2 million hectares of natural forests. In 2024, Indonesia's State Forest Area produced around 57 million m^3 of round wood logs. Almost 90 percent of the logs were sourced from plantation forests, and the remaining 10 percent were sourced from natural forests (Directorate General of Sustainable Forest Management).

Historically, from 1966 to the 1980s, Indonesia held the position of the world's largest raw log exporter and leading plywood producer. In 1982, timber became the second-largest contributor to Indonesia's economy, after oil and gas (Ministry of Environment and Forestry 2022a). With the enforcement of the raw log export bans in 1985 and again in 2001, the country shifted its forestry sector focus to value-added wood products, particularly plywood. Plywood emerged as the dominant forest product, driving export earnings and helping Indonesia become the world's leading plywood producer during that period.

Today, plywood continues to be a major contributor to Indonesia's wood-based product exports, supported by other value-added items such as engineered wood panels, furniture, pulp, and paper. The technological know-how gained from this robust wood products industry can help position Indonesia to develop a mass timber sector that supports both its environmental and economic goals. However, challenges around sustainable sourcing and regulatory compliance remain critical for the sector's long-term resilience.

1.7. Challenges of Indonesia's mass timber industry

Maximizing the potential for mass timber in Indonesia requires a sustainable supply chain that starts from the source (forest) to the end-of-life (waste). Focusing on the forestry aspect, this requires sustainable forest management that not only optimizes the carbon stock in the forest but also increases carbon pools in long-lived wood products. Unfortunately, as of 2020, Indonesia's forests still act as a carbon source rather than a carbon sink. Carbon sinks absorb more carbon than they emit, whereas carbon sources release more carbon than they absorb. Indonesia's national GHG emissions based on sectors from 2000-2020 are presented in Figure 1-1. The sectors are energy, industrial processes and product use (IPPU), agriculture, forestry and other land use (FOLU), as well as waste.

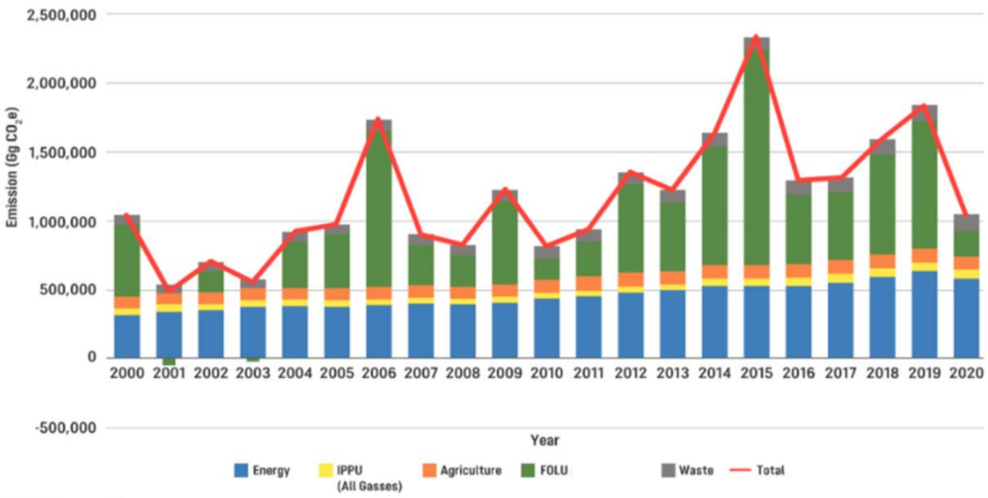


Figure 1-1 Indonesia's National GHG Emissions Based on Sectors

(Source: Ministry of Environment and Forestry 2022a)

Indonesia's average GHG emissions level from the FOLU sector during the period 2000-2020 stood at 499 MTon CO_2e/year, with around 40% of the emissions coming from peat fires (see Figure 1-2). Excluding peat fires, the average annual emissions level was around 230 MTon CO_2e (Ministry of Environment and Forestry 2022a). The study suggests that El Nino was likely responsible for the long and high intensity fires, covering large areas of peatlands.

Contributors to Indonesia's forest carbon emissions include broader land use, land use change (LULUC). The term land use refers to the changes in the carbon of soil and biomass as a result of the use or management of land within the relevant boundary. In this case, land conversion does not occur. For example, wood harvesting activities where the forest remains as forest. Meanwhile, land use changes refer to the changes in the carbon of soil and biomass as a result of changes in land use. In this case, land conversion does occur. An example is forest land converted into cropland.

The GHG emissions and removals for the FOLU sector were categorized based on the six categories of land use as per the IPCC Guidelines 2006. These are forest, crop land, grassland, wetland, settlement, and other land. Each land use category is further categorized into land use or land use change. The emissions included CO_2, CH_4, and N_2O, but the CH_4 and N_2O were calculated from peat fires only. Forest remaining as forests were treated as removals, hence the negative values. As seen in Figure 1-2, forest area that remains as forest is declining. It can be observed that among all the land use change categories, the conversion of non-cropland areas (e.g., forest, wetlands, other lands) into cropland contributes the most to the GHG emissions. There was no information on how much of the converted cropland came from forests or other land types. Despite some fluctuations and a general increasing trend from 2010 to 2018, it has shown a decreasing trend since 2018.

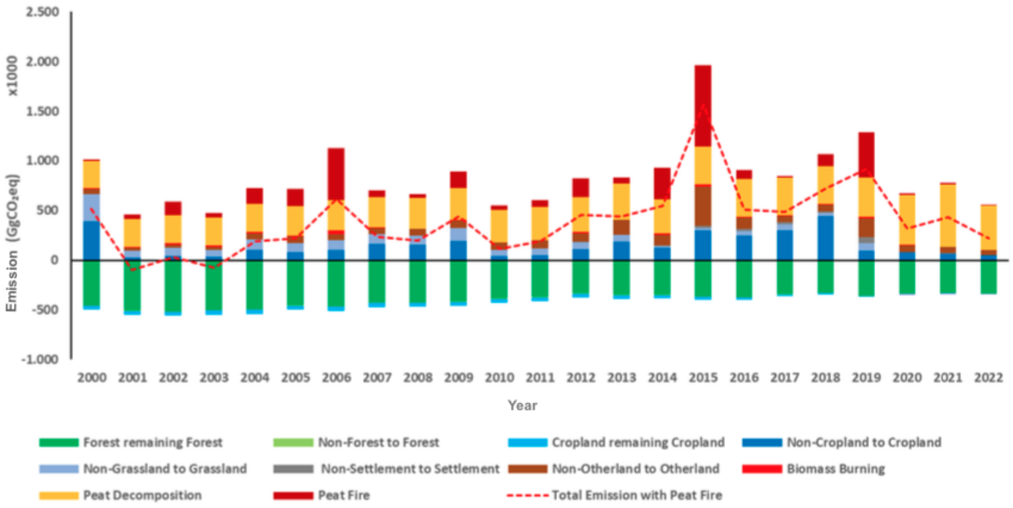


Figure 1-2 GHG Emissions and Removals from Indonesia's FOLU Sector

(Source: Ministry of Environment and Forestry, 2024)

Another study by Friedlingstein et al. (2022) specifically projected Indonesia's net CO_2 fluxes from LULUC using data and bookkeeping models from (i) BLUE (Hansis et al. 2015), (ii) updated H&N2017 (Houghton and Nassikas 2017), and (iii) OSCAR (Gasser et al. 2020). Processes relevant to LULUC were included in the models, including CO_2 fluxes from deforestation, afforestation, logging, and forest degradation (including harvest activity); shifting cultivation (cycle of cutting forest for agriculture, then abandoning); regrowth of forests following wood harvest or abandonment of agriculture; and emissions from peat burning and drainage. Indonesia was the second highest emitter during 2012-2021 after Brazil, followed by the Democratic Republic of Congo. Based on this projection, the three countries contributed more than half of the global total LULUC emissions.

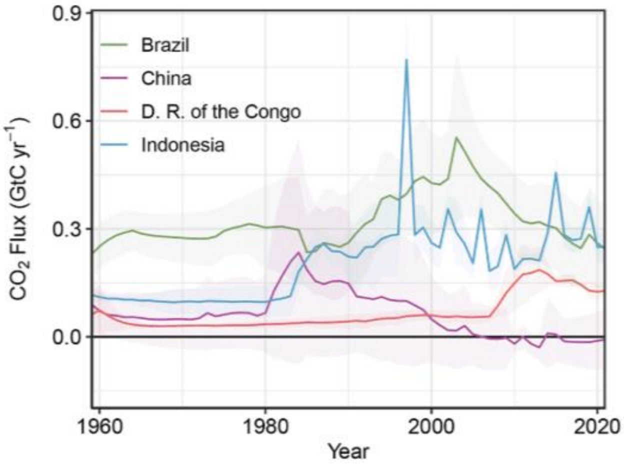


Figure 1-3 Average CO_2 Fluxes from Land Use Land Use Change
(Source: Friedlingstein et al. 2022)

Deforestation and forest degradation are of major concern and a source of LULUC emissions in many tropical countries, including Indonesia. Indonesia's net deforestation in 2021-2022 was 113.5 thousand hectares, which was the lowest rate since 1990 (Ministry of Environment and Forestry 2022a). The rate of deforestation from 1996 to 2000 was 3.51 million hectares (see Figure 1-4). Over the years, the decline in the deforestation rate was driven by a decrease in forest and land fires. Meanwhile, natural forest degradation between the period 2006 and 2020 averaged around 208.8 thousand hectares per year. Of this, about 84% were natural primary dryland forest converted to natural secondary dryland forest (Ministry of Environment and Forestry, 2022b). Description of Indonesia's natural forest cover class is provided in Table 2-6. To achieve a net sink, the forest degradation rate within concession areas has to be lower.

To address the issues with deforestation, a presidential instruction was enacted in 2011 which instructed ministries, governors, and regents to postpone the issuance of new business licenses in primary forests and peatlands in 2011-2013 (Presidential Instruction No. 10 of 2011 on Moratorium of the Issuance of New Licenses and Governance Improvement of Primary Forests and Peatlands). The moratorium was extended three times and finally made permanent in 2019. In 2021, the Ministry of Environment and Forestry established a map for the termination of the issuance of business licenses. With this regulation, new permits were no longer issued until the governance of primary forests and peatlands are improved. The permanent moratorium covers approximately 66.2 million hectares of primary forests and peatlands (Ministry of Environment and Forestry 2022a).

To address forest degradation, Indonesia has rehabilitated approximately 3 million hectares of degraded land over the past decade. The country also participates in the UNFCCC's REDD+ program, which supports efforts to enhance forest carbon stocks. As part of this program, Indonesia is required to quantify, monitor, and report GHG emissions and removals from LULUC-related activities. Most forest gains, as a result of afforestation and reforestation activities, come from the conversion of dry shrubland (50%), with secondary dryland forests receiving the largest share of the total gains (48%) (Ministry of Environment and Forestry 2022b).

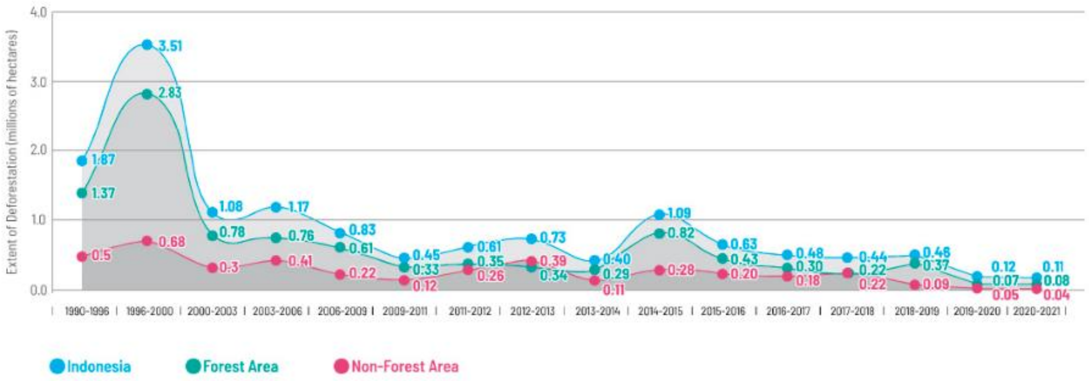


Figure 1-4 Indonesia’s Deforestation Trends

(Source: Ministry of Environment and Forestry 2022a)

Further complicating the issues of deforestation are illegal deforestation and its associated trade risks (IDAT), which continue to challenge tropical countries like Indonesia. As of 2021, Indonesia is the first and currently the only country globally to implement an operational Forest Law Enforcement, Governance, and Trade (FLEGT) licensing scheme. This reflects the Indonesian government's substantial efforts to establish a mandatory national system for tracking and verifying timber legality and combating illegal logging, known as the *Sistem Verifikasi Legalitas Kayu* (SVLK) or Timber Legality Verification System, introduced in 2009. Indonesia began issuing FLEGT licenses on November 15, 2016. By 2019, the SVLK encompassed 99 percent of the total concession area (Forest Trends 2021).

Although Indonesia has implemented a national system to track and verify timber legality and curb illegal imports, reports of illegal logging persist. Corruption, especially at the local level, remains a challenge that can weaken the effectiveness of the system. According to Forest Trends’ Timber Legality Country Risk Dashboard, Indonesia has a legality risk score of 49.8 out of 100, placing it in the medium-risk category (Forest Trends 2021). This score was determined based on factors such as corruption, governance, and political and harvest risks associated with a trading country (Forest Trends 2022).

Given Indonesia's GHG emission profile over the past years (as seen in Figure 1-1), the government has targeted the forestry and other land use (FOLU) sector to serve as the country's carbon sink by 2030 to achieve carbon neutrality. The initiative is known as FOLU Net Sink 2030, where Indonesia aims to have a FOLU sector that contributes to the removal of carbon emissions of 140 MTon CO_2e by 2030, and 304 MTon CO_2e by 2050 (Ministry of Environment and Forestry 2023). This sector is expected to be the largest contributor to GHG emissions reductions (approximately 60%) outlined in Indonesia's Nationally Determined Contributions (NDC) under the Paris Agreement. The GHG emissions projection under the current policy scenario (CPOS), transition scenario (TRNS), and low carbon scenario compatible with the Paris Agreement (LCCP) are provided in Figure 1-5.

According to the Ministry of Environment and Forestry (2022), shifting FOLU from a net emitter to a net sink by 2030 will be highly dependent on the success of several actions, including: (i) reducing emissions from deforestation and peatlands; (ii) increasing the carbon sequestration capacity of natural forests by reducing degradation and increasing forest regeneration; (iii) restoring peatlands; (iv) implementing forest restoration through enrichment planting and increasing carbon sequestration; (v) adopting sustainable forest management practices; and (vi) maximizing the use of unproductive or low-carbon land for the development of forest plantations, and other perennials (industrial crops).

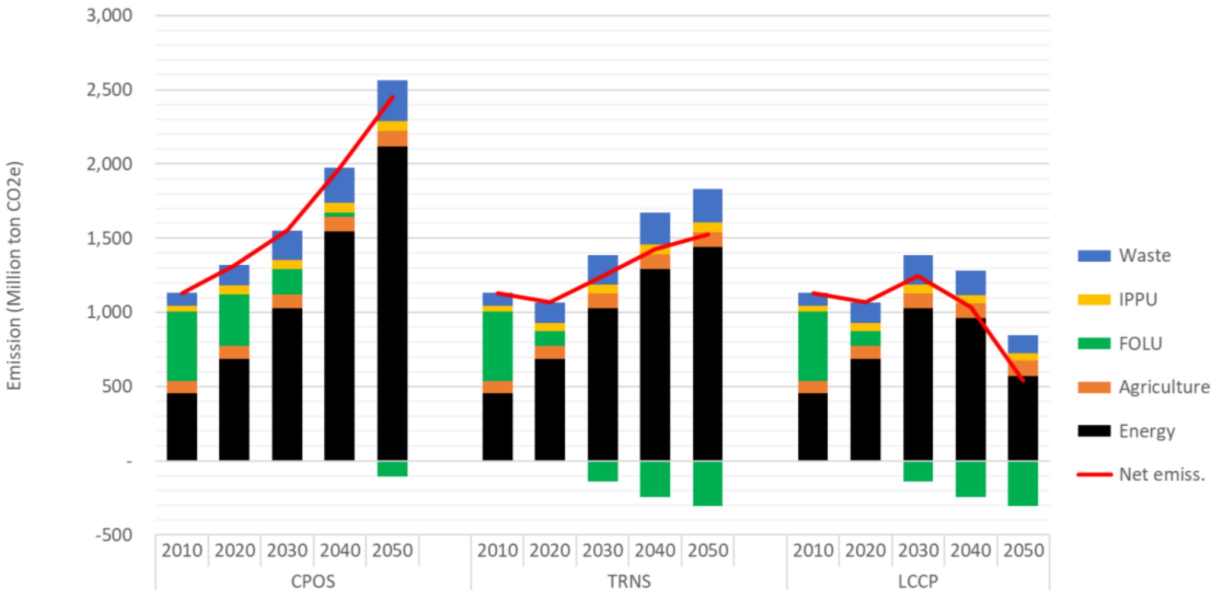


Figure 1-5 Indonesia's GHG emissions projection under the current policy scenario (CPOS), transition scenario (TRNS), and low carbon scenario compatible with the Paris Agreement (LCCP)

Source: (Ministry of Environment and Forestry 2022c)

Indonesia's climate target of achieving carbon neutrality by 2030 will play a key role in maximizing the environmental benefits of mass timber construction. As seen in temperate regions, long-lived forest products such as mass timber can contribute to enhancing carbon pools and extending carbon storage over time. Thus, the combined carbon stocks in both forests and wood products create a feedback loop, promoting stability and contributing to long-term sustainability.

1.8. Study needs and objectives

Indonesia's consideration of adopting mass timber for ambitious construction projects like the development of Indonesia's new capital city, Nusantara, highlights the need to understand its environmental impacts and benefits. However, there are currently no LCA studies specifically on mass timber construction in Indonesia. The first step in understanding the environmental benefits and impacts of mass timber construction in Indonesia is through a regionally focused LCA at the product level. Since glulam is currently the primary mass timber product manufactured in Indonesia, this study will document its supply chain and perform a cradle-to-gate LCA of glulam produced in Indonesia.

In addition, LULUC is a major contributor to Indonesia's GHG emissions and can affect the overall climate impacts of wood products. However, LCAs of wood products often exclude LULUC emissions, partly due to the lack of consensus on how to consistently and accurately account for them. This study aims to address that gap by incorporating LULUC into the LCA of glulam production in Indonesia. A baseline was developed based on the existing production conditions, where logs are harvested from forests that remain as forests, i.e., with no LULUC emissions. In addition, two LULUC scenarios were assessed to reflect conditions where logs are harvested from forest lands that have undergone conversion. One scenario involves conversion from primary to secondary dryland forest, representing forest degradation, while the other involves conversion from dry shrubs to secondary dryland forest, representing forest gains. The objective is to demonstrate how such impacts can be integrated into LCA and to evaluate how LULUC contributes to the overall climate change impacts of glulam.

2. Methodology

To achieve the above objectives, this study uses a Life Cycle Assessment (LCA) approach based on the ISO 14040 and ISO 14044 standards (ISO 2006a, 2006b).

2.1. Scope of the Study

2.1.1. *Declared unit*

The object of this study is a structurally-rated glued laminated timber (glulam) produced in Indonesia using two local hardwood species, namely jabon and red meranti. A declared unit of 1 m^3 of glulam was used for this study. The combined production capacity of glulam produced in Indonesia by two companies is estimated at 10,000 m^3/year. This study surveyed both companies, representing 100 percent of the total structural glulam production in Indonesia.

2.1.2. *System boundary*

The system boundary of this LCA covers the life cycle stages A1-A3, as shown in Table 2-1 and Figure 2-1. This cradle-to-gate LCA considers all the relevant products and processes to produce a structurally rated glulam ready to be delivered from the manufacturing site. This includes the production of all upstream processes including upstream transportation (e.g. log and lumber transportation) (A1), transportation of main resources and materials to the glulam facility (A2), and glulam production (A3).

Impacts associated with transport to construction sites, assembly, use, and end-of-life were excluded from this study. Due to the exclusions of these modules, this study is not intended to make comparative assertions per ISO 14040. Other processes such as the manufacturing of capital equipment, facility maintenance, and labor costs are beyond the scope of this LCA.

Table 2-1 Description of the System Boundary Modules

Production			Construction		Use							End-of-life		Benefits and Loads Beyond the System Boundary		
A1	**A2**	**A3**	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Resource extraction	**Transportation to facility**	**Manufacturing**	Transportation to site	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Building operational energy use during product use	Building operational water use during product use	Deconstruction	Transport	Waste processing	Disposal	Reuse, recovery, recycling potential
√	√	√	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI

NI: Not included in this study

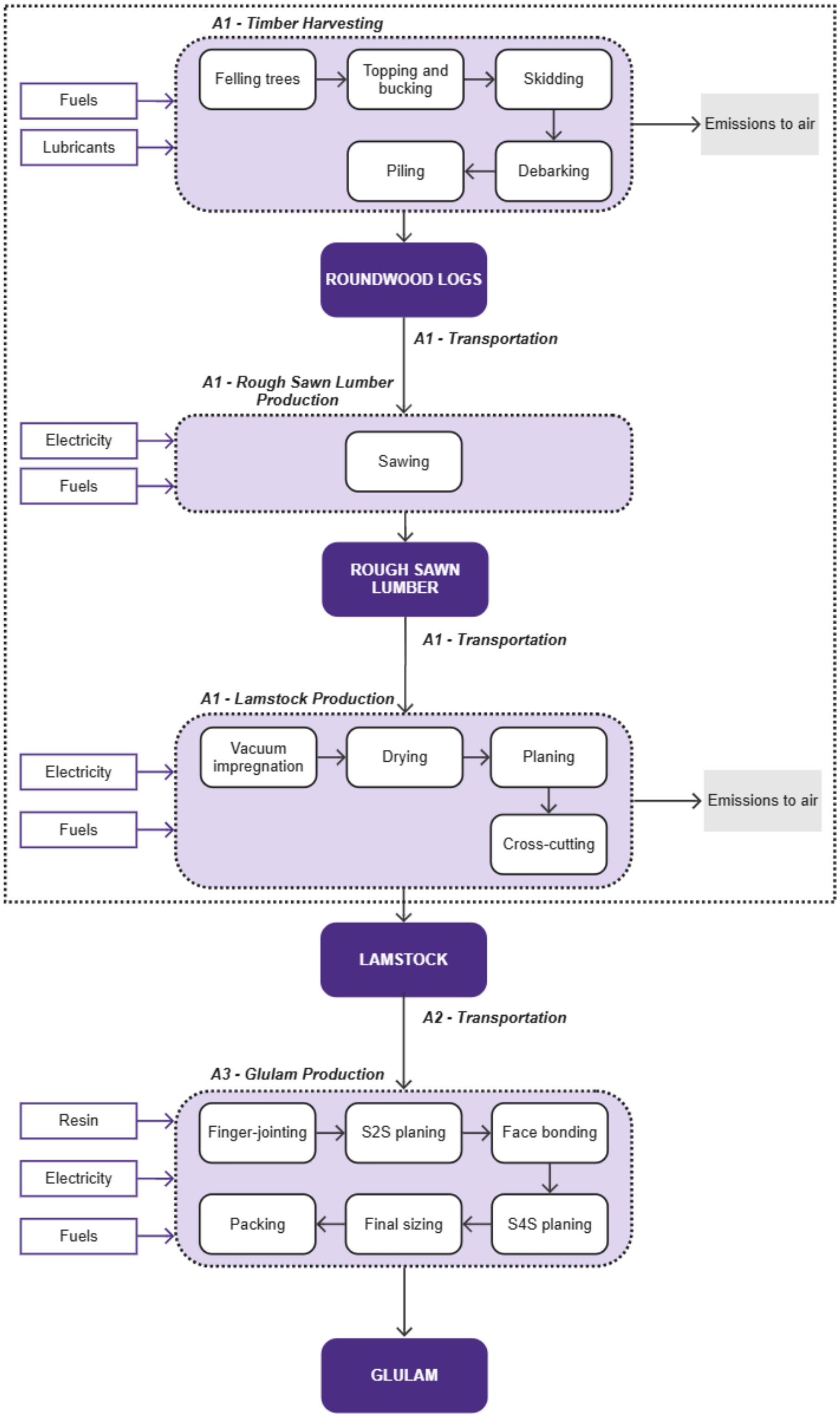


Figure 2-1 System boundary of glued laminated timber included in this LCA

2.1.3. *Allocation rules*

Allocation is the approach used to divide the environmental burdens of a process when multiple products or functions share that process. In this case, the input material is a round log that is processed into rough-sawn lumber, then lamstock, and subsequently into glulam. Co-products are generated during each processing stage, including off-cuts, slabs, sawdust, planer dust, trimmings, and wood chips. These co-products are either sold for other economic uses or processed into other products such as finger-jointed laminated boards or pallets. This study applies a mass allocation to the product and co-product generated. Thus, the environmental impacts were allocated between the main product and co-products based on their mass.

2.1.4. *Calculation rules*

To reflect the production of the two surveyed mills, a combined average was calculated using a production-weighted approach (Equation 1). This gives greater weight to data from the larger producer. Missing data was carefully recorded so they would not be treated as zeros.

$$w_1 = \frac{y_1}{(y_1 + y_2)} = \frac{y_1}{Y_{total}}$$

Equation 1 Production-Weighted Approach

w_1 = weighting factor for mill 1
y_1 = annual production of mill 1
Y_{total} = total annual production of "y" mills

2.2. Data Collection Process

Both primary and secondary data were collected for this study. Primary life cycle inventory (LCI) data were obtained through tailored surveys (see Appendix A) for the production of rough sawn lumber, lamstock, and glulam, including their associated transportation requirements for the 2024 calendar year. Two glulam manufacturers were surveyed, which account for 100% of Indonesia's glulam production in 2024. Data collected included the overall manufacturing process, the resources required (inputs) and emissions generated (outputs) during production activities. All surveys were conducted manually during on-site visits, followed by Zoom interviews. Site visits to the glulam manufacturing facilities took place in September 2024, while sawmill visits occurred in April 2025.

Secondary LCI data were collected from academic literature and LCI databases. The LCI database used was primarily from ecoinvent, applying country-specific processes whenever available, or using global and rest-of-the-world processes when local data was not available. For processes lacking regional or global data, U.S.-based databases such as CORRIM, US-EI 2.2, and USLCI were used. The secondary LCI data sources used in this LCA are listed in Appendix B.

In addition to the LCI data, insights into the broader state of the mass timber industry in Indonesia were gathered through stakeholder engagement activities, which included a dedicated workshop and discussions conducted during site visits. The workshop was held on September 24, 2024, aimed at deepening the understanding of current practices, challenges, and strategies related to mass timber production and construction in Indonesia. The event was hosted by the Ministry of Public Works and Housing of the Republic of Indonesia and brought together key stakeholders, including representatives from government agencies, research and academic institutions, producers, and the general public. The workshop provided valuable qualitative data on industry dynamics, regulatory and technical barriers, and the potential for future development. Combined with the discussions during site visits in September 2024 and April 2025, these insights helped provide context for the life cycle data and supported the interpretation of results in this study.

2.3. Life Cycle Inventory Analysis

The life cycle inventory (LCI) was developed using 2024 production data and the corresponding material flows during that period. As illustrated in Figure 2-1, this study adopts a cradle-to-gate approach for glulam production. The LCI data were grouped into modules aligned with EN 15804. The A1 module covers all upstream processes, such as timber harvesting and log transportation, rough sawn lumber production and transportation, as well as lamstock production. The A2 module covers the transportation of main resources and materials to the glulam facility, such as lamstock, resin, and packaging materials (collectively referred to as “lamstock transport”). The A3 module specifically covers the glulam production.

2.3.1. Resource extraction (A1)

Timber harvesting

Wood used for glulam production in Indonesia is sourced from natural secondary dryland forests designated as production forests within the Central Kalimantan and Central Sulawesi regions. Secondary dryland forest is described as a natural tropical forest growing on non-wet habitat that exhibit signs of logging activities indicated by patterns and spotting of logging (appearance of roads and logged-over patches). According to Ministry of Environment and Forestry Regulation No. 8 of 2021, timber harvesting in natural forests is permitted under a timber utilization license (IUPHHK-HA). Clear cutting is prohibited, and selective cutting is required. The commonly implemented silviculture method is locally known as *Tebang Pilih Tanam Indonesia* (TPTI), or selective cutting and planting. After harvesting, companies are required to restore the productivity of areas used for temporary infrastructure, such as skidding tracks and temporary log yards, through planting and monitoring. The logged forest areas are left to regenerate through natural succession. Planting and monitoring activities are not included in this study.

Harvesting red meranti typically occur on a 30 to 40 year cycle, targeting trees with a diameter of 40 cm or more. For *jabon*, at 10 to 15 years, it can reach a diameter of 20 to 30 cm or more since it's a fast-growing species. Under TPTI guidelines, at least 25 core trees per hectare, such as commercial trees with a minimum diameter of 20 cm, must be left standing to ensure regeneration for the next cycle (Indrawan, 2002). Also, license holders are also required to implement reduced impact logging (RIL) practices.

For timber harvesting, this LCA considers the following activities aligned with RIL practices: (i) felling, topping, and log bucking; (ii) skidding; (iii) debarking and piling at the temporary log yard. LCI data were sourced from an LCI database, such as ecoinvent, for meranti harvesting in Malaysia and were adjusted using primary data based on typical harvesting practices for a red meranti in natural secondary dryland forests of the Kalimantan region. Primary data collected from a forest management company for this study included the average designated forest area logged per year, the annual volume of logs produced, the types, and the sizes of harvesting equipment used.

Table 2-2 summarizes the inputs and outputs considered in this LCA for timber harvesting. Land occupation refers to the area designated for harvesting activities in a year to produce 1 m^3 of logs, expressed in m^2a, where 'a' indicates annually. Land transformation represents the area where harvesting occurs. Since the forest remains forest, the land cover type "from" and "to" is the same. The biogenic carbon removal from the atmosphere was estimated using the dry density of the wood. The dry density was based on the production-weighted average of red meranti and jabon, which is 475 kg/m^3.

Harvesting is done manually. Trees are felled with chainsaws and cut into logs below the first branches. The logs are bucked into lengths of 4 to 6 meters. Crowns and branches are left on the forest floor. Crawler tractors are used to haul logs from their felling site to the temporary log yard located near the felling site. Tractors are restricted to skidding tracks. At the temporary log yard, a wheeled loader is used to load/unload the logs for log debarking and piling. Debarking is done using a chainsaw.

Table 2-2 Inputs-Outputs for Timber Harvesting

Products	**Value**	**Unit**	**Mass Allocation**
Input			
Hardwood, standing	2	m^3	
Land occupation	300	m^2a	
Land transformation, from forest, extensive	180	m^2	
Land transformation, to forest, extensive	180	m^2	
Carbon dioxide, biogenic, sequestered in wood	1742	kg	
Diesel	177.27	MJ	
Lubricants	0.160	lb	
Output			
Logs	1	m^3	100%
Residues: stump, bark, crown, branches	1	m^3	
Emissions to air			
Carbon dioxide, biogenic, loss from harvesting, residues left on site	853	kg	
Dinitrogen monoxide	0.0051	kg	
Methane, biogenic	0.75	kg	
Particulate matter < 2.5	2.60	kg	
Particulate matter > 10	1.73	kg	
Particulate matter > 2.5 and < 10	2.17	kg	

Log transportation

This stage covers the transportation of debarked logs from the temporary log yard to the main log yard, and to the sawmill. Transport between log yards is typically carried out using heavy-duty logging trucks with a capacity of 60 m^3 and an average distance of 30 km. The average transport distance from the main log yard to the sawmill is 70 km. In some cases, logs are transported from the main log yard to the sawmill using a floating barge pulled by a tugboat with an average distance of 100 km. These transport distances reflect the condition where all logs are processed at sawmills located within the same region as the harvest site.

Rough-sawn lumber production

Production begins with processing logs into rough-sawn lumber at the sawmill. A large diesel tractor equipped with a claw attachment transports logs from the landing area into the mill. An electric crane lifts each log onto the log conveyor deck for positioning. Logs are first squared up into cants and then further sawn into slabs using a bandsaw, producing large flitches. These are then resawn on a pony bandsaw to the desired thickness. The resulting pieces are further sawn to the required width with ripsaws and finally trimmed to length using a circular saw. The conveyor deck facilitates the movement of lumber between each processing stage. The sawing machines and conveyor deck are powered by electricity.

Primary data was from two sawmills handling red meranti from the natural secondary dryland forests of the Kalimantan region. These values may differ for other species or locations. Table 2-3 summarizes the inputs and outputs for this production stage.

Table 2-3 Inputs-Outputs for Rough Sawn Lumber Production

Products	**Value**	**Unit**	**Mass Allocation**
Input			
Logs, green	1.61	m^3	
Electricity	39.58	kWh	
Diesel	147	MJ	
Lubricants	0.14	kg	
Output			
Rough sawn lumber, green	1	m^3	62%
Offcuts/slabs	222.14	kg	19%
Sawdust	133.29	kg	11%
Wood chips	88.86	kg	8%

Rough-sawn lumber transportation

This stage covers the transportation of rough-sawn lumber from sawmills to the next processing facility, which may be either an intermediate facility or a glulam manufacturing facility. When both the sawmill and the processing facility have their own ports, the lumber can be shipped directly by vessel. The average transport distance is 600 km. Otherwise, it is first transported by truck to a port, shipped by vessel to another port, and then moved by truck to the processing facility. In this scenario, the average transport distance is 750 km by road (i.e., truck) and 1000 km by water (i.e., vessel).

Lamstock production

This stage involves processing rough-sawn lumber into lamstock for glulam production. Lamstock is defined as a special grade of lumber used in the production of laminated timbers. The rough sawn lumber arrives at the facility in a green state, with an average moisture content ranging from 40% to 70%. This moisture content varies depending on whether it has been previously air-dried. The processing steps included in this stage are vacuum impregnation, drying, planing, and cross-cutting.

Vacuum impregnation is carried out in a 12 m^3 chamber, where the lumber is treated with a borax-, boric acid-, or boron-based solution to prevent mold. A typical impregnation cycle lasts around four hours. After treatment, the lumber is loaded into drying chambers to reduce its moisture content to 10 to 12%. The drying process usually takes between 22 and 28 days, depending on the initial moisture levels. At 12% moisture content, jabon has an average density of 400 kg/m^3, while red meranti averages 650 kg/m^3. Finally, the lumber is planed and crosscut to remove defects and achieve consistent dimensions and quality suitable for glulam production.

The standard lamstock dimensions for glulam production are generally 40-50 mm thick and 140-150 mm wide.

All machinery used in this stage is powered by electricity. For the drying process, the kiln dryers also rely on steam produced by on-site boilers. Wood waste from the production process, such as trimmings, is used as feedstock for boilers. Any remaining trimmings are used to make other products, such as finger jointed laminated boards, or sold. Transportation within the facility is done using a diesel-powered forklift. Table 2-4 summarizes the inputs and outputs for this production stage.

Table 2-4 Inputs-Outputs for Lamstock Production

Products	**Value**	**Unit**	**Mass Allocation**
Input			
Rough sawn lumber, green	1.63	m^3	
Electricity	117.82	kWh	
Diesel	68.49	MJ	
Disodium Octaborate Tetrahydrate	0.13	kg	
Water	28.43	kg	
Trimmings combusted in boiler	173.77	kg	
Output			
Lamstock, dried	1	m^3	83%
Sawdust	49.94	kg	9%
Trimmings (sold)	46.98	kg	8%
Trimmings for fuel	173.77	kg	

2.3.2. Transport of materials (A2)

This section describes the transportation modes and average distances for materials used in glulam manufacturing. A production-weighted average was then applied to account for the mix of supply chain logistics.

Lamstock transportation

Lamstock is transported from an intermediate processing facility to the glulam manufacturing facility using 20 m^3 diesel trucks with an average distance of 30 km.

Resin transportation

The resins used for glulam production in Indonesia are phenol-resorcinol-formaldehyde (PRF) and polyurethane (PUR). Resins sourced locally are transported by diesel trucks for an average of 382 km to the glulam mill. Imported resins travel by truck for 430 km and by vessel for approximately 25,743 km to the glulam mill.

Packaging materials transportation

Materials used for glulam packaging are wrapping material, strapping, and cardboard protectors. These were assumed to be sourced from local suppliers located in the nearest city to each glulam mill. The average distance is 28 km by diesel truck.

2.3.3. Glulam manufacturing (A3)

All structural-rated glulam in Indonesia is manufactured on the island of Java. Glulam production begins with finger-jointing the lamstock, followed by S2S (surfaced two sides) planing, face bonding, S4S (surfaced four sides) planing, final sizing, and packing. Finger jointing allows the length of the laminations to extend up to 15 meters. Joints are cut at both ends of the lamstock and structural resin such as PUR or PRF is applied and cold-cured. The finger-jointed lamstock is then planed on two sides to prepare for face bonding. The same resin (PUR or PRF) is applied to the lamstock faces manually or using a glue spreader. Primers or hardeners are not used in the production process. Due to the high humidity and weather temperature in Indonesia, the open time is 30 minutes. The laminations are then assembled into the specified layup, and pressure is applied. Face bonding is also cold-cured. Pressing times may vary depending on the layup configuration; but generally a standard layup of 140 mm × 280 mm × 12 m requires 8 hours of pressing.

After pressing, the layup passes through a four-sided planer to remove any adhesive squeeze-out. Depending on the intended application, the glulam undergoes final cutting, connector fitting, and finishing. Bifenthrin may be used as an envelope coating, mixed with the base coat of the glulam product after machining. This is to protect against a wide range of insects, including termites, wood borers, and beetles. Thinner is typically used as a mixing agent for topcoat applications during the finishing process at the factory. Finally, the finished glulam products are packed using wrapping materials, strapping, and cardboard.

All the glulam production machines are powered by electricity. Lubricants are used on all moving parts in a machine. In-house transportation is done using a diesel-powered forklift. The inputs and outputs collected from the glulam surveys for 1 m^3 of glulam produced are listed in Table 2-5. These values represent the weighted average of the two producers.

Table 2-5 Inputs-Outputs for Glulam Manufacturing

Products	**Value**	**Unit**	**Mass Allocation**
Input			
Lamstock, dried	1.46	m^3	
Electricity	186.21	kWh	
Resin, PUR	5.22	kg	
Resin, PRF	2.66	kg	
Diesel	67.23	MJ	
Lubricant	0.05	kg	
Water	1.52	kg	
Insecticide	0.0015	kg	
Coating	0.62	kg	
Thinner	0.85	kg	
Packaging, spacers	0.60	kg	
Packaging, wrapping material	0.64	kg	
Packaging, strapping	0.08	kg	
Output			
Glulam	1	m^3	69%
Co-products: sawdust, planer dust, trimmings	218.90	kg	31%

2.3.4. *Land use land use change (LULUC) data*

Survey results from glulam manufacturers indicate that logs used for glulam production are not associated with any land conversion. This serves as the baseline with zero LULUC contribution. Additionally, two LULUC scenarios were developed to reflect conditions where logs are harvested from forest lands that have undergone conversion. One scenario involves conversion from primary to secondary dryland forest, representing forest degradation, while the other involves conversion from dry shrubs to secondary dryland forest, representing forest gains. These land cover classes align with Indonesia's Land Cover Classification Standard (SNI 7645:2010) and their description is provided below:

Table 2-6 Description of Land Cover Classes used for LULUC Calculation

Land cover class	**Description**
Primary dryland forest	Natural tropical forests growing on non-wet habitat including lowland, upland, and montane forests. The class includes heath forest and forest on ultramafic and limestone, as well as coniferous, deciduous and mist or cloud forest, which is not (or low) influenced by human activities or logging.
Secondary dryland forest	Natural tropical forest growing on non-wet habitat including lowland, upland, and montane forests that exhibit signs of logging activities indicated by patterns and spotting of logging (appearance of roads and logged-over patches). The class includes heath forest and forest on ultramafic and limestone, as well as coniferous, deciduous and mist or cloud forest.
Dry shrub	Highly degraded logged-over areas on non-wet habitat that are in an ongoing process of succession but have not yet reached a stable forest ecosystem, with naturally scattered trees or shrubs

Source: SNI 7645:2010

For the two LULUC scenarios, this was calculated using a stock-difference approach (see Equation 2) using primary and secondary data. The carbon stocks were derived from above-ground and below-ground biomass stocks in primary dryland forest in Kalimantan, secondary dryland forest in Kalimantan, and dry shrubs (Ministry of Environment and Forestry 2022b). To allocate LULUC removals or emissions to the product (1m^3 of logs), the area affected by land use change was assumed to be the area required to harvest 1 m^3 of logs. This affected area was assumed to be 100% converted. To annualize the emissions, a timeframe of 55 years was used based on the forest concession duration. Data on the harvested area and amortization period were based on primary data, such as surveys with a forest management operator. Survey template is provided in Appendix A.

$$LULUC = \frac{(C_i - C_j) \times A}{t} \times (\frac{44}{12})$$

Equation 2 LULUC Stock-Difference Approach

$LULUC$ = Removals or emissions from land use change (kg CO_2e/1 m^3 of logs/year)
C_i = Carbon stock before land-use change in land use class *i* (kg C/ha)
C_j = Carbon stock after land-use change in land use class *j* (kg C/ha)
A = Area affected by land use change (ha/m^3)
t = Amortization period

Table 2-7 LULUC Data

Description	**Value**	**Unit**
Carbon stock change from primary to secondary dryland forest in Kalimantan	66,430	kg C/ha
Carbon stock change from dry shrubs to secondary dryland forest in Kalimantan	-69,134	kg C/ha
Harvested area for 1 m^3 of logs	0.0058	ha/m^3
Amortization period based on the forest concession duration	55	years
LULUC emissions due to conversion from primary to secondary dryland forest for 1 m^3 of logs	25.83	kg CO_2e/ m^3/year
LULUC removals due to conversion from dry shrubs to secondary dryland forest for 1 m^3 of logs	-26.88	kg CO_2e/ m^3/year

2.4. Data Analysis

2.4.1. <u>Impact assessment</u>

Data was analyzed using SimaPro, a software designed for LCA that incorporates various LCA databases and impact assessment methods. The EN 15804 + A2 method was used to model the environmental impacts, and the EF 3.1 normalization and weighting values (published in July

2022) were used. This method uses the same approach as the Environmental Footprint 3.1 method, except for the approach on biogenic carbon. Details on the biogenic carbon accounting done for this LCA are presented in Section 2.4.2. The environmental impacts that are assessed in this study are listed in Table 2-8.

Table 2-8 Environmental impact categories assessed in this study

Impact Category	Indicator	Unit	Model
Climate change, total	Global Warming Potential, total	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change, fossil	Global Warming Potential, fossil fuels	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change, biogenic	Global Warming Potential, biogenic	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change, land use and land use change	Global Warming Potential, land use and land use change	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013

Source: BS EN 15804-2019

2.4.2. Treatment of biogenic carbon

Mass timber is a bio-based material that contains biogenic carbon. Hence, the mass flows of biogenic carbon (uptake, transfer, and emission) to and from nature and mass timber throughout the system boundary will be reported in this LCA. A “-1 in/+1 out” method is used consistently across EN and ISO standards to account for biogenic carbon entering and leaving the product system. In this method, carbon enters the product system through biomass in the wood product (-1) and exits as emissions to the atmosphere (+1). The use of this methodology is contingent upon certain assumptions about wood sourcing, though terminology and definitions vary across standards. This variability is further discussed in Section 4.3.

In this LCA, all biogenic carbon flows were modelled under the “Climate change, biogenic” impact category, and the “-1 in/+1 out” method was applied, since the wood is not sourced from native forests (per EN 15804:2012+A2:2019). Native forests exclude short-term forests, degraded forests, managed forests, and forests with short-term or long-term rotations. The uptake of biogenic carbon by the product system will be documented in the A1 module (resource extraction) and the export of biogenic carbon leaving the product system will be documented in C3/C4 module (end-of-life).

2.4.3. <u>Land use land use change (LULUC) analysis</u>

This impact category accounts for biogenic carbon exchanges from deforestation, degradation, and other soil activities. The EN 15804 + A2 method, which adopts the EF 3.1 method, only accounts for direct land use change and excludes indirect land use change. The modelling guideline follows PAS 2050:2011. This LCA assessed 3 LULUC scenarios as follows:

1. No LULUC removals/emissions to represent the existing production conditions, where logs are harvested from a forest that remains as forest;
2. LULUC emissions from forest degradation due to conversion from primary to secondary dryland forest; and
3. LULUC removals from forest gains due to conversion from dry shrubs to secondary dryland forest.

Description of the different land cover classes used for the LULUC analysis is provided in Table 2-6.

2.5. Assumptions and Limitations

Several key assumptions and limitations of this study are as follows:

- Due to limited upstream data on jabon, these upstream processes, such as timber harvesting and rough sawn lumber production, were based on red meranti from the natural secondary dryland forests of the Kalimantan region.

- Most co-product amounts were not recorded by the mills. Allocations among co-products were primarily based on expert opinions (i.e., mill operator).
- Electricity consumption data were typically reported at the facility level, covering other production lines and office use. Consumption for the target production line was estimated based on its share of total production for the facility for that given year.
- Secondary LCI databases (resin, diesel, lubricants, etc.) reflect generic production averages, not actual mill data. Some used in this study were global datasets due to a lack of Indonesian-specific data (see Appendix B).
- Use and end-of-life stages are excluded from modelling but discussed in Section 4.4 as a consideration for future studies.
- This study used a mass allocation between the main and the co-products. Using a different allocation method, for example, economic allocation, is likely to influence the results.
- This study focuses on climate change impacts. Assessing other impact categories, such as acidification, eutrophication, or human toxicity, would provide a more comprehensive assessment of the potential environmental impacts.

3. Results

3.1. Life Cycle Impact Assessment Results

The Life Cycle Impact Assessment (LCIA) results were grouped into modules aligned with EN 15804. The A1 module covers all upstream processes, such as timber harvesting and log transportation, rough sawn lumber production and transportation, as well as lamstock production. The A2 module covers the transportation of main resources and materials to the glulam facility, such as lamstock, resin, and packaging materials (collectively referred to as “lamstock transport”). The A3 module specifically covers the glulam production.

The cradle-to-gate (A1-A3) impact results for 1 m^3 of glulam production are presented in Table 3-1. This represents the baseline condition, with no LUC impact. A detailed breakdown of the impacts by process within modules A1 to A3 is provided in Table 3-2. The fossil emissions from the production of 1 m^3 of glulam in Indonesia are 523.26 kg CO_2 eq. During tree growth, 1,176.67 kg CO_2 eq. was absorbed and stored in the wood used to make 1 m^3 of glulam (see Table 3-2). This represents the net removal of biogenic carbon from the atmosphere, after accounting for the portion released back due to harvesting residues left on site. In the lamstock production stage, 262.56 kg CO_2 eq. was released when trimmings were burned for drying. As a result, 914.11 kg CO_2 eq. of biogenic carbon remains stored in 1 m^3 of glulam. Thus, the overall product’s carbon balance is -390.85 kg CO_2 eq.

Table 3-1 Cradle-to-gate impact results for 1 m^3 of glulam

Impact category	**Unit**	**Total**	**A1**	**A2**	**A3**
Climate change, total	kg CO_2 eq.	(390.85)	(590.28)	6.70	192.73
Climate change, fossil	kg CO_2 eq.	523.26	323.83	6.70	192.73
Climate change, biogenic	kg CO_2 eq.	(914.11)	(914.11)	0	0
Climate change, luluc	kg CO_2 eq.	0	0	0	0

Table 3-2 Detailed impact results based on modules for 1 m^3 of glulam

Module	**Climate change, fossil (kg CO_2 eq.)**	**Climate change, biogenic (kg CO_2 eq.)**	**Climate change, luluc (kg CO_2 eq.)**
A1	**323.83**	**(914.11)**	**0**
Timber harvesting	25.96	(1,176.67)	0
Log transport	12.90	0	0
Lumber production	54.29	0	0
Lumber transport	84.80	0	0
Lamstock production	145.88	262.56	0
A2	**6.70**	**0**	**0**

Module	Climate change, fossil (kg CO_2 eq.)	Climate change, biogenic (kg CO_2 eq.)	Climate change, luluc (kg CO_2 eq.)
Lamstock, resin, packaging material transport	6.70	0	0
A3	**192.73**	**0**	**0**
Glulam Production	192.73	0	0

3.2. Contribution analysis on fossil emissions

The values from the "climate change, fossil" impact category reflect the reliance on fossil-based inputs throughout the life cycle of the product. A contribution analysis of fossil emissions across the life cycle stages is shown in Figure 3-1. Glulam production contributed the largest share of fossil emissions, accounting for 37% of the total. This was followed by lamstock production at 28% and lumber transport at 16%.

Electricity consumption was a major contributor to fossil emissions, responsible for 62% of the total cradle-to-gate emissions (Figure 3-2). At the individual production stages, electricity contributes 81% in glulam production, 54% in lamstock production, and 62% in lumber production (see Figure 3-4, Figure 3-5, and Figure 3-6). The second contributor to fossil emissions was lumber transport, accounting for 16% of the total cradle-to-gate emissions, and specifically 37% to the lamstock production. The remaining processes contribute to less than 10% of the total cradle-to-gate emissions. Detailed process contribution based on production stages are provided in Figure 3-3 and Table 3-3.

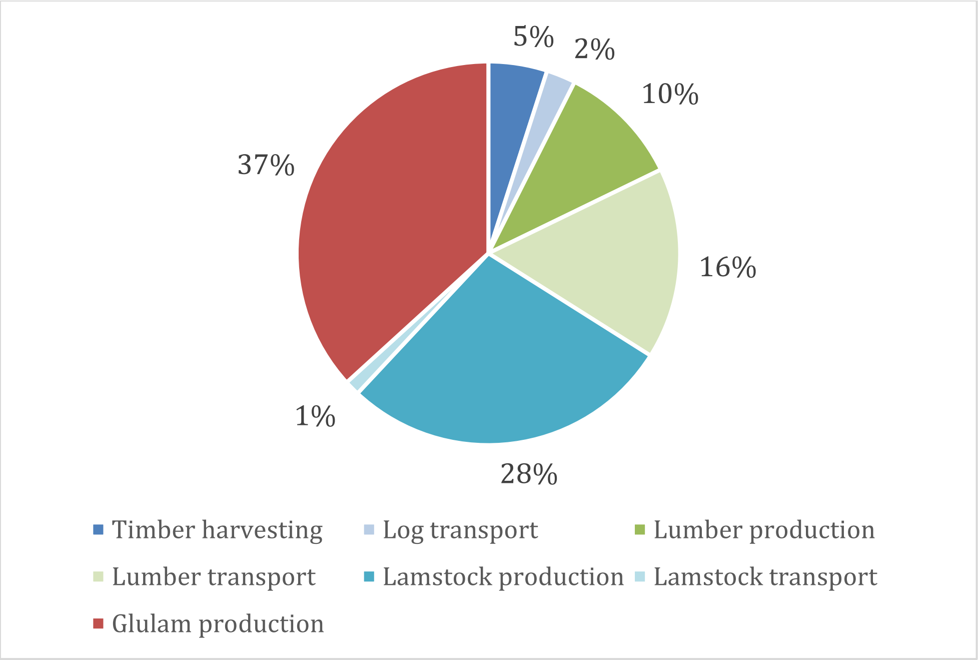
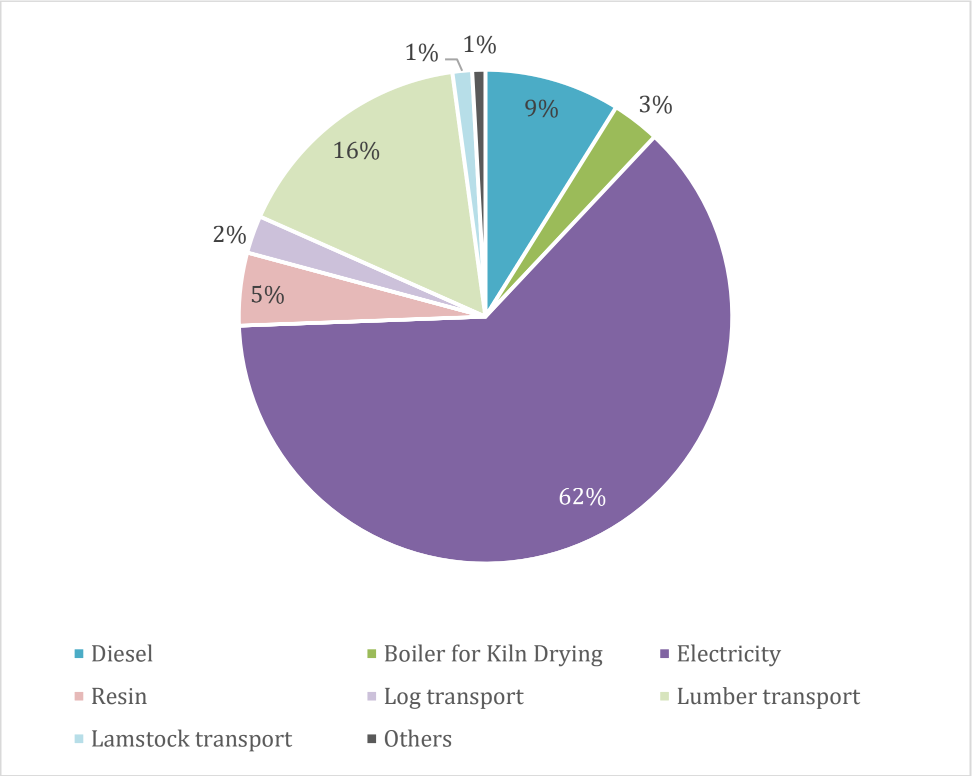


Figure 3-1 Stage Contribution to Total Fossil Emissions



Note: The category "Others" are lubricating oil, water, insecticide, packaging and air emissions

Figure 3-2 Process Contribution to Total Fossil Emissions

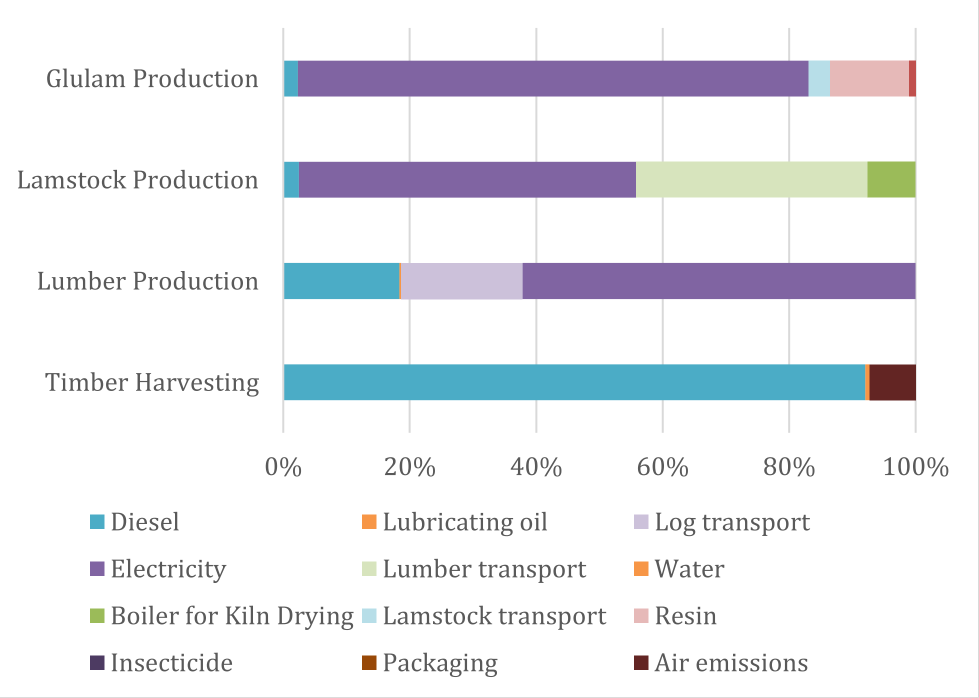
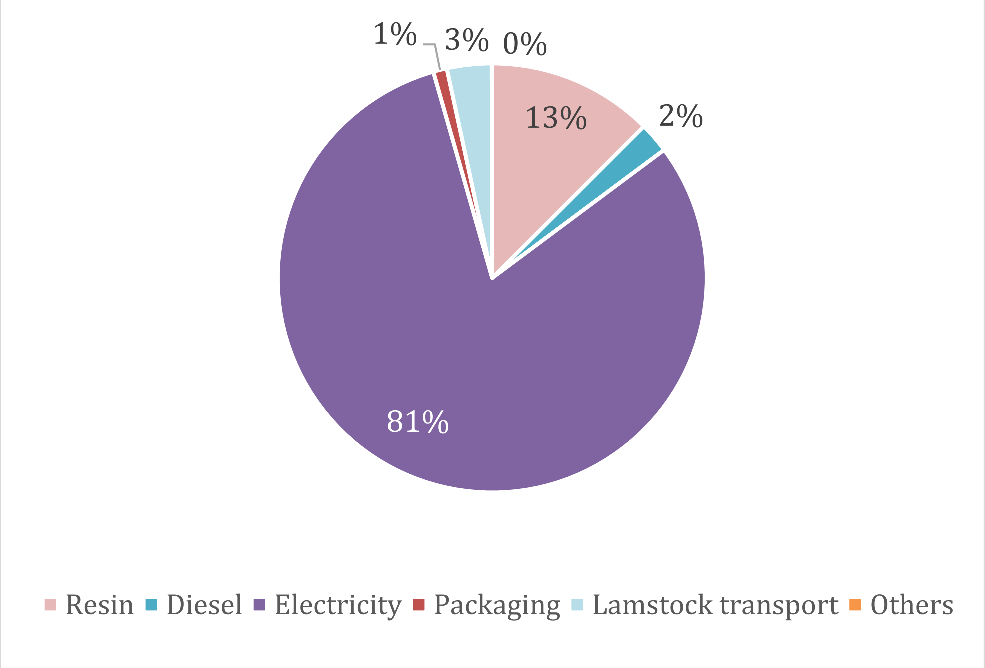


Figure 3-3 Process Contribution to Fossil Emissions based on Production Stages

Table 3-3 Process Contribution to Fossil Emissions based on Production Stages

Process	**Fossil Emissions (kg CO_2eq)**			
	Timber Harvesting	**Lumber Production**	**Lamstock Production**	**Glulam Production**
Resin				24.93
Water			0.15	7.92E-04
Insecticide				0.02
Electricity		41.80	123.69	161.06
Diesel	23.91	12.29	5.69	4.60
Lubricating oil	0.16	0.20		0.06
Boiler for drying			16.36	
Packaging				2.06
Log transport		12.90		
Lumber transport			84.80	
Lamstock transport				6.70
Air emissions	1.89			

Note: Blank cells indicate that the corresponding process was not included in that production stage.



Note: The category "Others" are lubricating oil, water, insecticide

Figure 3-4 Process Contribution to Fossil Emissions in Glulam Production

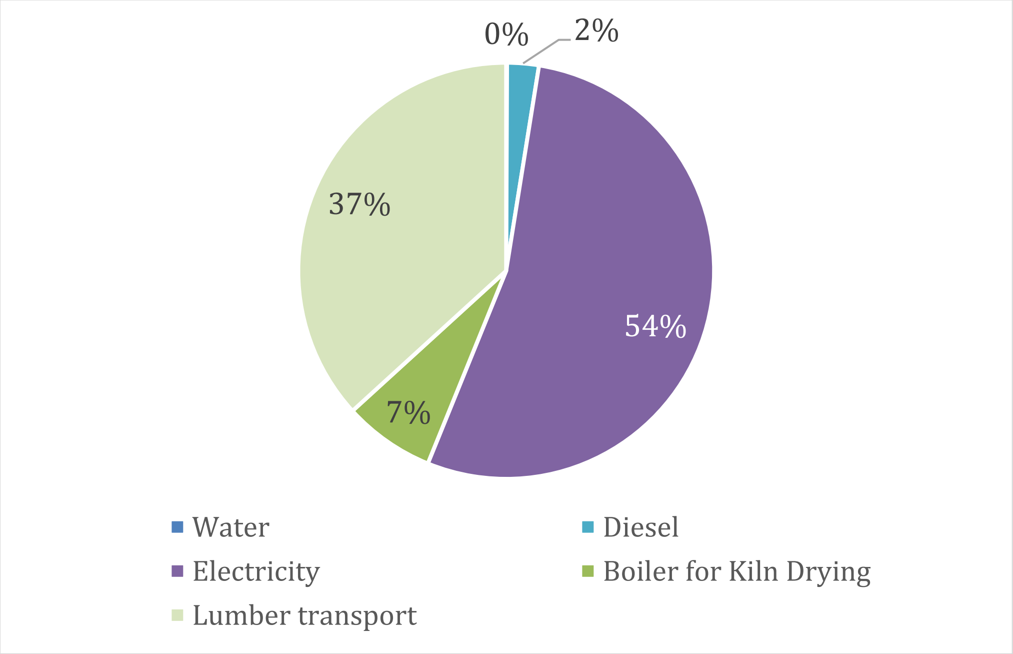


Figure 3-5 Process Contribution to Fossil Emissions in Lamstock Production

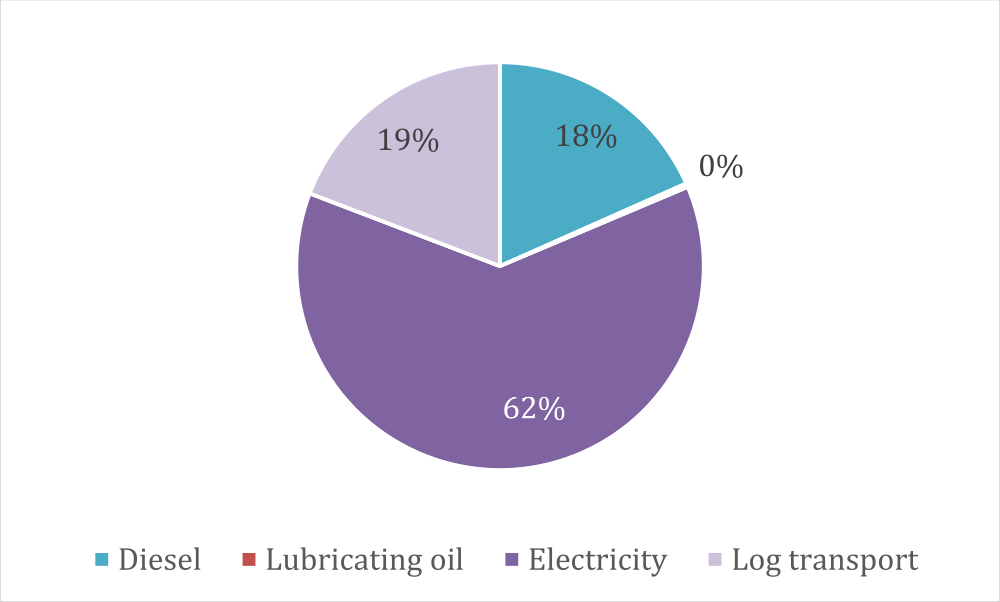


Figure 3-6 Process Contribution to Fossil Emissions in Lumber Production

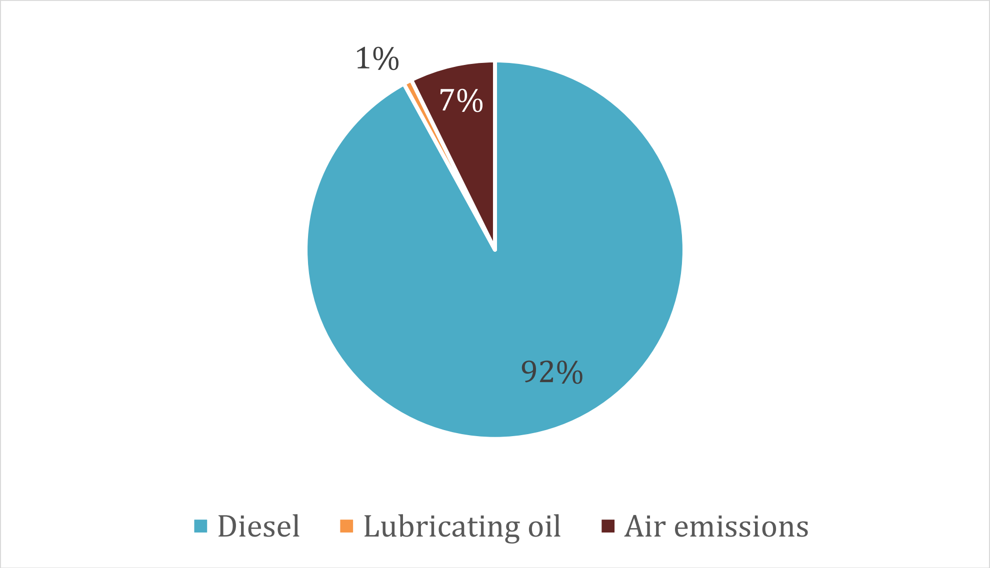


Figure 3-7 Process Contribution to Fossil Emissions in Timber Harvesting

3.2.1. *Contribution of Indonesia's electricity grid mix on the impacts*

The large contribution of electricity to fossil emissions warrants further analysis of the underlying factors. One potential factor is that Indonesia's electricity grid is heavily reliant on fossil fuels, accounting for 84% of the total, with coal alone constituting 69% in 2023 (IEA). To explore the effect of electricity grid composition on the results, the electricity process in ecoinvent was modified to reflect a lower-carbon electricity mix. Specifically, the renewable energy shares were increased to 45% compared to the current share of only 16%. The 45% target is based on projections indicating that, to align with the 1.5°C climate goal, Indonesia must increase its renewable energy share to at least 45% by 2030 (Climate Transparency, 2024). In this scenario, the climate impact of electricity drops to 0.84 kg CO_2 eq./kWh versus the current impact of 1.27 kg CO_2 eq./kWh. The fossil emissions from electricity can be expected to decrease by approximately 38% in each production stage (see Figure 3-8). Further discussion on the electricity impact is provided in Section 4.3.

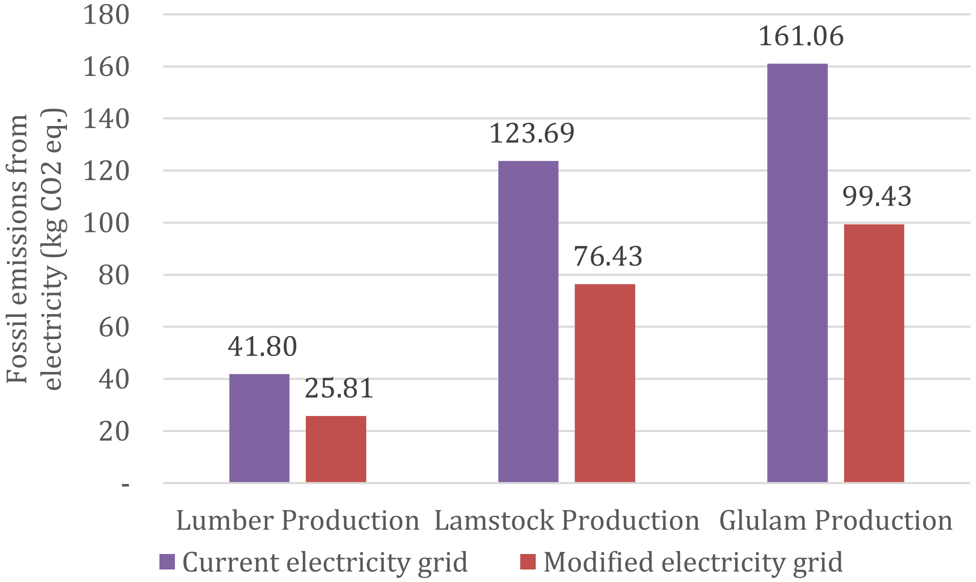


Figure 3-8 Difference in fossil emissions from electricity when using the current vs. modified electricity grid

3.2.2. Lumber transport sensitivity analysis

Lumber transport contributed 16% to the total cradle-to-gate emissions and specifically 37% to the lamstock production stage. This comes from transporting high density lumber over long distances from the forest sawmills in Central Kalimantan and Central Sulawesi to the processing facilities in the Java island. Given its contribution to the impact results, a sensitivity analysis was conducted on the lumber transport stage. This allows to better understand how variations in transport assumptions may affect the climate impact results. This analysis focused on three parameters, such as truck transport distance, truck emission standard, and vessel transport distance. Each parameter was varied independently to assess its individual influence on the fossil emissions, followed by a combined scenario in which all parameters were changed simultaneously. The results are summarized in the table below.

Table 3-4 Lumber transport impacts based on scenarios

Scenario	Transport by truck (tkm)	Truck emission standard	Transport by vessel (tkm)	Climate change, Fossil (kg CO_2 eq.)	% change from baseline
Baseline	392.91	EURO3	523.88	84.80	-
Decreased truck distance by 20%	**314.33**	EURO3	523.88	68.73	19%
Changed truck emission standard	392.91	**EURO6**	523.88	84.02	1%
Decreased vessel distance by 20%	392.91	EURO3	**419.11**	83.91	1%
All changes combined	**314.33**	**EURO6**	**419.11**	67.21	21%

Note: bold values indicate changed parameter(s) compared to the baseline scenario

The results indicate that the impacts can be reduced by decreasing truck transport distances alone. This is because 95 percent of the lumber transport impact is from the land travel portion by truck. Upgrading truck standards from EURO3 to EURO6 shows minimal reductions. This is expected since this parameter targets air quality pollutants, such as nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC), rather than GHG pollutants. Reducing vessel distance also contributes minimal reductions, since it only contributes 5 percent to the lumber transport impact. This suggests that reducing travel distance by truck, may be an effective step toward lowering climate impact.

3.3. Biogenic carbon reporting as per EN 15804

The biogenic carbon removal and emission were estimated using the production-weighted average dry density of red meranti and jabon, which is 475 kg/m^3. This resulted in a net removal of 1,176.67 kg CO_2 eq. from the atmosphere and stored in the wood used to make 1 m^3 of glulam. In the lamstock production stage, 262.56 kg CO_2 eq. was released when trimmings were burned for drying. As a result, 914.11 kg CO_2 eq. of biogenic carbon remains stored in 1 m^3 of glulam. This biogenic carbon value is associated with an increase in the glulam density to be 498.60 kg/m^3, which can be expected with applied pressure during production (Das et al. 2023).

As per EN 15804, any carbon uptake during the product's life is assumed to be stored during the product's use and released back into the atmosphere when it is disposed, recycled, burned or decomposed, thus reported at the end of its life (C3/C4 module). The net contribution of biogenic carbon across the system is zero, as shown in the table below.

Table 3-5 Biogenic Carbon Reporting as per EN 15804

Impact category	Unit	A1	A2	A3	C3/C4	Total
Climate change, biogenic	kg CO_2 eq.	(914.11)	0	0	914.11	0

3.4. LULUC scenarios and impacts

Results from the LULUC scenarios are compared in Table 3-6. If the wood used to produce glulam was sourced from a forest that has not gone through conversion, the LULUC impact is zero. If the wood was sourced from a forest that experienced degradation, specifically from a primary to a secondary dryland forest, 35.66 kg CO_2 eq of emissions are attributed to the product. Meanwhile, if the wood was sourced from a forest that was restored, specifically from a dry shrub to a secondary dryland forest, 35.90 kg CO_2 eq of carbon removal can be attributed to 1 m^3 of the product.

Additionally, the forest degradation scenario affects the treatment of the biogenic carbon. The “-1/+1” approach, that is the biogenic carbon neutrality, is not considered suitable for this scenario since the wood is not sourced from sustainably managed forests. Therefore, the characterization factor for biogenic carbon entering the product system is set to 0 instead of -1. This means no sequestration credit is given, while all the biogenic emissions throughout the product life cycle are still fully accounted for. In this study, 262.56 kg CO_2 eq were released from biomass burning during the drying process. As a result, there is no negative biogenic impact in A1, leading to a net-positive biogenic impact of 821.48 kg CO_2 eq. Further discussion on the treatment of biogenic carbon is provided in Section 4.3.

In these cases, LULUC either improves the product’s overall climate impact to -426.75 kg CO_2 eq (in forest gain scenarios) or worsens the climate impact to 821.48 kg CO_2 eq (in forest degradation scenarios).

Table 3-6 LULUC impacts based on scenarios

Impact category	Unit	Baseline	Forest gain scenario	Forest degradation scenario
Climate change, total	kg CO_2 eq	(390.85)	(426.75)	821.48
Climate change, fossil	kg CO_2 eq	523.26	523.26	523.26
Climate change, biogenic	kg CO_2 eq	(914.11)	(914.11)	262.56
Climate change, luluc	kg CO_2 eq	-	(35.90)	35.66

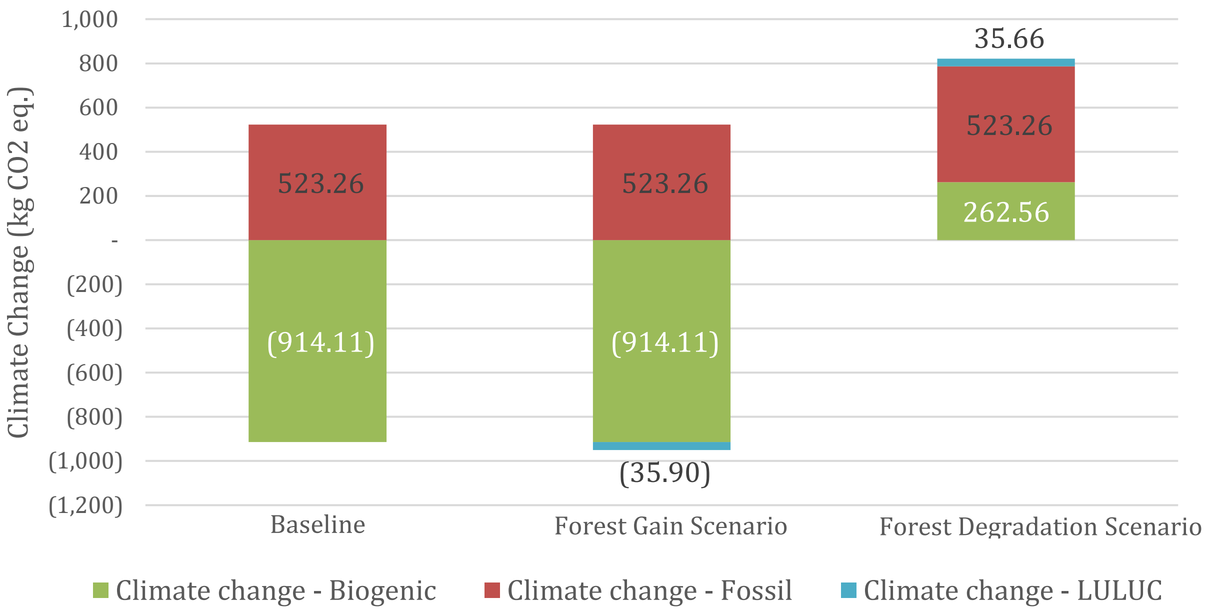


Figure 3-9 LULUC impacts based on scenarios

3.5. Insights from Stakeholder Engagement on Advancing Mass Timber in Indonesia

This section presents the results of stakeholder engagement activities conducted during this study, including a dedicated workshop held on September 24, 2024, and discussions during site visits in September 2024 and April 2025.

3.5.1. <u>Stakeholder Profile</u>

A total of 27 stakeholders were engaged, representing a range of sectors relevant to the mass timber industry. The number of participants reflects the total number of individuals involved in the engagement. In some cases, multiple participants represented the same organization or company and were counted individually.

Table 3-7 Stakeholder Profile

Stakeholder Group	Number of Participants	Affiliation Type
Government, policymakers	6	- Ministry of Public Works and Public Housing - Ministry of Environment and Forestry - USDA Forest Services International Program - USDA Foreign Agricultural Services
Industry, manufacturers	13	- Sawmill and wood processing industry - Mass timber producers
Academia, researchers	7	- Gadjah Mada University - Parahyangan Catholic University - IPB University - Bandung Institute of Technology (ITB) - Indonesia National Research and Innovation Agency (BRIN)
Intergovernmental organizations	1	- UN Environment Programme
Total	**27**	

3.5.2. Key Themes

The results of the stakeholder engagement are organized by key themes that emerged across discussions. The key themes were (1) research and standard development, (2) innovations across the supply chain, (3) market development, and (4) climate commitments. While stakeholders came from different sectors and had varying priorities, they shared a common interest in advancing Indonesia's mass timber industry and identified several important challenges that need to be addressed.

Research and standard development

A consistent focus among stakeholders, particularly academia, was the importance of understanding the physical, mechanical, and durability properties of Indonesia's tropical hardwood species and their suitability for mass timber applications through comprehensive research and testing. They also emphasized the need for research to improve the durability of these local species, especially to address concerns about termites and mold in Indonesia's humid tropical climate. Although research on this topic has grown in recent decades, efforts have often been fragmented, partly due to limited funding and access to full-scale testing facilities.

Most of the existing research has not been directed toward developing design values needed for building code standards. As a result, there is a shared concern about the lack of updated standards for mass timber in Indonesia. Indonesia still follows SNI 7973:2013, which is based on the 2012 US National Design Specification (NDS) and is now considered outdated. Stakeholders agreed on the need to update this standard to reflect current developments in mass timber production and construction. There was interest in fostering collaboration between the government, national universities, and research centers, and potentially involving international partners, to support this effort. One possible approach discussed was to adopt existing standards, like ANSI A190.1-2022 and PRG 320, and incorporate design values for Indonesia's tropical wood species into them. While the need for action was widely recognized, specific plans or next steps were not discussed.

Innovations across the supply chain

Industry actors stressed the need for upstream innovations to address production inefficiencies. A major concern is the low wood recovery rate in current processing practices, which increases costs and reduces product yield. Currently, producing glulam using tropical hardwood species in Indonesia requires at least three times the amount of raw materials (i.e., logs). This low recovery rate can be tied to natural defects in the logs, outdated machinery and equipment, and limited technical skills among machine operators. Investments in technology advancement and capacity building were identified as critical to improving quality and profitability.

In Indonesia, there is a common preference for exposing wood elements in building exteriors. However, this practice may need to be revisited, especially given the high humidity and biological risks in tropical climates. Stakeholders emphasized the importance of developing construction guidelines that are climate-specific and ensure that moisture-related challenges, pests, and durability concerns are properly addressed in wood design and construction.

Domestic and international market development

Government representatives expressed concerns about the vulnerability of wood product exports to economic shocks and highlighted the importance of strengthening the domestic market. However, Indonesia's domestic wood consumption has slowed in recent years. A reference was made to a collaborative study conducted by the International Tropical Timber Organization (ITTO), Japan's Ministry of Agriculture, Forestry and Fisheries (MAFF), and Indonesia's Ministry of Forestry, which examined the factors behind this slowdown (Ministry of Forestry, 2025). The study found that weak domestic consumption is largely due to a mismatch between consumer preferences and available products, as well as limited institutional and policy support. Contributing factors include strong competition from cheaper substitute materials and the absence of a national body to oversee and coordinate the domestic market. While the study focused on wood products in general, a future study is expected to focus more on promoting the use of engineered wood in the construction sector. This is particularly important in Indonesia, where public perception of wood as a building material is often negative due to concerns over its susceptibility to termites and other insects. Therefore, strengthening the domestic market will also require shifting consumer perceptions toward recognizing the durability and benefits of engineered wood.

Stakeholders also acknowledged that international markets play an important role in the long-term sustainability of the industry. Industry representatives emphasized the need to continue exploring opportunities abroad, for example, the US construction sector, where interest in mass timber is expanding. One area of focus was the certification of Indonesian wood species for structural use in the US market. This reinforces the earlier concern about the need for standard development/adoption. Gaining international certification requires compliance with standards such as ANSI A190.1 or PRG 320, which involves extensive material testing and documentation of Indonesian species with performance criteria. This further highlights the importance of coordinated efforts to support both domestic and international standardization pathways. There was also interest in exploring export options for modular structures like Accessory Dwelling Units (ADUs). This pathway would require a better understanding of the import/export requirements and building code requirements, among others.

Climate commitments and carbon accounting

There was strong alignment between stakeholders on the potential of engineered wood to contribute to Indonesia’s climate goals, particularly under the FOLU Net Sink 2030 commitment. Timber from sustainably managed forests can function as a long-term carbon pool when used in buildings, offering both climate mitigation and economic value. Stakeholders expressed interest in using LCA to quantify and capitalize the carbon storage in wood products through carbon markets. However, international standards for accounting carbon storage in wood products are still being developed. Once the method is standardized, this may allow carbon storage to be claimed in carbon trading. Meanwhile, at the national level, carbon accounting for wood products remains underdeveloped in both policy and practice in Indonesia.

4. Discussion

The results of this study demonstrate the potential of glulam produced in Indonesia to contribute positively to climate change mitigation. Despite the fossil emissions of 523.26 kg CO_2 eq. that were associated with the material processing and transport, the amount of biogenic carbon retained in the final product of 914.11 kg CO_2 eq. leads to a net negative carbon balance of -390.85 kg CO2 eq.

Although LCA results from different studies are not directly comparable due to differences in scope, data, and methodology, a broad evaluation was conducted on the reported cradle-to-gate fossil impacts of glulam production in different regions to provide general insights. The reported cradle-to-gate fossil emissions for glulam production in Europe and North America were consistently below 200 kg CO_2 eq/m^3, ranging from approximately 79.9 to 184.1 kg CO_2-eq/m^3 across 10 EPDs (American Wood Council 2025; Kalesnikoff 2022; Mercer 2025; Vaagen Timbers 2021; Canadian Wood Council 2018; Laurent et al. 2013; Hasslacher 2021; Stora Enso 2024; Rubner Holding 2018; CODIFAB 2024). In Japan, the cradle-to-gate fossil impacts of glulam production were generally higher than Europe and North America, ranging widely from 203 to 662 kg CO_2 eq/m^3 (as cited in Nakano et al. 2025).

Based on current knowledge, there are no existing LCAs specifically focused on glulam made from tropical hardwood species in the Southeast Asia region. Therefore, relevant wood production LCAs and EPDs from Southeast Asia that have been published were examined to provide possible insights. For example, Malaysia's green rough-sawn timber from tropical hardwoods reported fossil climate change impacts as high as 211–337 kg CO_2-eq (Ratnasingam et al. 2015), while plywood production in Indonesia showed fossil impacts in the range of 700–817 kg CO_2-eq (PT Kayu Lapis Indonesia 2023; PT Kutai Timber Indonesia 2024). These results suggest a potential trend. The underlying factors driving this variation warrant further investigation, as no studies have yet explored this in detail. This also highlights the importance of being able to compare LCA results and EPDs across regions to draw more useful conclusions.

Another important aspect to consider when making comparisons is the scale of production. The combined capacity of the two glulam producers in Indonesia is 10,000 m^3/year, while North America produces at least 70x this capacity (Anderson et al. 2024). With an increased in production, the LCA results can be expected to improve. This follows the concept of economies of scale, where increasing production volume reduces the cost per unit. This suggests that the environmental impacts may also improve accordingly. A recently published study (Lan et al. 2025), found that scaling up mass timber production could lead to improved outcomes by increasing planted forests, thereby storing more carbon both in the growing forests and in the products.

4.1. Wood recovery rate

One of the challenges expressed by the stakeholders was the low wood recovery rate. Currently, to produce 1 m^3 of glulam requires at least three times the number of logs. Based on the data collected for the life cycle inventory, the recovery rate from log to lumber was 62%, from lumber to lamstock was 61%, and from lamstock to glulam was 68%.

The log-to-lumber recovery rate in this study is on the lower end but still falls within the standard set by Indonesia’s Director General of Forestry Business Development No. P.12/VI-BPPHH/2014 which requires a recovery rate of 60 to 70% for logs from natural forests. However, studies on large-diameter logs from natural forests often report lower recovery rates than the standard. For example, one study found a rate of just 50–53% (Sopianoor et al. 2016).

Recovery rates can vary widely depending on the wood species, log diameter, cross-sectional shape, and sawing method.

The lumber-to-glulam recovery rate in this study was 41%. This aligns closely with the 43% recovery rate reported for Indonesia's glulam production in Koger (2023). However, this is below the recovery rate established by the Director General of Forestry Business Development. Although the standard does not specifically mention glulam, it provides recovery rates for lumber to finger-jointed or laminated boards, which are expected to be around 60–75%. Although standardized dimensions for rough sawn lumber are outlined in SNI 03-2445-1991, lumber arriving at processing facilities is often inconsistent in size, particularly the width and the thickness. As a result, additional trimming and processing are required. Several studies point to contributing factors such as natural defects, outdated equipment, and limited technical skills among machine operators. If the processing from lumber to lamstock can be minimized, a higher recovery rate can be achieved.

Applying lessons from Europe, many mass timber producers there operate under vertically integrated systems, where logs are cut specifically for mass timber production. This approach helps reduce processing waste. A similar strategy in Indonesia could involve requesting sawmills to produce special cuts tailored to glulam dimensions, though the feasibility of this remains uncertain.

4.2. Fossil emissions from electricity

Several factors may explain the high contribution of electricity to fossil emissions. These include high electricity consumption during production, Indonesia's electricity grid being heavily reliant on fossil fuels, and potential limitations or inaccuracies in the data. Each of these factors is discussed further below.

Electricity consumption in the A3 module is 186 kWh/m³, which is comparatively higher than values reported in other regions. For example, glulam production in the Pacific Northwest, USA requires 71.21 kWh/m³, while in Quebec, Canada, it requires 114 kWh/m³ (Bowers et al. 2020; Laurent et al. 2013). A study on glulam production in Japan reports electricity consumption ranging from 77 to 236 kWh/m³, depending on the dimensions of the glulam produced (Nakano et al. 2025). However, it is unclear whether this range reflects electricity use solely in the A3 module or across the entire cradle-to-gate system boundary. Although many LCA studies and EPDs on glulam production have been published, the limited reporting of detailed LCI data presents challenges for comparison.

However, additional considerations are necessary when comparing electricity consumption, as several factors may influence these values. One key factor contributing to higher electricity use in Indonesia, compared to the U.S. and Canada, is the use of hardwood species in glulam production. In contrast, the U.S. and Canada primarily use softwood. According to local manufacturers, the higher density of hardwoods requires longer processing times, particularly for drying, sawing, planing, and pressing. Hardwoods also wear down cutting tools more quickly, leading to production pauses for maintenance. This observation aligns with findings by Adhikari et al. (2020), which highlight the challenges of manufacturing CLT panels with hardwood lumber. Additionally, manufacturers noted that the use of older, less efficient machinery can further increase electricity consumption.

Electricity is sourced from the national grid rather than from a company-owned power plant. Therefore, the high fossil emissions from electricity use are not only due to the large amount of electricity consumed during manufacturing, but also because Indonesia’s electricity grid is heavily reliant on fossil fuels. As presented in Section 3.2.1, Indonesia’s current electricity mix of only 16% renewable energy results in a climate impact of 1.27 kg CO_2 eq./kWh. This climate impact drops to 0.84 kg CO_2 eq./kWh when the renewable energy share is increased to 45%. The fossil emissions from electricity can be expected to decrease by approximately 38% in each production stage.

Referring to the previously cited glulam studies in the Pacific Northwest and Quebec, the electricity consumption for glulam production in the PNW is 71.21 kWh/m^3, resulting in a fossil emission impact of 135.65 kg CO_2-eq/m^3. In contrast, Quebec reports a higher electricity consumption of 114 kWh/m^3 but a lower impact of 102 kg CO_2-eq/m^3. Moreover, Quebec's electricity accounts for less than 5% of total emissions. This is because approximately 97% of Quebec's electricity is generated from hydropower. This comparison highlights the influence of grid decarbonization on the overall climate impact of the product.

Another factor contributing to the high electricity impact may be that the consumption data were typically reported at the facility level, covering other production lines and office use. Consumption for the target production line was estimated based on its share of total production for the facility for that given year. Installing electricity meters on individual machines associated with the production line would improve the data accuracy.

4.3. Treatment of biogenic carbon removal and emissions

In this study, the biogenic carbon removal from the atmosphere in A1 was estimated using the dry density of the wood. The dry density was based on the production-weighted average of red meranti and jabon, resulting in a dry density of 475 kg/m^3. This approach aims to give a more representative carbon removal estimate than using the dry density of a single species. It should be noted that the dry density value influences the results, for example, using a higher dry density value would result in a higher carbon removal.

Approximately half of the carbon uptake is assumed to be released back into the atmosphere during harvesting. This is from the harvesting residues left on site, including tops and branches. This estimate was based on the information that the amount of residues left on the forest floor is roughly equal to the volume of logs recovered. This aligns with a literature review on harvesting residues from natural forests in Indonesia, which found that residues can range from as low as 6.52% to as high as 52.23% of the total harvested tree volume (Budiaman & Audia 2022). This wide variation depends on several factors, including tree diameter, topography of the harvest site, harvesting methods, and felling notch height. The same study found that most of the harvesting residues come from the branch-free stem (60%), followed by the stem above the first branch (23%), and the stump (17%). This indicates that the harvesting residues from natural production forests are mostly made up of large-diameter wood, especially from the lower and upper ends of the branch-free stem, but are short in length.

More residues left after harvesting mean more biogenic carbon is released back into the atmosphere. Many studies have highlighted the need to reduce residues to limit carbon loss. Research on reduced impact logging–carbon (RIL-C) has provided evidence supporting this approach (Ellis et al. 2019). However, its potential for wider on-site implementation remains uncertain, as even the current reduced impact logging (RIL) practices are already challenging to carry out in practice.

The biogenic carbon removal and emissions considered in this study only account for harvesting activities. They do not include temporary forest openings for log yards and skid roads, or the land rehabilitation and planting for the temporary areas following harvesting activities. It was assumed that these efforts would restore the forest to its original condition. However, in reality, it is unclear whether full recovery of the temporary openings actually occurs. Therefore, for a more comprehensive assessment, it is important to also account for the impacts of these temporary disturbances and the effectiveness of rehabilitation efforts.

In terms of biogenic carbon accounting in LCA, the terminology and definitions for biogenic carbon accounting still vary across different standards, specifically when the "-1/+1" approach can be applied (see Table 4-1). As a result, the conditions under which the biogenic carbon neutrality cannot be applied also vary. In such cases, the characterization factor for biogenic carbon entering the product system is set to 0 instead of -1. For example, EN 15804:2012+A2:2019 applies this when wood comes from native forests, while ISO 21930 applies when the wood is from non-sustainably managed forests. Depending on the standard used, results may differ.

This study applied the "-1/+1" approach for the baseline scenario (no LULUC) and the forest gain scenario, given that the wood was not sourced from native forest and was sourced from sustainably managed forests. Meanwhile for the forest degradation scenario, a conservative approach was taken. Although the wood did not come from native forests, it was not sustainably managed, so a characterization factor of 0 was used instead of -1. This is to emphasize the importance of sourcing the raw materials sustainably in order to claim the carbon benefits of wood products.

Table 4-1 Treatment of biogenic carbon across standards

Standard	**The "-1 in/+1 out" approach can be used when…**	**Definitions/Criteria**
EN 15804:2012 +A2:2019	Product was **not** sourced from "*native forest*"	Native forest excludes short term forests, degraded forests, managed forests, and forest with short-term or long-term rotations
EN 16485:2014	Product sourced from "*Sustainably managed forests*"	- Stable or increasing carbon stocks - Can be identified through forest certification schemes

Standard	The "-1 in/+1 out" approach can be used when…	Definitions/Criteria
		- All wood from countries "that have decided to account for Art. 3.4 of the Kyoto Protocol,"
ISO 21930:2017	Product sourced from "*Sustainably managed forests*"	- Stable or increasing carbon stocks - Can be identified through forest certification schemes
ISO 14067:2018	Product sourced from "*wood from forest land that remains forest land*"	

Note: terms in italics and quotation marks reflect the exact terms used in the standards.

4.4. LULUC: Factors influencing the results and recommendations for future studies

Although there are no direct land use change (LUC) emissions linked to glulam production in Indonesia, scenarios were created to explore potential impacts under different land use histories. This helps capture a more complete picture of how past land use, such as forest degradation or regeneration, can influence the overall climate impact of the wood product. This is especially important given that LULUC is a major concern in the country, as discussed in Section 1.7. However, incorporating land use and land use change (LULUC) in LCA is still a topic of debate. Accounting for LULUC emissions and removals is challenging because carbon stock changes are complex and dynamic. Additionally, there are still gaps in internationally accepted methods. For example, the EN 15804 standard only includes direct land use change and excludes indirect land use change due to the lack of an agreed methodology. This has led many LCAs to exclude LULUC altogether.

With the approach used in this study as per PAS 2050:2011, the results are influenced by three main factors, such as the data used, the time period chosen to annualize the emissions, and the area used in the calculation. The carbon stock data used in this study were derived from biomass stock calculated in Indonesia's latest national forest reference emission level (Ministry of Environment and Forestry 2022b). The biomass stock data for forest cover was available at a provincial level and was differentiated based on different land cover class, e.g. primary versus secondary. Meanwhile, the biomass stock data for non-forest cover was available at the national level. This could be improved if more detailed data were available at a finer scale, such as at the regional level or site-specific data. Additionally, the biomass stock currently only includes above-ground and below-ground biomass. This could be improved by including other types of carbon stocks, such as soil organic carbon and litter or dead organic matter.

In terms of the time approach, the current practice is to divide (amortize) the estimated emissions associated with direct land use change that has occurred over the last 20 years by another 20 years, or a single forest rotation, based on the IPCC guidelines. In this study, the time was chosen based on the average concession period of 55 years. In reality, changes in carbon stock can happen over shorter or longer periods. This time frame was chosen instead of the forest rotation length (i.e., 40 years) because the harvesting method used is selective cutting. Only trees with a minimum diameter of 40 cm are harvested, while at least 25 core trees per hectare with a diameter of at least 20 cm are left standing. If clear-cutting were the practice, using the forest rotation length would have been more appropriate. Additionally, there has been growing interest in incorporating time-dependent carbon fluxes into LCA. There have been different attempts to address this. For example, De Rosa et al. (2017) developed a parametric model to evaluate carbon fluxes in time-dependent LULUC assessments for bio-based products. However, there are still uncertainties about how the model should be applied.

For the area used in the calculation, this was based on the average area where trees are removed or harvested, not the entire area designated for logging. This approach reflects the selective cutting practice used in the forest. For future work, satellite images can be used to more accurately identify the areas that were previously converted and are now used to source logs for the product. This approach would allow for a more precise assessment of land use change by mapping the actual harvesting zones, rather than relying on general estimates.

4.5. Life cycle inventory data availability and quality

This study relied heavily on collecting primary data and using global databases (as listed in Appendix B), since there is still no complete LCI database for Indonesia. Indonesia's national LCA guideline was only recently established in 2021 (Ministry of Environment and Forestry 2021). Since then, an increasing number of LCA studies have emerged, but they are largely concentrated in high-emission sectors like mining and oil and gas. This trend is partly driven by the implementation of Indonesia's PROPER rating system, which encourages these companies to go beyond compliance by using tools like LCA to identify and reduce their environmental impact. Meanwhile, LCA applications in Indonesia's wood product sector remains limited. Existing studies primarily focuses on bioenergy and furniture.

The development of an Indonesian LCI database has been underway for some time, using data from companies participating in the PROPER program as a starting point. However, this effort faces several significant challenges, particularly in terms of data quality, consistency, and completeness. Much of the data requires extensive cleaning and validation, and the process demands strong commitment from the government and transparency from companies, both of which have often been lacking.

The role of LCA in identifying emission hotspots and informing strategies for emission reduction is increasingly recognized in Indonesia. However, its full potential remains underutilized especially in sectors like forestry and wood products. To address this gap, future efforts should focus on expanding LCI data coverage beyond high-emission sectors, strengthening institutional support for data governance, and building the technical capacity of both industry stakeholders and researchers. Integrating LCA into policy frameworks will be essential to ensure that LCA becomes a mainstream tool for advancing Indonesia's sustainability goals across all sectors.

4.6. Use and End-of-Life Phase in LCA

This study covers only the cradle-to-gate stages. Including the use and end-of-life (EoL) phases could influence the overall results. In existing LCAs of mass timber products globally, there is a growing number of studies that incorporate the use and EoL phases. The use phase is typically considered to have minimal environmental impacts from the periodic maintenance, repair, or replacement activities. For the EoL stage, most studies consider four primary EoL scenarios: reuse, recycle, incinerate, and landfill. Depending on the modeling methods and regional practices, the results can vary. However, most studies have shown that reuse tends to have the lowest environmental impacts compared to the other options (Lin et al. 2025).

In Indonesia, the use of mass timber in building is still emerging. Maintenance practices are not yet standardized, although proper protection from moisture and termites is critical given the tropical climate. Additionally, since most mass timber buildings in Indonesia have been constructed only within the past decade, there is currently no practical experience with their end-of-life demolition or deconstruction, making it impossible to collect primary data for this phase. Information gaps to be addressed to allow a robust cradle-to-grave LCA are as follows:

- The required maintenance, repair, replacement, or refurbishment activities needed to ensure durability of the product, with consideration of Indonesia's tropical climate;

- Expected service life of the product and potential for service life extension;
- The recovery rates, reuse potential, and recycling pathways specific to local construction and demolition practices;
- Data on infrastructure for the collection, sorting, and processing of deconstructed mass timber products;
- Carbon storage accounting under Indonesian disposal scenarios, including landfilling and open dumping;
- Policy, guidelines, or standards on how to reuse mass timber products in buildings, including quality assurance, sorting requirements, and handling procedures.

4.7. Recommendations for Stakeholders

This section summarizes key recommendations for stakeholders, derived from sector development challenges identified through stakeholder engagement (provided in Section 3.5) and insights from this LCA study. The main challenges and findings are outlined below:

- Fragmented research partly due to limited funding and access to full-scale testing facilities
- Outdated national building codes resulting in a lack of production and construction guidelines
- Market hesitancy and negative perceptions related to termite risks hinder adoption
- High volumes of harvesting residues and low wood recovery rates reduce material efficiency
- Electricity consumption and lumber transportation are major contributors to the product's climate impact
- Lack of LCI data availability and quality, combined with low LCA adoption in the sector

The recommendations are structured based on stakeholder groups and areas of development, as follows.

4.7.1. Government & Policymakers

Institutional framework:

- Establish a national body to oversee and coordinate the development of this sector. This organization will be responsible for creating, implementing, and monitoring a comprehensive action plan to advance the industry, covering research, standards development, market expansion, and innovation throughout the supply chain.

Standard and policy development:

- Collaborate with local and international researchers and industry partners to update the national building code. Develop a clear roadmap outlining the process and timeline. Ensure that moisture-related challenges, pests, and durability concerns are addressed in design and construction.
- Establish competency standards for logging and machine mill operators, with regular monitoring to ensure compliance. This will help reduce wood waste due to operator skill gaps and improve production efficiency. Include capacity building as a key part of these standards to support skill development.
- Integrate LCA into policy frameworks, including sectors with lower emissions, to promote broader implementation. Increased LCA implementation will enhance database development and improve the overall quality of assessments.

Supply chain and market development:

- Transportation impacts can be reduced through improved infrastructure and connectivity between Indonesia's islands and cities. Better roads, ports, and overall transportation networks will allow efficient routing, thus reducing travel distances and fuel consumption.
- Negative public perceptions of mass timber, particularly concerns about termites and durability, can be addressed through government investments in mass timber construction projects, complementing the private sector initiatives that have been leading industry development. These buildings can serve as tangible proof of the material's quality and performance. The government can collaborate with other stakeholder groups to provide

education and outreach programs to communicate the benefits of mass timber construction to the public.

Technology and innovation:

- Given the contribution of grid decarbonization to the product's climate impact (as discussed in Section 4.2), Indonesia should accelerate the effort to reduce reliance on fossil fuels and increase the renewable energy share in the electricity mix.

4.7.2. Industry & Manufacturers

Supply chain management:

- Operating under vertically integrated systems where logs are cut specifically for mass timber production can improve wood recovery rate. A similar strategy can involve requesting sawmills to produce special cuts tailored to glulam dimensions. Wood recovery rates can be expected to improve with increased production scale by using upgraded machinery and having optimized processes.
- Explore alternative logistics routes and identify raw material sources closer to processing facilities to optimize travel distances and reduce transportation impacts.
- Improve record-keeping of inventory data to enhance LCA data quality. Data management training can be obtained in collaboration with the government and academia.

Technology and innovation:

- Install power meters on individual machines associated with the production line to improve electricity data accuracy.
- Upgrading to more efficient machinery and ensuring regular maintenance can reduce electricity consumption while improving wood recovery rates.
- Provide capacity-building programs for machine operators to enhance operational efficiency and product quality.
- Explore on-site renewable energy generation to reduce reliance on the fossil fuel-dominated national grid.

Market development:

- Strengthen the domestic market by leveraging social media platforms, implementing public awareness campaigns, and increasing the number of demonstration projects to showcase the applications and benefits of mass timber. As production and construction scale grows, the market can be expected to develop more naturally through increased visibility and acceptance.
- Explore opportunities in international markets by meeting global standards and obtaining necessary certifications.

4.7.3. Academia & Researchers

Research collaboration and standardization:

- Address the current fragmentation in research on the properties of tropical hardwood species by fostering stronger collaboration among national researchers, institutions, and industry stakeholders. This includes establishing centralized databases, adopting standardized testing protocols, and promoting joint research initiatives to consolidate knowledge and improve data quality.
- Collaborate with neighboring tropical countries that share similar hardwood species and characteristics to complement Indonesia's research efforts. These partnerships can accelerate progress in updating the national building code, expand funding opportunities, and provide access to full-scale testing facilities that may not be available domestically.

Species selection:

- With current production relying on natural species, more coordinated research is essential to identify suitable plantation species that support a consistent and sustainable timber supply. As the use of plantation species increases, logistics-related impacts can be expected to decrease due to improved accessibility. This is because many plantations are located primarily on Java Island, reducing transportation distances compared to sourcing from Kalimantan or Sulawesi, which is the common practice today.
- In addition to identifying suitable species for mass timber production and improving the wood quality through modification, a potential research area that remains understudied is how different wood species and densities affect production process and time. This

research may require collaboration with manufacturers to identify the optimal species and wood densities that enhance production efficiency.

Market research and development:

- Collaborate with stakeholders to conduct market research to identify gaps within the mass timber sector and develop strategies to address these challenges effectively.

5. Conclusion

This study conducted a regionally specific cradle-to-gate LCA for glulam production in Indonesia to better understand its potential environmental impacts and benefits. The results demonstrate the potential of glulam produced in Indonesia to contribute positively to climate change mitigation. The production of 1 m^3 of glulam in Indonesia results in 523.26 kg CO_2 eq. of fossil emissions, while 914.11 kg CO_2 eq. of biogenic carbon is stored. Thus, the overall product's carbon balance is -390.85 kg CO_2 eq.

The contribution analysis showed that electricity consumption was a major contributor to fossil emissions, responsible for 62% of the total cradle-to-gate emissions. Factors that may influence this large contribution were discussed, including high electricity consumption during production, Indonesia's electricity grid being heavily reliant on fossil fuels, and potential limitations or inaccuracies in the data. The combination of using hardwood species with high densities and less efficient machinery may be driving the high electricity use. Additionally, the dominance of fossil fuels in Indonesia's electricity grid also contributes to the overall impact. Raising the renewable energy share from the current 16% to 45% could reduce fossil emissions by 38% in each production stage. This shows how grid decarbonization can lower the overall climate impact.

Reducing wood waste throughout the supply chain, from harvesting residues to production waste, is essential to increasing biogenic carbon storage. Currently, producing 1 m^3 of glulam requires at least three times the volume of logs. While the log-to-lumber recovery rate of 62% meets Indonesia's national standard, the lumber-to-glulam recovery rate is only 41%, which is below the expected 60–75%. Improving this can start with standardizing rough sawn lumber dimensions as outlined in SNI 03-2445-1991. This requires improved sawmill technology and stronger technical capacity among machine operators. Cutting logs specifically to glulam dimensions could also be explored.

Although there are no direct land use change (LUC) emissions linked to glulam production in Indonesia, scenarios were created to explore potential impacts under different land use histories. This helps capture a more complete picture of how past land use, such as forest degradation or regeneration, can influence the overall climate impact of wood product. When considering a forest gain scenario, the product's overall climate impact can be improved from -390.85 to -426.75 kg CO_2 eq, while a forest degradation scenario can worsen it to 821.48 kg CO_2 eq. The forest degradation scenario takes away the biogenic carbon sequestration credit while still accounting for all the biogenic and fossil emissions throughout the product's life, resulting in a significantly higher climate impact. This highlights the importance of sourcing wood from sustainably managed forests to ensure lower climate impacts and maintain the carbon benefits of wood products.

Limitations in this research methodology should be addressed in future studies with the expansion of the system boundary to include the use and end-of-life phase, the inclusion of more primary data for upstream processes, and consideration of other relevant impact categories. For LULUC, future studies should incorporate remote sensing to more accurately identify areas of forest conversion. In addition, accounting for carbon stock changes beyond biomass, such as dead organic matter and soil organic carbon, will offer a more complete assessment. Applying a time-dependent approach can better reflect how carbon fluxes over time, leading to improved results. Together, these steps will provide a more comprehensive understanding of the climate impacts associated with land use change.

The stakeholder engagement revealed strong interest and momentum around advancing the use of mass timber in Indonesia, with shared concerns across industry, government, and research sectors. Key issues included the need for updated standards, improved testing capacity, strategies to strengthen the domestic market and enter international market. This highlights the need for coordinated action across sectors to support sustainable mass timber development. This strong commitment from all stakeholders must be supported by clear policy and institutional frameworks. Financing tools will be needed to support local production and market adoption. Scaling demonstration projects, public education campaigns and international collaboration will be key in building trust and expanding market access.

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Appendix A Survey

SAWMILL SURVEY

GENERAL INFORMATION

- The data given shall represent the annual production of sawn lumber.
- Documents that can be useful for this data collection include transfer passes, invoices, log book, and electricity bills.
- Units are generally specified. But if the mill uses a different unit, please cross off the specified unit and replace it with the unit that is used by the mill.
- If the actual data is not recorded or missing, estimations can be made with note.

PART A: SAWMILL COMPANY OPERATION OVERVIEW

1	Production in 2024:	______________________ m^3
2	Production output:	☐ Air dried sawn timber ☐ Kiln dried sawn timber
3	Number of bandsaws in the factory:	______________________ unit
4	Do you have any downstream production?	☐ Yes, specify: __________________________________ ☐ No
5	Sawmill normal operating hours:	No. of hours per day: _______________ hours/day No. of days per week: _______________ days/week Holiday breaks per year: _______________ days/year

PART B: HARVESTING

HARVESTING SPECIFICATIONS	
Location	
Forest area	Ha
Harvested area	Ha/year
Harvesting period	From: to:
Harvesting volume	m^3/year

TREE SPECIFICATIONS	
Tree diameter	
Tree height	
Log length	
Crown length	
Stump height	

Recovery rate from **tree** to **log**:

PART C: TRANSPORTATION OF LOGS TO SAWMILL

Location origin	Travel distance to sawmill (km)	Log species	Volume (m^3)	Fuel consumption (L)

PART D: SAWMILL

Log species	Log volume	Sawn timber volume (m^3)

MILL RESIDUES

Type of residue	Sold (tons)	Selling price (IDR/ton)	Internally used for fuel (tons)	Internally used for other (tons)	Landfilled (tons)
Sawdust					
Off-cuts					
Bark					
Slab					

ELECTRICITY

Electricity (purchased):	______________________________ kWh/year
Electricity (self-generated):	

Fuel Type (e.g. diesel, wood residues)	Amount (L or kg)

WATER CONSUMPTION

Water use:	______________________________ Liter/year

MACHINES/EQUIPMENT

Machines/ equipment	**Number in mill**	**How many are in the operation?**	**Rated power (kW)**	**Running capacity (m^3)**	**Duration for the running capacity (hours)**
Band saw					
Circular saw / cross-cut saw					
Dust extractor					
Treatment plant					
Air compressor					
Chainsaw					
Saw doctoring equipment Side dresser (band saw) Sharpener (band saw) Sharpener					

Machines/ equipment	**Number in mill**	**How many are in the operation?**	**Rated power (kW)**	**Running capacity (m^3)**	**Duration for the running capacity (hours)**
(circular saw)					
Pony saw					
Others, specify: ____________					

FUEL CONSUMPTION FOR IN-HOUSE TRANSPORTATION

Fuel Type	**Fuel Amount (L) by Machines or Equipment**				
	Forklift	**Loader**	**Log Grabber**	**Chainsaw**	**Other: ____________**
Diesel					
Petrol					
Lubricants					
Other: ____________					

PART E: KILN DRYING SYSTEM OVERVIEW

Fan-rated power (kW)	
Number of fans	
Number of drying chambers	
Chamber capacity (m^3)	
Average drying duration (hours)	
Average moisture	

content before KD	
Target moisture content after KD	

TRANSPORTATION OF SAWN TIMBER TO KILN DRYING MILL

Destination Name	**Distance to kiln drying mill (km)**	**Volume of timber (m3)**	**Fuel consumption (L)**

ELECTRICITY

Electricity (purchased):	______________________________ kWh/year
Electricity (self-generated):	

Fuel Type (e.g. diesel, wood residues)	Amount (L or kg)

WATER CONSUMPTION

Water use:	______________________________ Liter/year

FUEL CONSUMPTION BY BOILER

Fuel Amount				
Diesel (L)	**Sawdust (tons)**	**Off-cuts (tons)**	**Empty fruit bunch (EFB) (mass)**	**Other: ____________**

FUEL CONSUMPTION FOR IN-HOUSE TRANSPORTATION

Fuel Type	**Fuel Amount (L) by Machines or Equipment**				
	Forklift	**Loader**	**Log Grabber**	**Chainsaw**	**Other: ____________**
Diesel					
Petrol					
Lubricants					
Other: ____________					

DRYING PROCESS

Species	**Dimension of timber (thickness x width x length)**	**Input volume**	**Output volume**	**Drying duration (day)**

GLULAM MANUFACTURERS SURVEY

Annual Production Period: 2024
Annual Glulam Production: m^3/yr
Type of Facility: Cold Cure or Radio Frequency (*circle one*)

ANNUAL PRODUCTION INFORMATION

No	Products	Dimensions (cm) *(length, width, height)*	Quantity (m^3)	Density (kg/m^3)
Glulam Production				
Other Products (e.g. cross-laminated timber, laminated veneer lumber, etc.)				

RAW MATERIALS

Only provide data for glulam portion of production in this section

Products	Quantity	Units (m3)	Moisture Content (%)	Distance from source to facility (km)	Mode of transport	Volume of transport
Total Lumber:						
Lumber by wood species:						

Modify/add the dimensions accordingly. Only provide data for glulam portion of production in this section.

Lumber Stock (Dimensions in cm)			**Dimension mix %**
Length	**Height**	**Width**	
400	3	22	
400	4	22	
400	6	8	
400	6	12	
400	6	18	
400	8	8	
400	8	10	
400	8	12	
Total			**100%**

RESIN AND CURING METHOD

Type resin used for Finger Jointing (*check appropriate box*)

☐ Phenol Resorcinol Formaldehyde
☐ Melamine
☐ Melamine Urea Formaldehyde
☐ Melamine Formaldehyde
☐ Resorcinol
☐ Others, specify:

Type of curing method for Finger Jointing (*check appropriate box*)

☐ Radio frequency
☐ Cold cure

Type resin used for Face Bonding (*check appropriate box*)

☐ Phenol Resorcinol Formaldehyde
☐ Melamine
☐ Melamine Urea Formaldehyde
☐ Melamine Formaldehyde
☐ Resorcinol
☐ Others, specify:

Type of curing method for Face Bonding (*check appropriate box*)

☐ Radio frequency
☐ Cold cure

Inputs	Type	Quantity	Range % of solids when used	Distance from source to facility (km)	Mode of transport	Volume of transport
Resin						
Catalyst/ fillers/ extenders						
Primer						
Other:						

MISCELLANEOUS INPUTS

Only provide data for the glulam portion of production in this section. If the items are sourced from multiple locations, please provide a comprehensive list of all sourcing locations.

Inputs	Quantity	Units	Type or Source	Distance from source to facility (km)	Mode of transport	Volume of transport
Water						
Coatings						
Thinner						
Chemicals						
Others						
Shrink wrap						
Pallets (not reused)						
Cardboard						
Strapping						
Wrapping Material						
Spacers						

CO-PRODUCTS

Co-products	Where in the process is the co-product generated	Quantity (kg)	Sold (kg)	Disposed (kg)	Reuse/recycle (kg)	Other treatment (kg)
Sawdust						
Planerdust						

Co-products	Where in the process is the co-product generated	Quantity (kg)	Sold (kg)	Disposed (kg)	Reuse/recycle (kg)	Other treatment (kg)
Shavings without resins						
Shavings with resins						
Trimmings						
Wood chips						
End cuts						

ON-SITE TRANSPORTATION

Transport Type	Fuel Type	Amount used in 2024	Used for

ELECTRICITY AND FUELS

Inputs	Quantity	Units
Purchased Electricity		
Cogeneration Electricity (CoGen)		
Purchased Steam		
Natural Gas		
Liquid Propane Gas[1/]		
Kerosene		
Diesel Fuel[1/]		
Gasoline[1/]		
Hog Fuel (self-generated)		
Hog Fuel (purchased)		
Wood Fuel (shavings, trimmings)		
Engine Oil		
Hydraulic Fluid		
Hydraulic Oil		
Transmission Fluid		
Residual Fuel Oil		

Inputs	Quantity	Units
Distillate Fuel Oil		
Ethylene glycol		
Oil		
Solvent		
Others, specify:		

BOILER

- ☐ **Do not have a boiler**

If you have a boiler, please fill in the table below:

FUEL CONSUMPTION BY BOILER

Diesel (L)	Sawdust (tons)	Off-cuts (tons)	Empty fruit bunch (EFB) (kg)	Other, specify:

KILN

- ☐ **Do not operate a kiln**

If you operate a kiln, please fill in the table below:

Kiln fan-rated power (kW)	
Number of fans	
Number of drying chambers	
Chamber capacity (m^3)	
Average drying duration (hours)	
Average moisture content before KD	
Target moisture content after KD	

FUEL SOURCE

- ☐ Steam
- ☐ Natural gas
- ☐ Hogged fuel
- ☐ Oil
- ☐ Other

DRYING PROCESS

Species	Dimension of lumber	Input volume (m^3)	Output volume (m^3)	Drying duration (day)

MACHINERIES AND EQUIPMENT

Glulam Production Stage	Machinery Name	Rated Power (kW)	Running capacity (m3)	Duration for running capacity (hours)	Source of power

AIR EMISSION CONTROL DEVICES

- ☐ Facility is equipped with an air emission control device
- ☐ Facility is **not** equipped with an air emission control device

ANNUAL WASTE GENERATED

Type	Method of disposal or end use (e.g. landfill, landscaping)	Quantity	Transportation method and distance (if applicable)
Resin waste			
Hydraulic fluid			
Lubricants			
Shrink wrap			
Pallets			
Cardboard			
Wood waste			
Boiler ash and fly ash			

ANNUAL WASTEWATER GENERATED

Where in the production process was this wastewater generated	Method of disposal	Quantity	Transportation method and distance (if applicable)

Appendix B Secondary LCI Data used in this LCA

Inputs	LCI Database	Process	Geography
Electricity	Ecoinvent 3	Electricity, low voltage {ID}| market for electricity, low voltage | Cut-off, U	Indonesia
Diesel	Ecoinvent 3	Diesel, burned in building machine {GLO} | market for diesel, burned in building machine | Cut-off, U	Global
Lubricant	Ecoinvent 3	Lubricating oil {RoW} | market for lubricating oil | Cut-off, U	Rest of the World
Water	Ecoinvent 3	Water, ultrapure {RoW}| market for water, ultrapure | Cut-off, U	Rest of the World
Resin, PUR	Ecoinvent 3	Polyurethane adhesive {GLO}| polyurethane adhesive production | Cut-off, U	Global
Resin, PRF	Ecoinvent 3	Phenolic resin {RoW}| phenolic resin production | Cut-off, U	Rest of the World
Insecticide	US-EI 2.2	Insecticides, at regional storehouse/US- US-EI U	US
Trimmings combusted in boiler	CORRIM	Wood combusted, at boiler, at mill, kg, US	US
Packaging, spacers	CORRIM	Cardboard	US
Packaging, wrapping materials	USLCI	Low density polyethylene resin, at plant/RNA	US
Packaging, strapping	USLCI	Cold rolled sheet, steel, at plant/RNA	US
Trucking	Ecoinvent 3	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U	Rest of the World
Trucking	Ecoinvent 3	Transport, freight, lorry 7.5-16 metric ton, EURO3 {RoW}| market for transport, freight, lorry 7.5-16 metric ton, EURO3 | Cut-off, U	Rest of the World
Trucking	Ecoinvent 3	Transport, freight, lorry 16-32 metric ton, EURO3 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	Rest of the World
Shipping, bulk	Ecoinvent 3	Transport, freight, sea, bulk carrier for dry goods {GLO}| market for transport, freight, sea, bulk carrier for dry goods | Cut-off, U	Global
Shipping, container	Ecoinvent 3	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	Global