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Energy efficiency and carbon footprint of veneer manufacturing from *Dipterocarpus spp.* toward low-carbon industry

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Abstract. The increasing global demand for wood products has driven a rise in energy consumption, consequently contributing to higher greenhouse gas (GHG) emissions as the primary factors that are accelerating global warming. This study aims to evaluate the energy efficiency and carbon footprint of the veneer wood production process using *Dipterocarpus spp.* as raw material in a manufacturing industry. This research was conducted in support of climate change mitigation based on the Nationally Determined Contribution (NDC). The CO_2 emissions were analyzed using two methods: a national method based on the guidelines from the Ministry of Energy and Mineral Resources (ESDM) and an international method using DEFRA standards. The results showed total emissions of 370.22 tonnes CO_2e using the national method and 344.10 tonnes CO_2e using DEFRA's standard. The majority of emissions originated from fossil fuel consumption, particularly in heavy equipment operations. Then, energy efficiency was evaluated using the Energy Productivity Ratio (EPR) with an average value 2.04. This indicates that the industry is operating at a level compatible with sustainable practices. Moreover, the findings reveal a positive correlation between the proportion of raw materials converted into primary products and improvements in energy efficiency. This study provides a critical quantitative foundation for enhancing energy management strategies in the industrial sector and for preparing future integration into carbon credit schemes. Furthermore, the research contributes to the achievement of the Sustainable Development Goals (SDGs) in supporting the transition toward a greener and low-carbon industry.

Keywords: *Life cycle assessment, CO_2 emissions, energy efficiency, wood veneer, sustainable industry.*

1. Introduction

Keruing *(Dipterocarpus spp.)* is a type of hardwood plant endemic to tropical forest areas. In Indonesia, keruing is found in the islands of Kalimantan, Sumatra, and Java [1]. Keruing was chosen for the veneer raw material because of its hardwood yet has high flexibility with a unidirectional fiber pattern [2]. In Southeast Asia, this species is not only known for its timber, but also for its non-timber products, including resin, oil, and renewable energy sources [3]. Veneer is a very thin sheet of wood used as a furniture coating to increase aesthetic value [4]. Moreover, wood is an environmentally friendly material that is widely sought after for the needs of green building projects. The veneer production process consists of three main stages, namely debarking, peeling, and drying wood, which involves the use of fossil fuels to operate heavy equipment and electricity for the energy source of wood processing machines.

Reporting from The Observatory of Economic Complexity, in 2023, Indonesia will be included as the 10 countries with the largest exporters in the world for wood products, including veneer, worth US$ 4.53 billion. This value shows that Indonesian wood products are in high demand in the international market. The demand for wood continues to increase by 4-8% every year to support the need for environmentally friendly materials [5]. The increase in demand for wood certainly requires more energy for the wood processing process, which has an impact on the carbon dioxide emissions produced. These sources of pollutants trigger global warming, which exacerbates the phenomenon of climate change [6].

A climate system is assumed to be a thermal machine that converts heat from solar radiation into mechanical energy with low efficiency because this system is affected by *irreversible mechanisms* such as friction and energy dissipation, thus degrading the ideal workability of the system [7]. Energy imbalances occur when the concentration of greenhouse gases from human activities increases, which results in the phenomenon of climate change. Climate change is defined as long-term changes in climate conditions that are dominated by human activities that produce greenhouse gas emissions. The main contributor to global greenhouse gas emissions comes from CO_2 gas at 79.7% [8], where industry accounts for 23% of total global emissions [9].

As a follow-up to this problem, the Paris Agreement was triggered at the United Nations Climate Change Conference, which contains a target to limit the global temperature rise to below 2°C, and as much as possible to 1.5°C compared to the pre-industrial era. This target is realized if greenhouse gas emissions fall by 43% by 2030 [10]. This value is a parameter for the balance of global emissions towards net zero so that it can reduce the concentration of greenhouse gases in the atmosphere [11]. The core of the Paris Agreement is realized through a national-scale commitment to reduce emissions and adapt to climate change, known as *the* Nationally Determined Contribution (NDC) [12].

The implementation of NDC commitments is evidenced by measurable data to determine realistic climate targets. The initiative of the program is an evaluation of the amount of greenhouse gases, called the carbon footprint. The carbon footprint is a benchmark in assessing the level of greenhouse gas emissions from energy use, transportation, and production processes [13]. The carbon footprint is a reference to determine what steps are strategic in climate mitigation actions.

1.1 Carbon footprint

Based on the standards set by the UNFCCC, there are several methods that are being developed for calculating the carbon footprint. For companies, carbon footprint calculation provides an overview of how much environmental impact results from their industrial operational activities. The carbon footprint is a benchmark in assessing greenhouse gas emission levels from energy use, transportation, and production processes[13].

1.1.1 The ministry of energy and mineral resources

The GHG inventory in the energy sector is under the auspices of the Ministry of Energy and Mineral Resources, based on the mandate of the Minister of Energy and Mineral Resources Regulation No. 22 of 2020 concerning Guidelines for the Implementation of GHG Inventory and Mitigation in the Energy sector, which refers to the guidelines for the national inventory of

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greenhouse gas emissions according to the IPCC. Based on this protocol, the calculation of the carbon footprint begins with an inventory of emission sources to be classified into three scopes.

1.1.1.1 Scope 1

This scope includes the burning of fossil fuels to run industrial machinery, heavy equipment, and vehicles. The calculation of carbon emissions from fuel consumption is calculated using the formula:

$$GHG = m \times NCV \times EF \quad (1)$$

By GHG total CO_2 emissions ($kgCO_2$), m is the mass of fuel used (Gg), NCV *Net Calorific Volume* per unit mass (TJ/Gg), and EF CO_2 conversion factor (kg CO_2e/TJ).

1.1.1.2 Scope 2

In this category, emissions are generated from the use of energy sources in the form of electricity purchased from electricity companies to operate electronic goods. Mathematically, the carbon footprint is calculated by:

$$GHG = \sum \text{consumption} \times EF \quad (2)$$

Where GHG is the amount of CO2 emissions (kgCO2), ∑ consumption of the amount of electrical energy consumption activities (kWh), and EF conversion factor (0.6373 kg CO_2e/kWh) [14].

1.1.1.3 Scope 3

This scope contains other indirect emissions derived from industrial mobility activities in the form of industrial upstream and downstream activities, shipping goods, colleague visits, and other business interests that are not included in scopes 1 and 2. These emissions take place outside the company, but are still closely related to the company's interests.

1.1.2 The palmGHG calculator

Furthermore, there is one method used on a global scale, namely The PalmGHG Calculator, which is a calculation of the carbon footprint of the palm oil processing process by an international palm oil certification body called The Roundtable on Sustainable Palm Oil (RSPO) [15]. Each issuer source is calculated as CO_2e equivalent to the basic formula for carbon emission estimates from the IPCC, which is the multiplication of the issuer's source activity data by the conversion factor of each energy consumption [16] The development of low carbon technologies such as renewable energy innovation from waste, carbon capture and storage, and environmental conservation are counted as carbon credits that reduce emissions. Industrial operational carbon emissions are calculated by the following equation:

$$E_{ME} = E_{MF} + E_{WASTE} + C_{GE} - C_C \quad (3)$$

Where is E_{ME} Total industrial emissions (tCO_2e), E_{MF} Emissions from industrial fuel consumption (tCO_2e), E_{WASTE} Emissions from unmanaged waste (tCO_2e), CGE Emissions from electricity use (tCO_2e), and C_C Carbon credits from waste to energy conversion (tCO_2e).

Reducing greenhouse gas emissions in climate change mitigation actions requires significant changes in the use of fossil fuels, transitioning to low-emission energy, alternative energy adoption, and improving efficiency [17]. One way to achieve this is through an energy audit, which evaluates energy use to identify savings opportunities [18]. The main focus is to increase efficiency to minimize the impact of emissions by maximizing the use of energy sources[19].

An energy audit is a thorough evaluation of emission sources to determine which aspects need to be controlled by offering environmentally friendly solutions. Energy conservation practices with the development of renewable energy on high-efficiency tools are key in climate mitigation initiatives [20]. Energy efficiency is defined as how optimally the input energy is converted into a product without waste [21]. In addition to reducing waste, energy efficiency is also a strategy for the industry in increasing the competitiveness of companies [22].

1.2 Energy productivity ratio (EPR)
Energy efficiency analysis can be done in several ways, one of which is the energy productivity ratio (EPR). EPR is the ratio of the value of physical or economic production to input in the form of energy used to assess the operational feasibility of productivity while helping to better plan energy needs[23]. If the energy ratio is more than 1, where the production produced is greater than the energy used (output > input), then the productivity of the system is called efficient. Meanwhile, the process that takes place shows that it is inefficient if the energy ratio is less than 1, where the product produced is smaller than the energy used (output < input) [24].

The calculation of energy efficiency using the Energy Productivity Ratio (EPR) method is carried out through several main stages. The first stage is the calculation of the energy input of the material, which is mathematically formulated as the ratio between the total price of the material (in Rupiah) and the price of fuel (in Rupiah), then multiplied by the calorific value of the fuel in megajoules (MJ). Furthermore, the calculation of electrical energy input is carried out, namely by multiplying the electrical power consumed by the industry in kilowatt-hours (kWh) units by an energy conversion of 3.6 MJ per kWh. Total energy input is obtained from the sum of energy derived from electricity consumption, fuel, and engine depreciation. Meanwhile, energy output is calculated based on the value of the material products produced. The formula for calculating energy output is to divide the total value of material products (in Rupiah) by the price of fuel (in Rupiah), then multiply by the calorific value of the fuel (in MJ).

The EPR value to determine how efficient the production operations are mathematically is formulated by:

$$EPR = \frac{Output\ energy}{Input\ energy} \tag{4}$$

Based on the urgency of the problem, this study was conducted to calculate the value of carbon dioxide emissions produced from the use of energy for veneer operations and the energy efficiency value of the production process.

2. Methods

2.1 Data and sample
The object of this study is focused on the veneer production process in the company, as one of the production lines during 2023 with complete operational data and its existence as the highest foreign exchange contributor. Sample selection was carried out purposively to obtain representative and relevant data for the research objectives. The data used in this study consisted of primary data obtained through direct observation and interviews with related parties in the veneer division of timber companies, particularly those involved in the production process and energy management. This data includes information on the use of electrical energy, fuel, the type and number of materials used or produced, as well as the depreciation of machines operating in the period from January to December 2023. Meanwhile, secondary data were obtained from credible literature.

2.2 Variable description
This research focuses on the calculation of the carbon footprint as the main objective, which is supported by an analysis of energy efficiency in the veneer production process. The first variable

is in the form of carbon footprint (tCO_2e), which is the total greenhouse gas emissions produced from all operational activities of the veneer industry. Emissions are calculated in tons equivalent to carbon dioxide (tCO_2e) using a two-method approach, namely the Ministry of Energy and Mineral Resources calculation method and the PalmGHG Calculator method. Each emission source is converted using the official emission factor in energy units or usage volumes, multiplied by the calorific value and emission conversion factor. The source of emissions consists of the use of fuel in the form of diesel, pertamax, and pertalite, which are used for production and transportation engines. Furthermore, the total monthly electricity consumption in the production process. Then, the difference between the volume of log wood and veneer is converted to tons using the density of keruing wood. The value of carbon credits as compensation from waste management to bioenergy, calculated based on 10% of waste used and a carbon content of 0.5 tC/ton of wood.

The evaluation of energy efficiency in production is calculated as the ratio between energy output (from the selling value of veneers and by-products in MJ units) to energy input (from raw materials, electricity, and engine depreciation in MJ). An EPR value greater than 1 indicates that production is going on in an energy-efficient manner. Linking carbon footprint and energy productivity analysis provides a comprehensive picture of the environmental performance of the veneer industry while providing an evaluative basis for decarbonization and energy efficiency efforts.

2.3 Statistical analysis

The research was carried out by collecting data related to keruing wood materials (m^3), veneer production (m^3), and the use of fossil energy related to the veneer production process. Carbon dioxide emissions are known by multiplying the units of energy by the conversion factor as equations (1), (2), and (3). Furthermore, the energy efficiency value is calculated by the energy productivity ratio as equation (4) to find out what the efficiency value is. If the ratio produced is more than 1 (EPR>1), the energy consumption during the veneer industry is said to be efficient, so that it is feasible to operate sustainably.

3. Result and Discussion

The veneer production process begins with the preparation of raw materials in the form of Keruing wood (*Dipterocarpus spp.*), which is then processed through several main stages. These stages include cutting wood in the logyard area, immersing logs in water to soften the material, debarking, peeling the wood into thin sheets (peeling), and drying the veneer that is sent to consumers for further processing. This entire series of activities requires a lot of energy so that the production process can run optimally. In its daily operations, the veneer industry also relies on a considerable amount of fossil energy. The energy is in the form of electricity from PLN to operate wood machines and fuel to drive various heavy equipment and vehicles.

According to studies conducted by Pavel and Polina (2024) in the energy sector, it contributes to 63-82% of total greenhouse gas emissions, which makes it a major contributor to industrial emissions. The calculation of carbon dioxide emissions is obtained based on data on energy consumption activities classified[26] based on the three scopes of emission sources in the veneer industry during 2023. In scope I or direct emission, fossil fuels are used in the form of pertamax to operate chainsaws and diesel to operate forklifts, generators, excavators, and trucks.

Scope 2 is indirect emissions which come from PLN's electricity consumption. The use of electricity in the company is no less important part of all operational activities, both in the veneer production area and in the administrative office. The electricity used is sourced from PLN with a capacity of 2180 kVA. During the veneer production process, electricity is used to operate various main machines spread across several stations, namely *Debarking, Rotary*, and drying. These machines require considerable power to function optimally and support the daily production process.

Scope 3 is an indirect emission that comes from energy for activities outside the veneer production process but is still related to industrial interests such as company colleague visits, employee pick-ups, social activities, and waste delivery. This scope consists of the use of fossil fuels in the form of gasoline for motorcycles, office cars, and diesel for trucks.

3.1 Carbon footprint

The veneer industry of the company in operating to process Keruing wood into veneer during 2023 has produced 5,358.76 m^3 of veneer. To produce veneer with this amount, the industry consumes 3,579 liters of pertamax fuel, 128,502 liters of diesel, and 6,961.50 kWh of electrical energy. In addition to producing veneer products, the veneer industry also produces by-products in the form of CO_2 emissions derived from the production process, fuel combustion for heavy equipment, and vehicle transportation for mobility to support other interests related to the veneer industry.

Based on the calculation results, it is known that the veneer industry produced total emissions in 2023 of 370.22 tons of CO_2e. This value is an accumulation of the total emissions of the three scopes of reporting, namely scope 1 is 352.92 tons of CO_2e, scope 2 is 4.44 tons of CO_2e, and scope 3 is 12.87 tons of CO_2e.

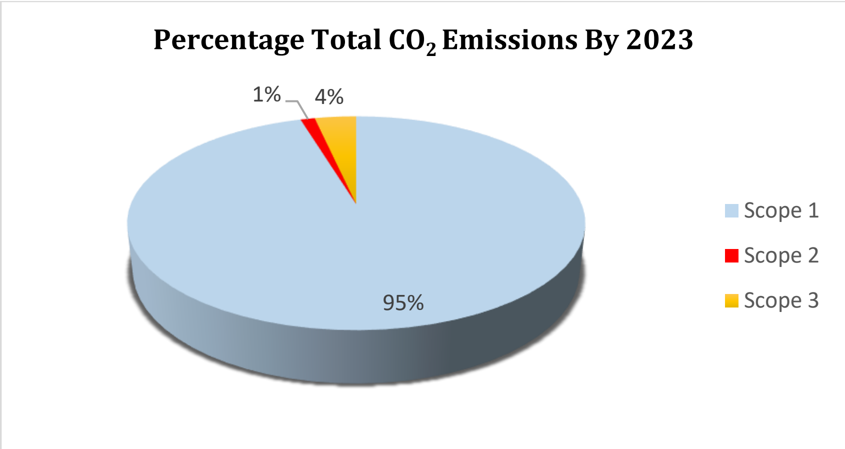

Figure 1. CO_2 emissions of the veneer industry in 2023

Based on the diagram shown in Figure 1, it is known that the largest emissions are produced by scope 1 constitute the majority of the total greenhouse gas footprint accounting for 95%, The dominant contribution stems from the combustion of fossil fuels, especielly diesel used to power heavy equipment and transportation in industry. The visual evidence from the diagram reinforces previous academic findings. It found that some industries studied also showed results that the highest greenhouse gas emissions came from fossil fuels as confirmed by numerous studies [27], [28], [29], [30].

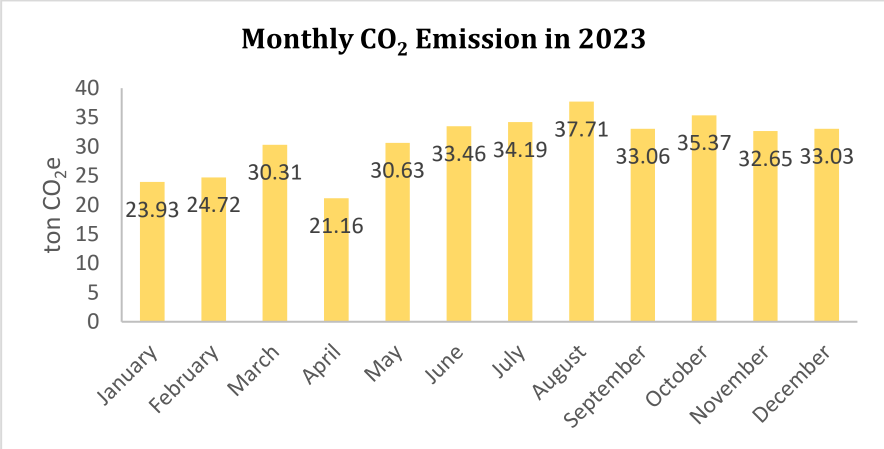

Figure 2. Monthly CO_2 emission tracking in 2023

The graph in Figure 2 illustrates the amount of emissions from the accumulated emission values in Scope 1, Scope 2, and Scope 3 generated during one year of operation. From the picture, it can be seen that there are fluctuations in emissions throughout the year with a tendency to increase quite significantly in the middle of the year, precisely in the period from May to August. The lowest emissions were recorded in April at 21.16 tons of CO_2e, while the peak of emissions occurred in August with a total of 37.71 tons of CO_2e. The increase in total monthly emissions is closely related to the increase in total monthly emissions. Some research before also affirmed that industrial production growth directly contributes to increased greenhouse gas emissions [31], [32], [33].

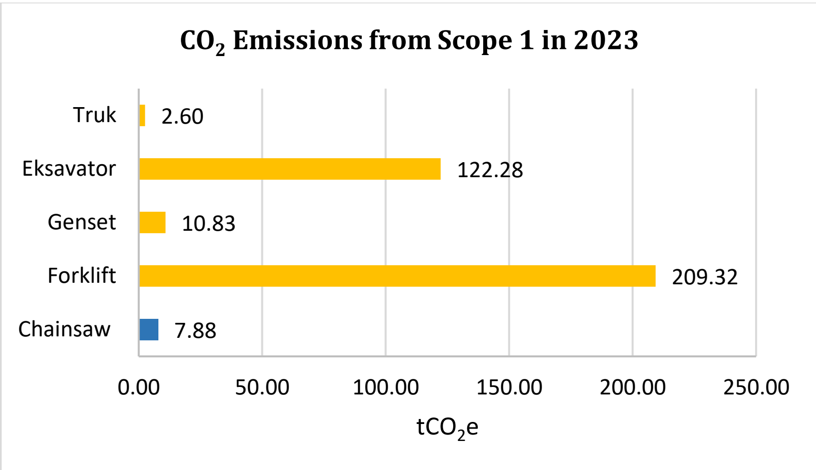

Figure 3. Scope 1 CO_2 emissions 2023

Based on the graph in Figure 3, it can be seen that the contribution of each tool to total CO_2 emissions during 2023 is large. All of the emitter's sources are part of scope 1 where emissions come directly from the burning of fossil fuels used to run this heavy equipment and vehicles. Overall, forklifts are recorded as the heavy equipment that contributes the highest CO_2 emissions in a year, which is 209.32 tons. This figure accounts for up to 59% of total emissions in scope 1. Forklifts are a major contributor to emissions due to their very high operational frequency in the production area, especially for the need to move internal logistics for wood raw materials, veneer, and waste.

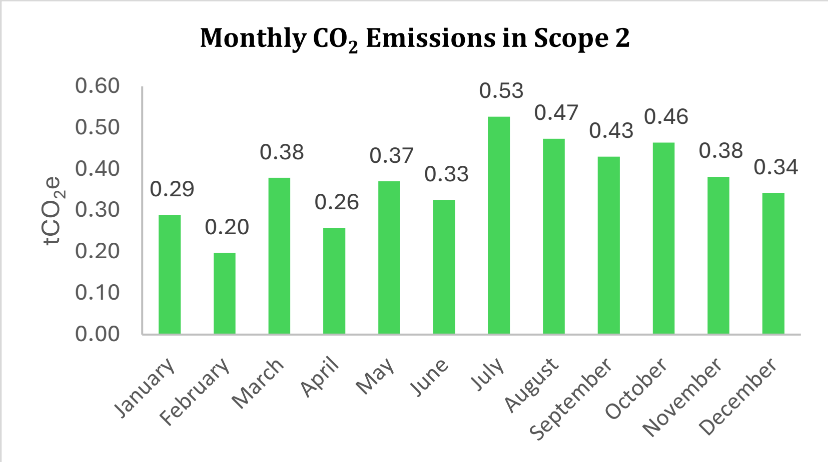

Figure 4. Scope 2 CO_2 emissions 2023

Throughout 2023, CO_2 emissions from electrical energy consumption in the veneer industry show a fluctuating pattern every month, with an average emission of 0.37 tons of CO_2 per month. Figure 4 shows that the peak of emissions was recorded in July, at 0.53 tons of CO_2. This increase reflects the high intensity of electricity consumption, which is used not only for lighting, but also for the operation of production machinery and other support systems. The increase in electricity consumption in the month was closely related to higher production volumes, along with the increase in the amount of raw materials for keruing wood processed into veneer. In contrast, the lowest emissions occurred in February, with a total of 0.20 tonnes of CO_2, indicating relatively lower production activity than in other months.

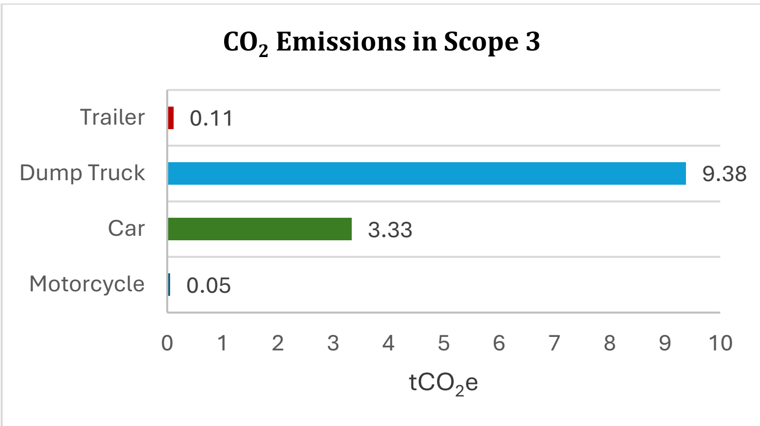

Figure 5. Scope 3 CO_2 emissions during 2023

The graph in Figure 5 shows the contribution of each source to the total scope 3 CO_2 emissions over one year. Transport trucks are the largest contributor to CO_2 emissions with a total of 9.38 tons, which shows that the intensity of use of these vehicles in product distribution and the transportation of raw materials is quite high. Furthermore, in second place, the contributor to CO_2 emissions comes from the use of office cars, which is 3.33 tons of CO_2. These two vehicles are widely used to support administrative activities, coordination between colleagues, and mobility of other operational supports.

Waste trucks and office motorcycles contribute the smallest emissions, 0.11 tons of CO_2 and 0.05 tons of CO_2, respectively. Low emissions from waste trucks indicate the lack of waste transport activities by companies to waste treatment plants. Likewise, the use of motorbikes for the delivery of documents related to companies whose intensity of use is decreasing, along with the transition of the administrative system from hard files to soft files.

For comparison, emissions calculations are also carried out using the PalmGHG Calculator method. The PalmGHG Calculator is a greenhouse gas emission calculation tool developed by the *Roundtable on Sustainable Palm Oil* (RSPO) to calculate and report emissions from palm oil production activities. This method takes into account various sources of emissions, including land use change, fertilizer production, fuel use, and plant waste handling. In addition to calculating total emissions, Palm GHG also calculates the potential carbon sequestration from the use of renewable energy to provide a *net emission estimate* that illustrates the balance between carbon emissions and sequestration in the palm oil production system [34].

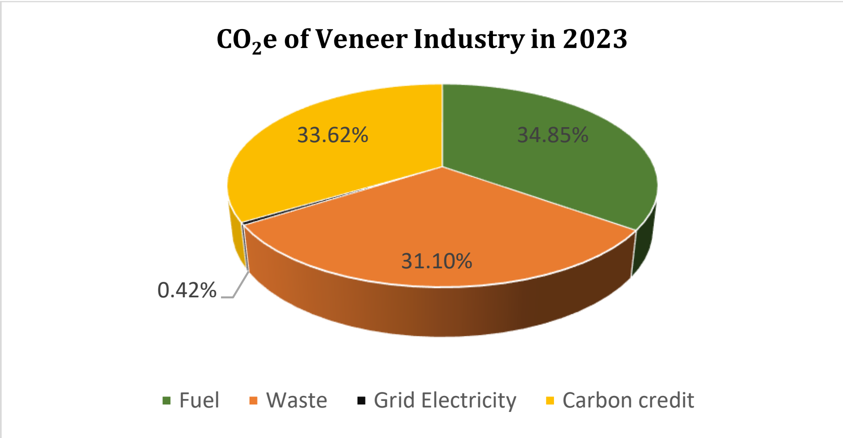

Figure 6. CO_2 Emissions in 2023 based on the palmGHG calculator method

Based on the PalmGHG Calculator method, the total emissions produced in 2023 will be 344,1 tons of CO_2e. The graph in Figure 6 shows that the largest contribution came from the use of fossil fuels of 366.12 tons of carbon dioxide equivalent, which dominated up to 35%, followed by production waste with a percentage of 31% or 326.72 tons of carbon dioxide equivalent. Meanwhile, electricity use contributes very little to emissions with a value of only 4,44 carbon dioxide equivalent or <1%. This method is more comprehensive because it considers carbon absorption from bioenergy potential, which is then called carbon credits as an emission reduction with a percentage of 34% with a value of 353.17 tons of CO_2e. The green energy transition is also a major concern in reducing the environmental impact of industrial growth[35]. The use of biomass as one of the renewable energies applied in the veneer industry is a reduction in emissions for the use of fossil energy sources or in other words, called carbon credits [3].

Each monthly value reflects the contribution of emissions from various sources, namely fuel consumption, electricity consumption, and waste by reviewing the potential of bioenergy or carbon credits as emission reductions. These monthly emissions trends are presented in the following graph.

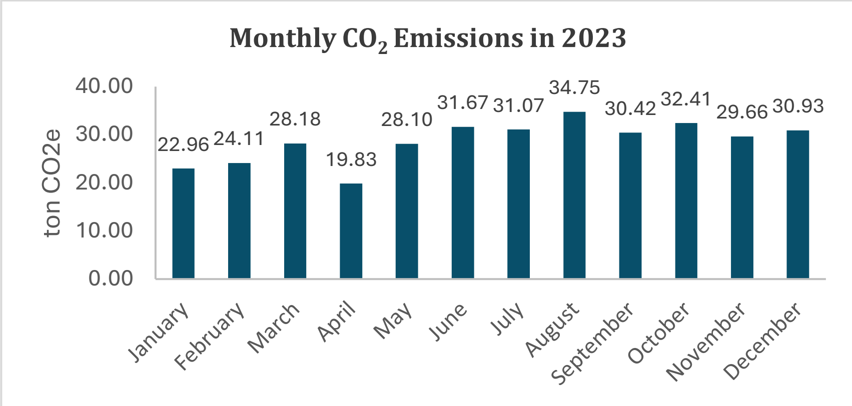

Figure 7. Monthly CO_2 emissions based on the palmGHG calculator method

Based on the graph in Figure 7, overall, there appears to be a trend of emission fluctuations every month. The highest emissions were shown in August 2023, where emissions were recorded at 34.75 tons of CO_2. While the lowest emissions occurred in April 2023 of 19.83 tons of CO_2. In calculations with this method, an average monthly emission of 28.66 tons of CO_2 was produced.

3.2 Energy efficiency

Measuring the intensity of emissions in an industry is the basis for assessing the effectiveness of a low-carbon production strategy. Companies can periodically monitor the environmental impact of their operations while setting more realistic emission reduction targets towards green industry practices in the future. Veneers with export target markets are directed to high-value products, which can encourage the adoption of efficient production processes.

Efficiency reflects the level of optimization of energy use, whether it is actually used effectively to support each stage of production or is wasted. Research from Menghi et al (2019), Dolge et al (2021), and Batouta et al (2023) said that energy management carried out by a number of industry practitioners found that efficiency is the key to sustainable production success that underlies managerial decision-making.

One of the energy efficiency assessment methods that can be implemented in the veneer industry is the energy productivity ratio (EPR) approach. EPR describes the level of energy productivity in a production system using energy prices.

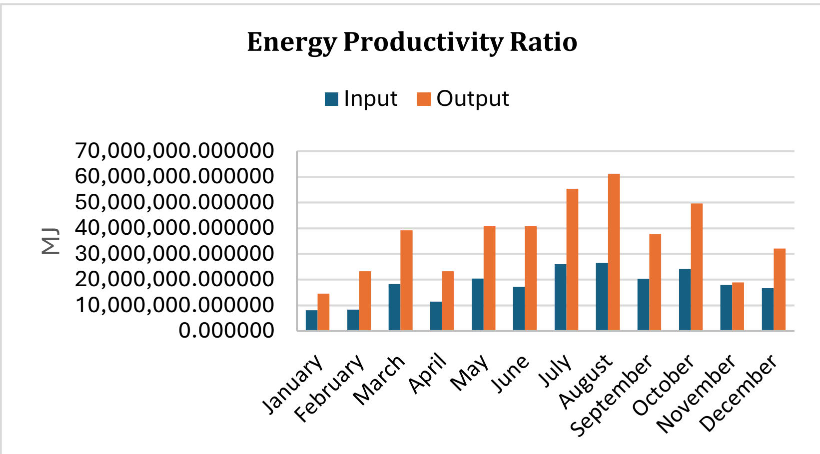

Figure 8. Energy productivity ratio

Figure 8 highlights the relationship between energy inputs and energy output. Energy input whose value is calculated from the sum of materials, electricity, and engine depreciation minus the value of the product. The output bar represents the energy output value of the veneer product produced. Based on the 2023 veneer energy productivity graph, it can be seen that the output line shows greater fluctuations compared to the input energy. This variability indicates the presence of factors that affect energy performance, such as fluctuations in demand, the availability of raw materials, and the performance of production equipment.

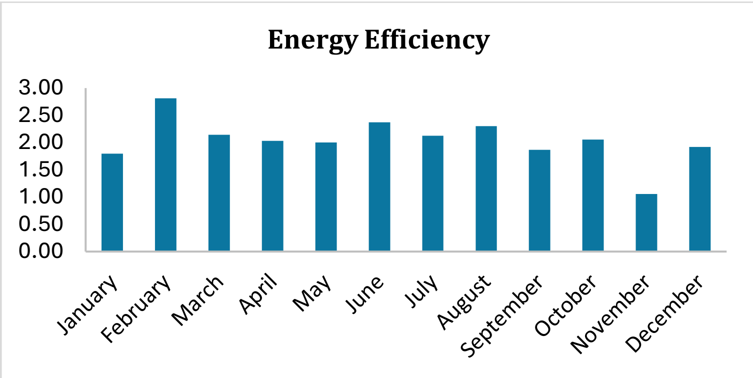

Figure 9. Energy efficiency

The results of the calculation of the energy productivity ratio (EPR) as presented in Figure 9, in each month show a value of more than 1. Efficiency is driven by operational stability and minimal energy wastage in the production process. The highest EPR value occurred in February, which was 2.81. On the other hand, the lowest efficiency value was recorded in November, which was only 1.06. The average EPR value of the veneer production process for a year is 2.04. This means that the veneer production process throughout 2023 is quite good at utilizing the energy used. A system is said to be efficient when the output energy is greater than the input energy, as shown by the results of the comparison of the two with a value greater than 1 [24].

While the Indonesian industry currently operates without a strict mandatory carbon cap, the dominance of Scope 1 emissions from diesel usage must be carefully contextualized. This facility's emission profile, specifically the very low Scope 2 contribution stands out significantly compared to similar industries across Southeast Asia, which typically show higher Scope 2 percentages due to reliance on grid electricity from coal. This low figure is a direct result of the facility's proactive mitigation strategy replacing a substantial portion of coal consumption with biomass as a renewable fuel source. As demonstrated by the PalmGHG analysis which accounts for carbon credits from bioenergy this internal fuel switch substantially reduces the net emissions. Thus, while Scope 1 (diesel) remains the main challenge, this facility establishes a voluntary benchmark for the Indonesian wood processing sector in its transition toward a more sustainable energy

4. Conclusion

The amount of carbon dioxide emissions according to the carbon footprint calculation method from the Ministry of Energy and Mineral Resources, the total emissions from Scope 1, 2, and 3 were recorded at 370.22 tons of CO_2e. Specifically, the highest emission peak occurred in August (37.71 tons of CO_2), while the lowest was recorded in April (21.16 tons of CO_2e), correlating directly with production volume fluctuations. with the largest contributor coming from the use of fossil fuels in heavy equipment (Scope 1). Meanwhile, based on a globally standardized formula, the *PalmGHG Calculator, a* total emission of 344.10 tons of CO_2e was obtained. These results clearly demonstrate that energy efficiency is highly sensitive to product yield, thereby confirming the necessity of optimizing the peeling and drying processes to reduce waste and, consequently, reduce the fuel demand required to process raw input. Moving forward, the low carbon strategy for the veneer industry must focus on substituting diesel in heavy equipment. The energy efficiency in the veneer production process, measured using *the Energy Productivity Ratio* (EPR) method, showed an average value of 2.04. This result indicates that the production process is running efficiently. The highest efficiency is achieved when the proportion of veneer produced exceeds 50% of the total dry wood raw material, which means that the higher the yield of the main product compared to *the by-product*, the better the energy efficiency achieved.

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