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Research Paper

Fuel Emission Projection of Indonesian Manufacturing Industry Towards Net Zero Emissions 2060

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Abstract
The growth of Indonesia's manufacturing industry has the potential to increase greenhouse gas (GHG) emissions. Therefore, this sector needs to become a key focus of emission control programs, aligned with the Sustainable Development Goals. The limited research comparing the contributions of manufacturing subsectors to national GHG emissions motivated this study. This research aims to (i) estimate projected GHG emissions from fuel consumption across medium- and large-scale manufacturing subsectors in Indonesia from 2025 to 2060 and (ii) determine the energy matrix with the lowest-emission scenario approaching the NZE-2060. GHG emissions are projected using LEAP software under four scenarios: business as usual (BAU), emission reduction (ER), clean transition 1 (CT-1), and clean transition 2 (CT-2). The projection results show that GHG emissions in 2060 will reach 593,520.08 Gg CO_2eq (BAU), 320,734.36 Gg CO_2eq (ER), 125,835.03 Gg CO_2eq (CT-1), and 72,834.14 Gg CO_2eq (CT-2). The CT-2 scenario produces the lowest emissions closest to the NZE-2060 target, while the ER scenario represents the most realistic pathway considering Indonesia's renewable energy potential, but has to be complemented by other decarbonization efforts such as CCU/CCS technologies and biomass certification to achieve NZE-2060.

Keywords
Fuel Consumption, Greenhouse Gas Emissions, Indonesia, Manufacturing Industry

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1. INTRODUCTION

Climate change is influenced by the increase in greenhouse gases (GHGs) in the atmosphere. GHGs are atmospheric gases that are naturally occurring or generated through human activities. These gases have the ability to emit radiation and enhance the greenhouse effect (Filonchyk et al., 2024). Types of natural GHGs include water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) (Soeder, 2021). Meanwhile, synthetic GHGs include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and chlorofluorocarbons (CFCs) (Kim et al., 2024; Zhu et al., 2024).

Human activities are the main contributors to the increase in GHG emissions, one of which is the manufacturing industry (Panagiotopoulou et al., 2022). Uncontrolled energy consumption in this sector can lead to a decline in air quality and cause air pollution (Xiao and Liu, 2023). Other consequences include deteriorating human health and environmental damage resulting from the disruption of natural ecosystem functions (Graciela, 2023; Health Effect Institute, 2024). Emissions in the manufacturing industry sector are classified into direct emissions from the production process and fuel combustion, and indirect emissions such as electricity (Zhu et al., 2024).

The industrial manufacturing sector contributed 20.39% to the national Gross Domestic Product (GDP) in 2023. However, this sector generates 33% of total emissions across all sectors (Secretariat General of the National Energy Council, 2024). The energy demand is still dominated by nonrenewable fossil fuels (Hariwan et al., 2021).

The highest industrial density in Indonesia is detected on Java (Ministry of Industry Republic of Indonesia, 2024b). In 2022, the province with the highest industrial units was West Java, followed by East Java, Central Java, Banten, and the Special Capital Region of Jakarta. In contrast, provinces with the fewest manufacturing industries included West Sulawesi, Gorontalo, North Maluku, Maluku, and North Kalimantan (Statistics Indonesia, 2024). The distribution of manufacturing industries by province is presented in Figure 1.

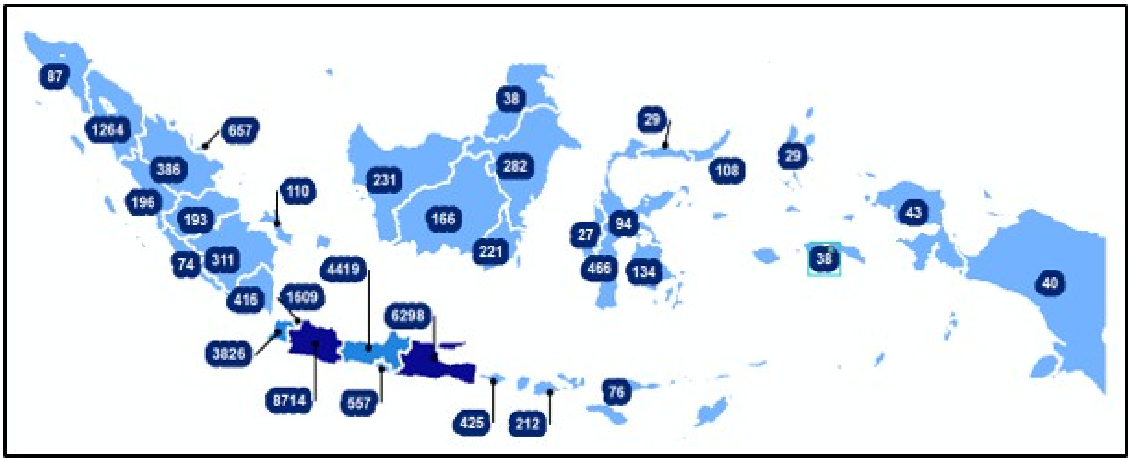

Figure 1. Number of Manufacturing Industry Distributions Across Indonesia in 2022

Decarbonization is considered as one of the most effective way to reduce emission. Some decarbonization initiatives that can be implemented in mufacturing sectors include improving energy efficiency by using environmentally friendly machinery and efficient production system, transitioning fuels and materials from fossil to biomass, and electrification (Gielen et al., 2019; Micieta et al., 2016).

Although several emission-reduction strategies have been implemented, their application remains far from optimal. According to the Ministry of Environment and Forestry Republic of Indonesia (2024), compliance among business operators remains at only 42.96%. Furthermore, only 245 out of 32,193 manufacturing industries in Indonesia have received green industry certification (Ministry of Industry Republic of Indonesia, 2024a).

Research related to emission control based on energy consumption modeling has been conducted at the national and regional levels. For example, Denis (2016) developed emission reduction scenarios in Semarang, which were business-as-usual, energy management, and optimistic scenarios. These scenarios were based on assumptions such as average Gross Regional Domestic Product (GRDP) growth, biomass consumption, electrification, and technological modification. A similar study was conducted in Bengkulu Province by Veven (2023). At the national level, projections have been made by Anindhita et al. (2024); Firmansyah et al. (2023); Siagian et al. (2017); Zaekhan et al. (2022), using macro approaches such as the Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE), Seemingly Unrelated Regression (SUR), and the Long-range Energy Alternatives Planning (LEAP) system to model energy and emission scenarios using various assumptions. In global level, energy and emission modelling have been highly developed in international studies, leading to the creation of various scenarios such as SA90, IS92, SRES, and RCP/SSP by IPCC, and also APS, STEPS, and NZE by International Energy Agency (Girod et al., 2009; International Energy Agency, 2024; Pedersen et al., 2021).

However, most studies using LEAP or other energy models tend to be conducted at the national or inter-sectoral level. This approach is unable to show differences in fuel consumption and emission patterns at the subsector level, particularly in the manufacturing industry. Furthermore, the focus on sector-level comparisons makes analysis within a particular sector less in-depth, resulting in less specific mitigation strategies. Therefore, this study analyzes fuel consumption and GHG emissions in the medium- and large-scale manufacturing subsectors in Indonesia through 2060. This research is expected to provide a more detailed picture in determining the lowest-emission energy combination in subsector level of manufacturing industry towards the 2060 NZE target.

2. EXPERIMENTAL SECTION

2.1 Data Sources

Data for medium- and large-scale manufacturing industries were collected from Statistics Indonesia. It includes fuel consumption (both fossil and non-fossil), production index, output value, and GDP, from 2010-2022. This data serves as the baseline for the emissions modeling in this study. The base year was set at 2021, and validation was performed using 2022 data, based on data availability. Data from other years was used to estimate industrial activity growth.

2.2 Data Processing

Fuel consumption data, originally presented in physical unit (volume), were converted into energy units (terajoules, TJ) using calorific values. The calorific values for unit conversion of energy content is shown in Table 1. Emission modeling is based on the energy consumption of each subsector. This study focuses on calculating scope 1 greenhouse gas emissions, namely, direct emissions from the use of energy from fuel combustion in the industrial sector. Emissions included in scope 2 (emissions from power plants) and scope 3 (emissions from the upstream-downstream supply chain), and emissions from industrial processes (IPPU) are excluded. Biomass is assumed not to contribute in carbon dioxide emissions, following IPCC guidelines, but is included in methane and nitrous oxide calculations. Electricity is assumed to be generated from renewable energy sources and therefore produces zero emissions.

2.3 LEAP Modelling Framework

This study uses a forecasting method by examining potential greenhouse gas emissions under several fossil and non-fossil fuel consumption scenarios up to 2060. The application used to model energy and emissions is the Low Emission Analysis Platform (LEAP) software version 2024.4.0.15. Data from 2021 was chosen as the base year due to the availability of the most up-to-date data. It is also chosen to avoid distortions associated with Covid-19 period. For this process, energy consumption and energy intensity data need to be entered into the current account as baseline data. The 2021 production output value is entered as the activity level. Energy intensity is assumed to remain constant over the projection period, implying no technological change. The energy intensity is counted using Equation (1).

$$IE_j = \frac{TE_j}{TA_j} \tag{1}$$

where IE refers to energy intensity (TJ per IDR output value); TE is total energy in Terajoule; TA is total activity, which is the output value in IDR; and j is the subsector.

Emission variations at each projection period are determined based on the average growth of the production index from 2010 to 2019. Specifically for the ISIC 19, the average GDP growth of the Coal Products and Petroleum Refining Industry from 2010 to 2019 was used due to the lack of production index data for this subsector. The equation used to calculate the average annual growth is shown in Equation (2).

$$R_j = \frac{(Pt_j - Pu_j)}{Pu_j} \times 100 \tag{2}$$

where R denotes as percentage growth rate of annual activity over the observed period (%), Pt is the final year production index/GDP (2019), and Pu is the initial year production index/GDP (2010). To avoid data bias due to the COVID-19 pandemic, 2020 was excluded from the calculations. However, the growth rate from 2021 to 2022 uses actual data from both years as a correction factor. The growth rate is assumed to be constant and is applied uniformly across the projection years. The activity growth rates for each subsector are shown in Table 2.

Based on the energy intensity and growth rate of the activity level, the energy in the projection years is estimated using Equation (3).

$$TE_{jn} = IE_j \times \left(TA_{j(n-1)} \times R_j\right) \tag{3}$$

where TE is total energy (TJ), IE is energy intensity (the value is considered fixed since 2021), TA is total activity at base year (2021), R is growth rate, n is projection year, and j is for subsector.

The scenarios used in this study are differentiated based on the fuel share of each type of fuel and energy efficiency or energy reduction efforts. The basic linear interpolation formula, as shown in Equation (4), is applied to LEAP by entering the "interp" command to set the fuel share and energy efficiency projections for the specified years according to the created scenario.

$$TE_{iy} = TE_{fy} + \lfloor TE_{ey} + TE_{fy} \rfloor \cdot \frac{(Year_{iy} - Year_{fy})}{(Year_{ey} - Year_{fy})} \tag{4}$$

where iy is the intermediate value or projected value, ey is the end year value, and fy is the first year value.

2.4 Emission Calculation

The final energy consumption obtained from the LEAP modeling results was then calculated for emission projections using the emission factors shown in Table 1. The types of greenhouse gases calculated in this study include carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The limitations of national emission factors prompted this study to use a combination of national and global emission factors for each greenhouse gas. Referring to the IPCC greenhouse gas inventory guidelines, biomass is not considered to contribute to the calculation of carbon dioxide emitted by the sector but is instead accounted for in agriculture, forest, and other land use (AFOLU). Therefore, in this study, biomass is assumed to contribute only to CH_4 and N_2O. Meanwhile for electricity is charged to the energy sector and therefore not taken into account. In the scenario, electricity is assumed to be generated from renewable energy sources such as water, wind, and solar, resulting in zero emissions. The emission calculation is carried out according to Equation (5).

$$Em_{(j,i)} = TE_{(j,i)} \times FE_i \tag{5}$$

where Em refers to emission, TE refers to energy consumption, FE is the emission factor, j is subsector, and i is for fuel type.

The three types of greenhouse gases were then converted into a single unit of measurement, carbon dioxide equivalent (CO_2e). This unit of measurement is used to compare the impacts of the three different types of GHGs, taking into account their global warming potential (GWP). The GWP value in this study refers to the IPCC Assessment Report 6. The formula for CO_2e is shown in Equation (6).

Table 1. Energy Conversion and Emission Factor

Fuel Type	Energy Conversion	Emission Factor (FE)		
		CO_2 (ton/TJ)	CH_4 (kg/TJ)*****	N_2O (kg/TJ)
Gasoline	35.93×10^{-6} TJ/liter*	72.80***	3	0.6
High-speed diesel	39.68×10^{-6} TJ/liter*	74.43***	3	0.6
Industrial diesel oil	40.43×10^{-6} TJ/liter*	74.07***	3	0.6
Biosolar	39.68×10^{-6} TJ/liter*	70.80***	3	0.6
Coal	21.14×10^{-3} TJ/ton*	99.70***	10	1.5
Briquette	21.8×10^{-3} TJ/ton*	97.50****	10	1.5
Natural gas	1.05×10^{-3} Joule / MBTU**	57.60***	1	0.1
LPG	52.15×10^{-6} TJ/kg	71.87***	1	0.1
Fuel oil	42.58×10^{-6} TJ/liter*	75.17***	3	0.6
Biomass	14.06×10^{-3} TJ/ton*	-	30	4
Electricity	3.75×10^{-3} Joule/kWh*	charged to the energy sector, not taken into account		

Notes: 1 BOE = 0.006118 TJ
*Ministry of Energy and Mineral Resources Republic of Indonesia, 2025
**Directorate General of Electricity, 2018
***Ministry of Energy and Mineral Resources Republic of Indonesia, 2020
****The Fiscal Policy Agency, 2013
*****IPCC, 2006

Table 2. Growth Rate in Each Subsector

ISIC	Avg R (%)	R 2021–2022 (%)	ISIC	Avg R (%)	R 2021–2022 (%)
10	8.35	3.77	22	0.87	-3.86
11	4.64	10.03	23	4.35	-6.65
12	2.65	16.16	24	4.46	12.42
13	-3.03	-6.1	25	4.32	11.97
14	6.26	24.9	26	-1.32	11.03
15	6.93	1.81	27	5.23	6.55
16	-3.06	-7.43	28	4.47	29.95
17	-0.56	4.68	29	4.51	9.66
18	6.9	-0.55	30	-3.03	2.08
19	-0.79	3.72	31	2.76	-21.56
20	3.75	-1.82	32	-1.66	-3.11
21	9.01	-8.73	33	-3.55	18.17

$$\begin{aligned} \mathrm{Em}_{(j,i)}\mathrm{CO_2e} = {} & (\mathrm{Em}_{(j,i)}\mathrm{CO_2} \times \mathrm{GWPCO_2}) \\ & + (\mathrm{Em}_{(j,i)}\mathrm{CH_4} \times \mathrm{GWPCH_4}) \\ & + (\mathrm{Em}_{(j,i)}\mathrm{N_2O} \times \mathrm{GWPN_2O}) \end{aligned} \tag{6}$$

where $EmCO_2e$ refers to carbon dioxide equivalent (kg CO_2e), $EmCO_2$ is carbon dioxide emission (kg), $GWPCO_2$ is carbon dioxide global warming potential (1), $EmCH_4$ is methane emission (kg), $GWPCH_4$ is methane global warming potential (fossil: 29.8; non fossil: 27), EmN_2O is nitrous oxide emission (kg), and $GWPN_2O$ is nitrous oxide global warming potential (273), j is subsector, and i is for fuel type.

2.5 Model Validation

Model validation is necessary to determine the model's reliability in predicting data close to the actual data. This study uses 2022 energy consumption data as the actual data to compare with the modeling data. Validation is determined based on the mean absolute percentage error (MAPE) in Equation (7).

$$MAPE = \frac{|a-m|}{a} \times 100\% \tag{7}$$

where a means actual or observed total energy (TE) in 2022 and m is the predicted total energy (TE) in 2022. Prediction results are considered excellent if the MAPE value is ≤ 10; good if the MAPE value is between 10 and 20; and reasonable if the MAPE value is between 20 and 50 (Hu and Jiang, 2017).

2.6 Scenario Development

The analysis is performed under 4 (four) scenarios which are BAU, ER, CT-1, and CT2. These scenarios are designed to represent a range of pathways from baseline conditions to policy and technology transitions. This framework is used to compare the impacts of maintaining current trends, implementing existing policies, and adopting low-carbon policy.

1. Business as usual (BAU) if the trends of industrial activities and fuel share remain unchanged, and the production output growth rate per sub-sector follows the average annual production (or GDP for ISIC 19) growth rate from 2010-2019. There is no specific policy for energy transition and energy efficiency. This scenario serves as a reference for comparison.
2. Emission reduction (ER) based on the introduction of energy efficiency policy from the National Energy General (2025: -17.4%; 2030: -21.9%; 2050: -38.9%). Energy transition policy from fossil to renewable energy is also implemented, following the energy mix target in the National Energy Plan in the final industrial sector demand modeling section. However, it was adjusted for 2050 by not adding the percentage of fuel and gas, and not reducing the percentage of electricity to the fuel share in 2025. This assumption is used to remain in line with the energy decarbonization target. Fuel shares used in ER scenario are listed in Table 3.
3. Clean transition 1 (CT-1) based on the activity growth rate per sub-sector follows the average annual production growth rate from 2010 to 2019, with the same fuel share and energy intensity as the BAU scenario. Replacing all fossil fuels (except gas) with bioenergy and electricity from renewable energy by 2060 based on previous study by Hernández and Fajardo (2021).
4. Clean transition 2 (CT-2) represents a more ambitious pathway. It is based on the activity growth rate per subsector follows the average annual production growth rate from 2010 to 2019. Energy intensity and fuel share until 2050 are the same as the ER scenario (already taking energy efficiency into account). Replacing all fossil fuels (except gas) with bioenergy and electricity from renewable energy by 2060.

3. RESULTS AND DISCUSSION

3.1 Fuel Energy Demand Projection from The Manufacturing Industry

Projecting GHG emissions from industrial activities is a crucial step in understanding the potential for climate change. Variations in fuel types, fuel consumption volumes, and activity growth trends mean that each type of industry has a different potential for GHG emissions growth. Therefore, projections of emissions from each manufacturing subsector are necessary to identify long-term trends as a reference for more targeted emission control policies (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2021).

Energy consumption projections from fuel consumption in the manufacturing industry are separated for ISIC outside ISIC 19 and ISIC 19 due to different activity growth assumptions. Activity growth for ISIC outside ISIC 19 is based on production index growth, while ISIC 19 uses GDP growth due to data limitations. The ISIC code of each subsector is shown in Table 4. The abbreviation (ABB) will be used in the graphic to clearly depict the condition of each subsector.

The energy demand of large and medium-sized manufacturing industries (excluding ISIC 19) in 2021 was estimated at 4,762.9 petajoules (PJ) (Figure 2). The subsectors with the highest energy consumption were the rubber, rubber goods, and plastics industry (ISIC 22) and the food industry (ISIC 10), with 1,801.8 PJ and 1,529.7 PJ, respectively. This is due to the high biomass consumption in both subsectors. Meanwhile, the lowest energy consumption in 2021 was in the printing and reproduction of recorded media industry (ISIC 18), with only 0.9 PJ.

However, based on the modeling results, the highest energy consumption in 2060 is in the food industry (ISIC 10) and the basic metal industry (ISIC 24), which reached 33,434.2 PJ and 3,198.3 PJ, respectively. This shift is due to the average annual growth rate of the food and basic metal industries reaching 8.35% and 4.46%, respectively, while the rubber, rubber goods, and plastic industries only grew by 0.87% per year. Meanwhile, the lowest projected energy consumption in 2060 is in the repair and installation services subsector of machinery and equipment (ISIC 33), which is only 0.6 PJ.

The error equivalent results for the energy model, compared to actual data from 2022, showed values no greater than 21.39%, indicating that the model is considered reasonable. Validation was conducted using 2022 data, as it is the most recent year with consistent data availability of subsector level. A longer time series for validation would improve the robustness of the model. However, recent dataset (currently only available up to 2023) do not provide sufficient disaggregation for subsector analysis. Therefore, single-year validation represents the most appropriate approach.

3.2 GHG Emission Projection from Fuel Consumption

GHG emissions from fuel consumption depend on the type of fuel used (Martins et al., 2021). Therefore, the subsector with the highest energy consumption does not always produce the highest emissions. Although some subsectors exhibit high energy consumption, their emissions contribution can vary depending on the type of fuel used.

Based on the results of this study, GHG emissions in 2021 from the manufacturing industry amounted to 83,046.66 GgCO_2e. The largest GHG emissions were generated by

Table 3. Fuel Share Accommodated in the ER Scenario

Fuel type	Fuel share			
	2025	2030	2040	2050
Fuel oil	$\leq$ 6.40%	$\leq$ 6.40%	$\leq$ 6.40%	$\leq$ 6.40%
Coal (including briquettes)	$\leq$ 31.80%	$\leq$ 30.50%	$\leq$ 28.10%	$\leq$ 25.90%
Gas (including LPG)	$\leq$ 28.30%	$\leq$ 28.30%	$\leq$ 28.30%	$\leq$ 28.30%
Bioenergy	$\geq$ 11.40%	$\geq$ 11.70%	$\geq$ 12.30%	$\geq$ 12.90%
	(unless the percentage has been fulfilled from electricity)			
Electricity	$\geq$ 24.10%	$\geq$ 25.10%	$\geq$ 26.90%	$\geq$ 28.50%
	(unless the percentage has been fulfilled from bioenergy)			

Table 4. List of Subsectors of the Manufacturing Industry in Indonesia

ISIC	ABB	Description	ISIC	ABB	Description
10	Food	Food products	22	Rubber and plastic	Rubber and plastic products
11	Beverages	Beverages	23	Non metallic mineral	Other non-metallic mineral products
12	Tobacco	Tobacco products	24	Basic metal	Basic metals
13	Textile	Textiles	25	Metal product	Fabricated metal products, except machinery and equipment
14	Wearing apparel	Wearing apparel	26	Computer and optic	Computer, electronic, and optical products
15	Leather and etc	Leather and related products	27	Electrical equipment	Electrical equipment
16	Wood and etc	Wood and products of wood and cork (except furniture)	28	Machinery	Machinery and equipment n.e.c.
17	Paper	Paper and paper products	29	Motor vehicles	Motor vehicles, trailers, and semi-trailers
18	Printing	Printing and reproduction of recorded media	30	Other transport	Other transport equipment
19	Coke and petroleum	Coke and refined petroleum products	31	Furniture	Furniture
20	Chemical	Chemicals and chemical products	32	Other manufacturing	Other manufacturing
21	Pharmaceutical	Basic pharmaceutical products and pharmaceutical preparations	33	Repair and installation	Repair and installation of machinery and equipment

the textile industry subsector (ISIC 13), reaching 21,570.79 $GgCO_2e$, followed by the food industry subsector with 19,041.30 $GgCO_2e$ (Figure 3). The textile industry is known to produce high emissions (Alici et al., 2024). However, based on 2021 data, the textile industry is not the subsector with the highest energy consumption. This is due to the dominance of coal in the energy mix. The food industry was found to have the highest energy consumption in 2021, with biomass as the dominant fuel. Biomass use can significantly reduce carbon dioxide emissions, but still poses risks through increased methane and nitrous oxide emissions. This is because methane and nitrous oxide emissions produced by biomass are greater than those from fossil fuels, with higher emission factors (IPCC, 2006). The climate change potential (global warming potential) of these two gases is also greater than that of carbon dioxide, namely 27 times greater for methane and 273 times greater for nitrous oxide, respectively (Oshita et al., 2014). The printing and reproduction of recorded media produced the least emissions, in line with its energy consumption.

Based on the business-as-usual (BAU) scenario, total GHG emissions from the manufacturing industry are projected to reach 593,520.09 Gg CO_2e. It represents a nearly eightfold increase compared to 2021. The average annual in-

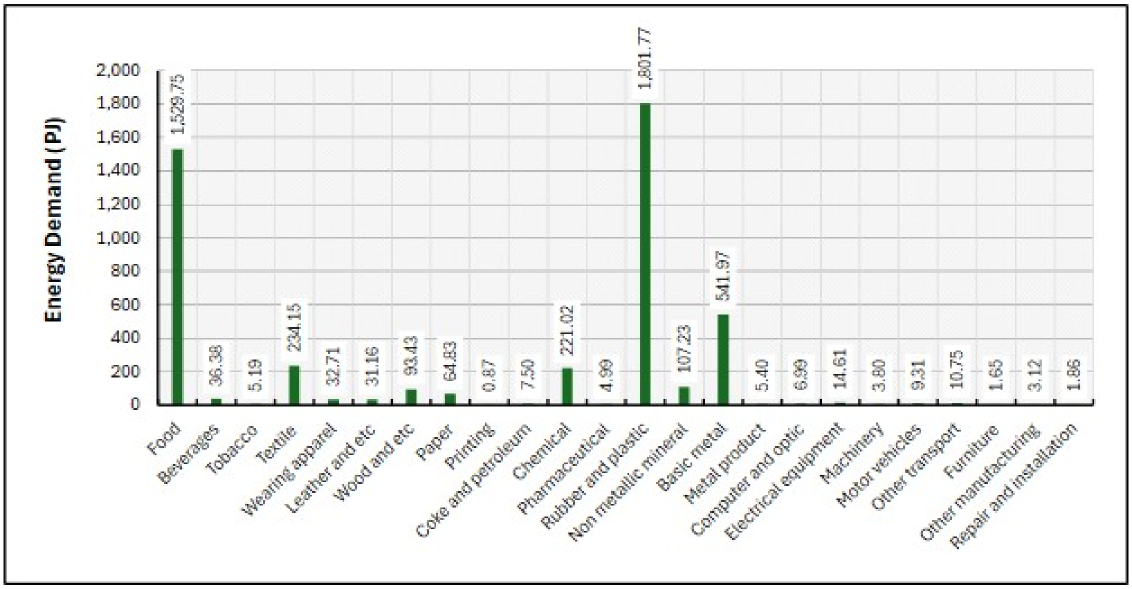

Figure 2. Final Energy Demand (TJ) in Each Manufacturing Subsector in 2021

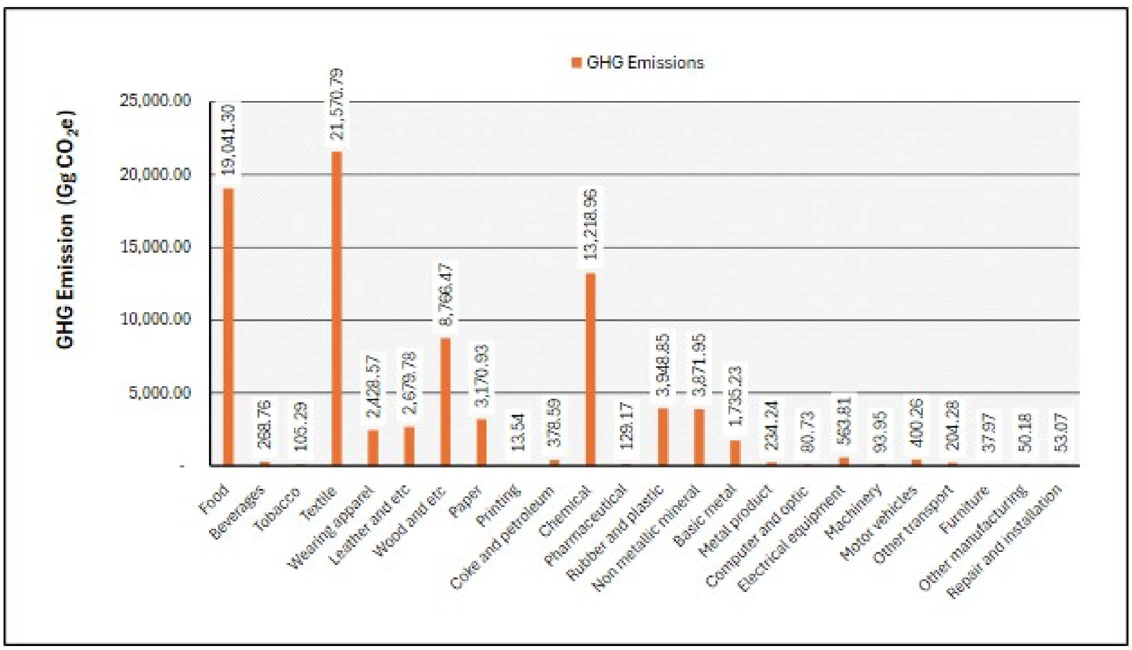

Figure 3. GHG Emissions from Fuel Consumption in Each Manufacturing Subsector in 2021

crease is approximately 5.2%. Several subsectors continue to experience increasing emissions, while others show declining emissions. This is influenced by the production growth rate used as the assumed activity level growth in this study. The results of the GHG emission projections for each subsector in the BAU scenario are shown in Figure 4.

The industrial subsectors that experienced an increase in GHG emissions due to positive production growth were ISIC 10, ISIC 11, ISIC 12, ISIC 14, ISIC 15, ISIC 18, ISIC 19, ISIC 20, ISIC 21, ISIC 22, ISIC 23, ISIC 24, ISIC 25, ISIC 27, ISIC 28, ISIC 29, and ISIC 31. The largest increase in GHG emissions was experienced by the food industry, which rose from 19,041.3 $GgCO_2e$ in 2021 to 416,166.56 $GgCO_2e$ in 2060. This condition was caused by the large energy consumption of the food industry and positive production growth reaching 8.35% per year.

The subsectors that experienced a decrease in GHG emissions due to negative production growth were ISIC 13, ISIC 16, ISIC 17, ISIC 26, ISIC 30, ISIC 32, and ISIC 33. The dependence of the textile industry (ISIC 13) on the need for raw materials in large quantities and prices that are often expensive due to imports, coupled with the pressure of imported textiles from China, makes this industry increasingly difficult to develop in Indonesia (Asmara et al., 2014). The paper and paper goods industry (ISIC 17) in Indonesia also faces ecolabel challenges, where the raw materials are mostly derived from wood that is considered illegal and not environmentally friendly, so it is hampered in exporting (Simangunsong and Wulandari, 2016). The computer, electronics, and optics industry (ISIC 26) is a significant contributor to Indonesia's manufacturing industry. However, this subsector experiences difficulty in obtaining imported raw materials which are essential for production (Martawardaya et al., 2023). The largest decline was experienced by the wood, wood products, and cork (excluding furniture), and woven goods from bamboo, rattan, and similar materials (ISIC 16), from 8,766.47 GgCO_2e in 2021 to only 2,491.21 GgCO_2e in 2060 (-71.58%). This industry experienced a production decline of up to -3.06% per year. Suboptimal product marketing is a constraint on the development of this subsector (Mutaqin et al., 2022).

The ER (emission reduction) scenario considers emission reduction efforts through the transition from fossil fuels to renewable energy and energy efficiency, referring to the National Energy General Plan (RUEN) targets. Through these efforts, GHG emissions are projected to be 45.96% lower than the BAU scenario, or 320,734.36 Gg CO_2eq in 2060 (Figure 5). The largest emission reductions occur in the textile subsectors (ISIC 16), at -94.71%. Fuel use in this subsector in 2021 was dominated by coal, reaching 90.89%. Most of the coal produced and used in Indonesia is low rank coal which can emit high amount of methane as on of the GHG emission (Arisanti et al., 2017). Therefore, in addition to negative production growth, the energy efficiency and coal consumption reduction scenario can significantly reduce emissions. A similar situation is also experienced by the wood and bamboo industry (ISIC 16). Meanwhile, there are also industries whose emissions have decreased significantly despite positive production growth, which are ISIC 22 and ISIC 31. Energy efficiency not only reduces emission, but also contributes in enhancing corporate sustainability (Erwin and Asbanu, 2018).

The decarbonization efforts implemented in the Clean Transition 1 (CT-1) scenario focus on the total transition of all fossil fuels to renewable energy (biomass and biofuels) and electricity from renewable energy sources, except for natural gas and LPG, which are maintained. The projected GHG emissions for each subsector in this scenario are shown in Figure 6, with total GHG emissions in 2060 projected at 125,835.03 Gg CO2eq or a decrease of -78.8% compared to the BAU scenario. The ISIC 13, ISIC 14, ISIC 15, ISIC 16, ISIC 18, ISIC 31, and ISIC 33 industries in this scenario also experienced a significant decrease in emissions compared to the BAU scenario, similar to the ER scenario. The food industry (ISIC 10) and the electrical equipment industry (ISIC 27) are also having significant emissions reduction.

This scenario utilizes only a total transition from fossil fuels to renewable energy, without involving energy efficiency efforts. However, the resulting emission reductions are greater than the ER scenario, which utilizes energy efficiency and fossil fuel reduction. Several subsectors, such as ISIC 10, ISIC 12, ISIC 14, and ISIC 15, which initially experienced positive growth, resulted in steadily increasing emissions. However, between 2050 and 2060, when the total transition from fossil fuels to renewable energy is implemented, emissions decrease significantly, resulting in a peak in 2055 before declining in 2060.

The Clean Transition 2 (CT-2) scenario differs from CT-1 in terms of the projected fuel share of gas and LPG in 2060. The CT-1 scenario assumes the fuel share of gas and LPG is projected to be the same as the initial condition until 2060, while in the CT-2 scenario, the fuel share of gas and LPG is assumed to be a maximum of 26.3% following the RUEN. This condition results in the projected GHG emissions in 2060 only increasing by around 5.57% compared to the conditions in 2025. The total projected aggregate GHG emissions in 2060 with the CT-2 scenario are only 72.834,1 Gg CO_2e, or decreasing by 87.73% compared to the BAU scenario (Figure 7). There are more subsectors that experience a decrease in emissions compared to the ER scenario and the CT-1 scenario, namely ISIC 19, ISIC 20, ISIC 21, ISIC 23, ISIC 25, ISIC 26, ISIC 28, ISIC 29, and ISIC 32. This shows that the total transition from fossil energy to renewable energy, accompanied by energy efficiency efforts, contributes to a greater reduction in GHG emissions. GHG emissions tend to increase until 2055 and then decrease in 2060 because the total transition to renewable energy in this study is assumed to be implemented from 2050 to 2060, after previously being reduced slowly from 2025 to 2050.

Emission trends across scenarios are mainly caused by the differences in activity growth, fuel type used, and policy intervention. In BAU, emissions keep increasing, which showing how production growth drives emissions when no action is taken. The ER scenario reducing the increase of emissions through energy efficiency aligned with the National Energy Plan. Meanwhile, CT-1 and CT-2 lead to more noticeable reduction as fossil fuels are replaced with renewable energy. This suggests that decarbonization in manufacturing sector require not only policy support but also shift in technology and energy use.

3.3 Optimal Energy Matrix Towards NZE-2060

Efforts to reduce greenhouse gas emissions to mitigate the impacts of climate change, also known as decarbonization (Kolmasiak, 2024; Victor-Gallardo et al., 2022), are aimed at reducing emissions and boosting the economy (Groves et al., 2020). The scenario implemented in this study covers only three of the five pillars of industrial decarbonization: energy efficiency, fuel substitution, and low-carbon electricity and electrification. The other two pillars, process

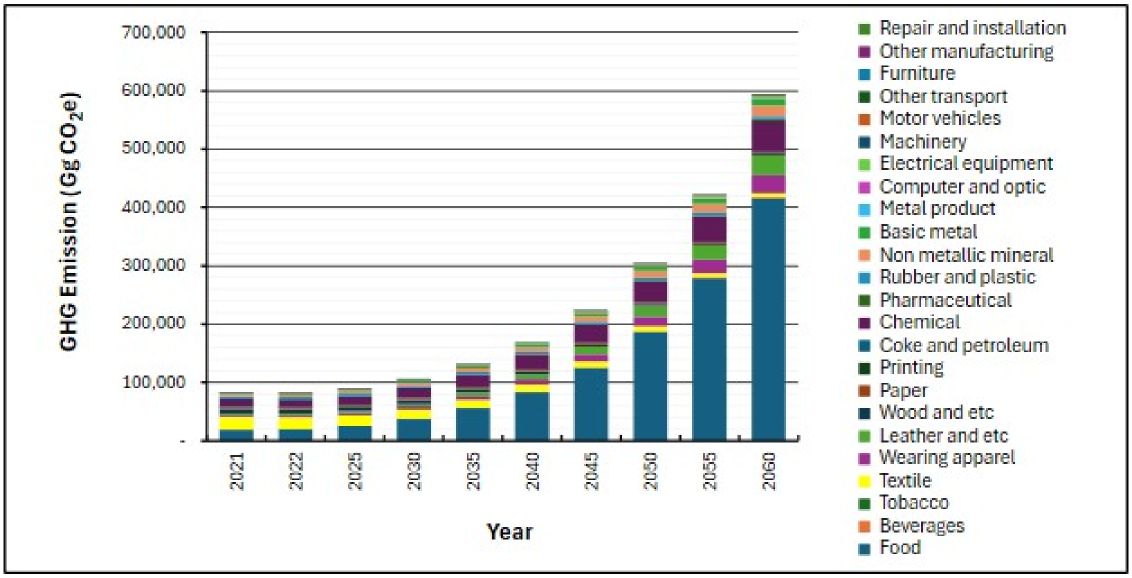

Figure 4. Projected GHG Emissions from Fuel Consumption Across Manufacturing Subsectors Under BAU Scenario 2021-2060

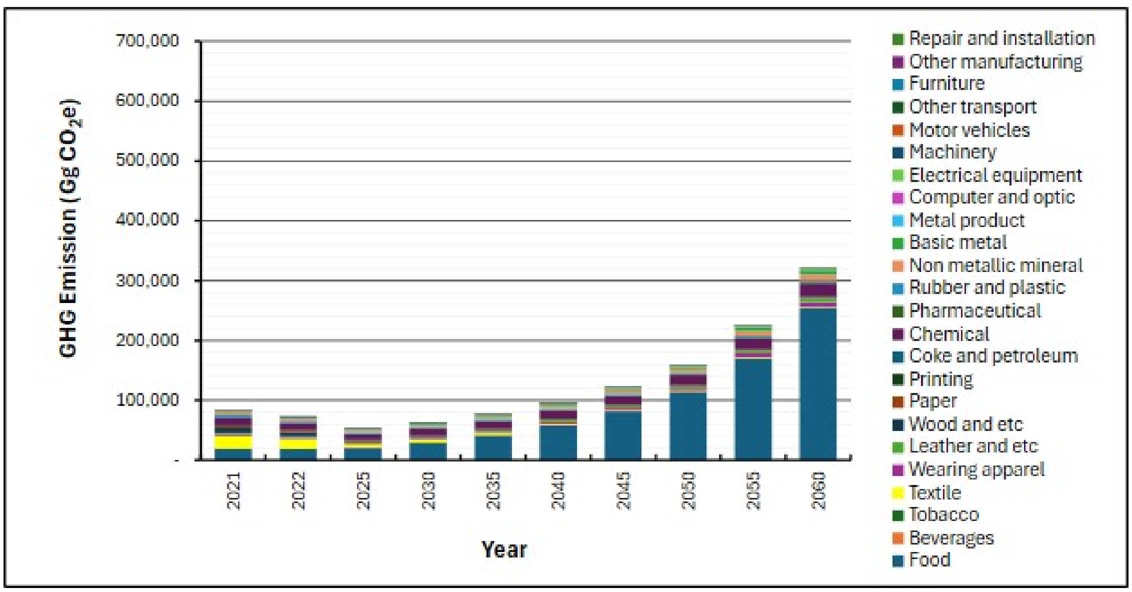

Figure 5. Projected GHG Emissions from Fuel Consumption Across Manufacturing Subsectors Under the ER Scenario, 2021-2060

upgrades and carbon capture, utilization, and/or storage, were not implemented in this study due to their specific technology requirements for each type of equipment. Furthermore, CCU/S technology is still under development and is currently available only for the cement and fertilizer industries.

The energy mix in the base year (2021) was generally dominated by biomass and coal. However, this dominance differed at the subsector level. Subsectors that predominantly used coal included ISIC 13, ISIC 14, ISIC 15, ISIC 16, ISIC 17, and ISIC 20. Meanwhile, subsectors that predominantly used biomass were ISIC 10, ISIC 11, ISIC 21, ISIC 22, ISIC 24, and ISIC 27. Gas fuel was used more in ISIC 20, ISIC 25, and ISIC 29. Electricity was predominantly used in ISIC 12, ISIC 18, ISIC 23, ISIC 26, ISIC 28, ISIC 30, ISIC 31, ISIC 32, and ISIC 33. Scenarios were then developed for transition to electricity from renewable sources but with different fuel shares.

Based on the projection results, the largest GHG emission reduction can be achieved through the CT-2 scenario,

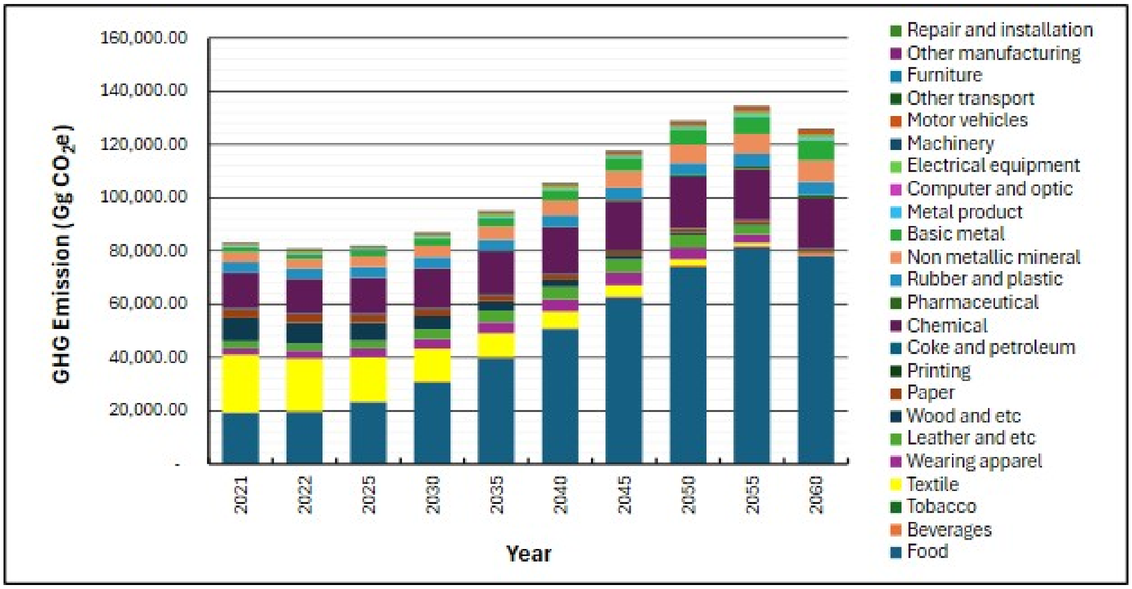

Figure 6. Projected GHG Emissions from Fuel Consumption Across Manufacturing Subsectors Under the CT-1 Scenario, 2021-2060

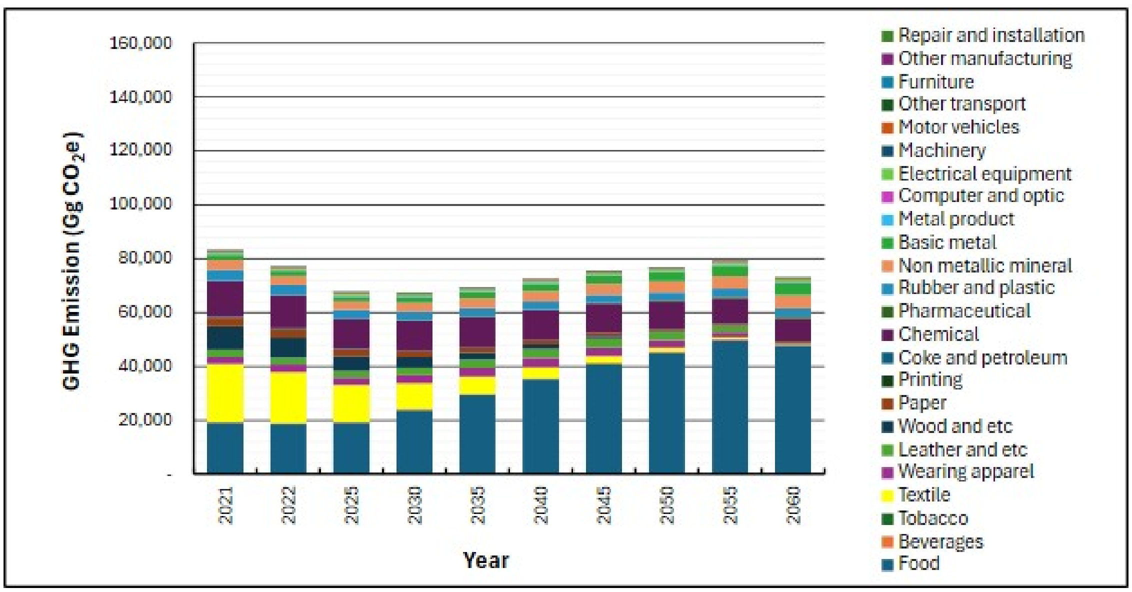

Figure 7. Projected GHG Emissions from Fuel Consumption Across Manufacturing Subsectors Under the CT-2 Scenario, 2021-2060

combining efforts to transition to electricity and renewable energy sources, and energy efficiency. The ER scenario can only reduce emissions by a maximum of 81.87%, CT-1 by a maximum of 99.4%, and CT-2 by a maximum of 99.5%, at ISIC 13 and ISIC 16 (Table 5). This condition occurs because the dominant energy used in this subsector in 2021 was dominated by coal, reaching 90.73% and 90.89%. As is known, coal is the largest contributor to emissions compared to other types of fuel. Therefore, decarbonization interventions in this type of fuel can have a significant impact on GHG emission reductions. Figure 8 shows the comparison in GHG emissions between all scenarios.

Based on the projection results, the scenario with the lowest emissions in 2060 is the CT-2 scenario, followed by CT-1, ER, and BAU, as shown in Table 6. The CT-2 scenario, which combines energy efficiency and fossil fuel transition, is capable of reducing emissions by up to 87.73% compared to the BAU scenario.

As a note, either CT-1 or CT-2 scenario assume that electricity used is fully sourced from renewable energy, so

Table 5. Percentage of Emission Reduction in Each Scenario Compared to the BAU Scenario

ISIC	Emission Reduction (%)			ISIC	Emission Reduction (%)		
	ER (%)	CT-1	CT-2		ER (%)	CT-1	CT-2
10	-38.90	-81.26	-88.55	22	-38.90	-9.55	-44.74
11	-38.90	-53.24	-71.43	23	-48.51	-55.53	-72.55
12	-63.78	-67.54	-79.36	24	-38.90	-25.89	-54.72
13	-81.87	-99.40	-99.36	25	-53.90	-44.02	-76.83
14	-75.05	-99.08	-99.39	26	-50.56	-60.28	-75.62
15	-80.16	-98.45	-99.04	27	-38.90	-73.55	-83.80
16	-81.23	-99.46	-99.50	28	-61.64	-56.60	-73.35
17	-44.12	-65.44	-79.84	29	-70.81	-12.40	-78.05
18	-72.39	-85.18	-90.89	30	-50.53	-44.12	-65.81
19	-73.37	-13.31	-81.50	31	-73.55	-77.87	-86.26
20	-56.81	-64.37	-84.19	32	-45.74	-64.04	-78.02
21	-41.41	-54.53	-72.21	33	-76.88	-79.55	-87.06

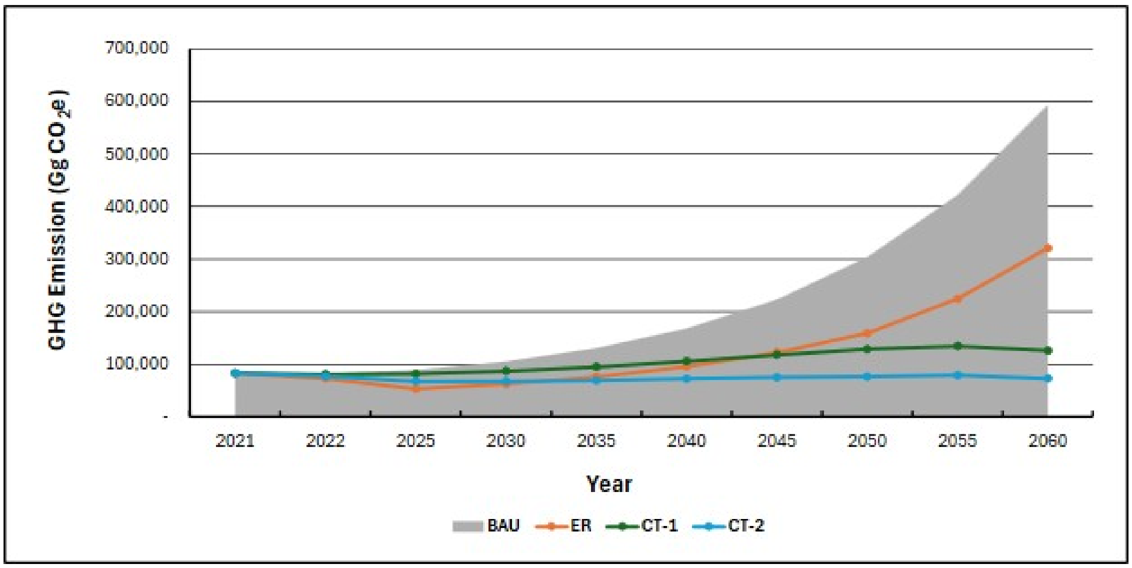

Figure 8. Comparison of GHG Emissions from Fuel Consumption Between Proposed Scenarios

Table 6. Remaining GHG Emissions for Each Scenario in 2060

Scenario	Remaining GHG emissions in 2060 (Gg CO_2e)	Reduction compared to BAU scenario
BAU	593,520.08	-
ER	320,734.36	-45.96%
CT-1	125,835.03	-78.80%
CT-2	72,834.14	-87.73%

upstream emissions associated with electricity generation are 0. Therefore, it will closely depended on the availability of the renewable energy in Indonesia. The renewable energy potential available in Indonesia, based on the RUEN data for various energy sources, is only 443,208 MW. Excluding bioenergy, the availability of renewable energy in Indonesia is approximately 410,554 MW for all sectors. The final energy demand modeling results based on the Indonesia General Energy Planning for industrial fuels in 2050 are approximately 40.3%. Therefore, assuming all sectors utilize renewable energy, the available renewable energy for the industrial sector is 178,612.82 MW, and the remaining renewable energy, excluding bioenergy, is 165,453.26 MW.

The total renewable energy requirement in 2060 for the CT-2 scenario is 25,133,831.93 TJ, or equivalent to 796,354.39 MW (conversion 1 TJ/s = 1 million MW). If the biomass requirement is not taken into account, considering that this energy source can be met from industrial manufacturing waste, then the renewable energy requirement for this scenario is 4,023,057.37 TJ, or equivalent to 127,570.31 MW. Although when compared to the overall potential, it is still sufficient, but later this medium and large industrial sector will utilize about 77.1% of the existing renewable energy potential, even though there are still other sectors, such as micro and small industries, transportation, households, and commercial, that need to be met. Likewise, the CT-1 scenario requires more renewable energy in 2060, reaching 40,984,215.19 TJ or equivalent to 1,299,600.94 MW, with a non-biomass renewable energy requirement of 207,415.71 MW.

The most feasible scenario, based on Indonesia's renewable energy potential, is the ER scenario. This scenario is projected to require 22,558,333.79 TJ of renewable energy, equivalent to 715,320.07 MW, by 2060. The need for renewable energy outside of biomass for this scenario is still smaller than the potential for renewable energy for industry, which is only 46,536 MW. Indonesia has set a roadmap toward NZE 2060 through some commitments, including Paris Agreement to Enhanced NDC which strengthened emissions reduction target from 29%–41% to 31.89%–43.2% aligned with a 1.5°C pathway (International Energy Agency, 2022). In this study, the ER scenario represents the current policy commitments, as this scenario is based on energy efficiency targets outlined in the National Energy Plan. However, the ER scenario does not fully reduce emissions from the manufacturing sector to net zero by 2060. It leaves 320,734.36 Gg CO_2e remaining, which is limited in achieving net zero emissions target in 2060. Some emission modelling studies show similar findings, indicating that energy efficiency alone is not sufficient to achieve NZE-2060 (Firmansyah et al., 2023; Li et al., 2023; Liu et al., 2024). Therefore, it needs to be combined with other efforts that are also part of decarbonization in order to achieve the NZE-2060 target.

Some programs can be implemented, such as upgrading processes and technologies for carbon capture, utilization, carbon capture storage, and reforestation. Technology plays a crucial role in reducing emissions in the manufacturing sector. It is not only applied to core facilities, but also to supporting facilities such as office equipment, vehicles, and lighting. The use of energy-efficient lighting in the food, beverage, and textile industries has been shown to reduce energy requirements and operational costs (ClimateWorks Centre, 2025).

Carbon capture utilization (CCU) is a major emission reduction technology currently being developed in the manufacturing sector. CCU technology captures carbon dioxide emitted by utilities and converts it into various by-products, such as fuels or chemicals, that can then be traded, generating additional profits (Lamberts-Van Assche et al., 2023). However, CCU is currently still in the research and development stage and is only targeted for implementation in Indonesia in 2040.

The ER scenario is still dominated by biomass fuels. Therefore, one important effort is to ensure the biomass used is low-emission and, if possible, certified. This is not only to obtain low-emission biomass, but also to ensure that the biomass used is sourced from environmentally sustainable sources with a minimal carbon footprint (Wiśniewski and Kistowski, 2020). Combining fossil and biomass can be a promising step in energy transition efforts. For example mixing oil sludge with biomass as an alternative fuel in cement industry (Ningsih et al., 2019).

Renewable energy investment in Indonesia faces several challenges. For example in biodiesel supply, issues include deforestation associated with palm oil-based feedstocks, institutional conflicts, and limited support for alternative sources (Kabinawa, 2014). In addition, energy infrastructure has also been a major challenge in supporting decarbonization in manufacturing sector. High investment costs leading to shared responsibilities between the government and the private sector (Ministry of National Development Planning/National Development Planning Agency and Economic Research Institute for ASEAN and East Asia, 2021).

4. CONCLUSIONS

Based on the modeling results, CT-2 scenario generates lowest GHG emissions closest to the 2060 net zero emission target for the Indonesian manufacturing industry compared to the other scenarios. However, the most feasible energy matrix when adjusted to Indonesia's renewable energy potential is the ER scenario To achieve the 2060 net-zero emissions target from the manufacturing industry sector, the implementation of the ER scenario needs to be combined with other decarbonization efforts, such as the use of CCU/CCS technology, biomass certification, and reforestation. Current emission reductions fall short of Indonesia's NDC targets. This shows that strong government support is needed. Specific decarbonizations plans for each manufacturing subsector, along with rules, guidance, and monitoring, are crucial to achieve the NZE 2060 target.

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REFERENCES

Alici, H., B. N. Yigit, B. Menemencioglu, K. Tumay Ates, O. Demirdelen, T. Demirdelen, and Z. Kıvanc (2024). Analysis of Carbon Footprint Including Process-Level Calculation and Its Influencing Factors of Process for Low-Carbon and Sustainable Textile Industry. *Sustainability*, **16**(23); 10168

Anindhita, J. Santosa, and K. Tokimatsu (2024). Comparative Analysis of Indonesia's Energy System Scenarios: Assessing Emissions Reduction Strategies and Cost-

Effectiveness. *IOP Conference Series: Earth and Environmental Science*, **1395**(1); 012033

Arisanti, R., M. Yusuf, and M. Faizal (2017). Study of The Effect of Coal Quality Parameters on Gas Methane (CH_4) Emission in Coal Fire for Sustainable Environment. *Indonesian Journal of Environmental Management and Sustainability*, **1**(1); 19–22

Asmara, A., Y. L. Purnamadewi, and A. Meiri (2014). Industrial Cost Structure and Its Impact on the Performance of the Indonesian Textile and Textile Product Industry. *Jurnal Manajemen & Agribisnis*, **11**(2); 110–118. [Text in Indonesian]

ClimateWorks Centre (2025). Decarbonization in Indonesia's Manufacturing Sector: Case Studies of the Food and Beverage, Textile and Chemical Subsectors. [Text in Indonesian]

Denis, D. (2016). *Low-Emission Energy Management Scenario in Semarang City*. Master's thesis, Universitas Gadjah Mada. [Text in Indonesian]

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (2021). Projections of Greenhouse Gas Emissions and Removals: An Introductory Guide for Practitioners

Erwin and H. Asbanu (2018). Corporate Sustainability Improvement Strategy in Manufacturing Industry with The Use of Controls in Environmental Pollution, Quality, and Occupational Health and Safety. *Indonesian Journal of Environmental Management and Sustainability*, **5**(4); 146–153

Filonchyk, M., M. P. Peterson, L. Zhang, V. Hurynovich, and Y. He (2024). Greenhouse Gases Emissions and Global Climate Change: Examining the Influence of CO_2, CH_4, and N_2O. *Science of The Total Environment*, **935**; 173359

Firmansyah, V., M. K. Adinarayana, R. Tetrisyanda, and G. Wibawa (2023). Scenario of Renewable Energy Transition from Fossil Energy Resources Towards Net Zero Emission in Indonesia. In *E3S Web of Conferences*, volume 467. page 04005

Gielen, D., F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini (2019). The Role of Renewable Energy in the Global Energy Transformation. *Energy Strategy Reviews*, **24**; 38–50

Girod, B., A. Wiek, H. Mieg, and M. Hulme (2009). The Evolution of the IPCC's Emissions Scenarios. *Environmental Science & Policy*, **12**(2); 103–118

Graciela, F. (2023). The Impact of Global Warming on Earth's Ecosystems and Future Sustainability. *Future Sustainability*, **5**

Groves, D. G., J. Syme, E. Molina-Perez, C. Calvo, L. Víctor-Gallardo, G. Godinez-Zamora, J. Quirós-Tortós, F. D. León, and A. M. Murillo (2020). The Benefits and Costs of Decarbonizing Costa Rica's Economy

Hariwan, P., B. Juanda, S. Mulatsih, and H. Hariyoga (2021). Analysis of Energy Efficiency on the Manufacturing Industry in Indonesia. *International Journal of Energy Economics and Policy*, **11**(4); 28–36

Health Effect Institute (2024). State of Global Air 2024

Hernández, K. D. and O. A. Fajardo (2021). Estimation of Industrial Emissions in a Latin American Megacity Under Power Matrix Scenarios Projected to the Year 2050 Implementing the LEAP Model. *Journal of Cleaner Production*, **303**; 126921

Hu, Y.-C. and P. Jiang (2017). Forecasting Energy Demand Using Neural-Network-Based Grey Residual Modification Models. *Journal of the Operational Research Society*, **68**(5); 556–565

International Energy Agency (2022). *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*. OECD

International Energy Agency (2024). Global Energy and Climate Model Documentation 2024

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 2 Chapter 2*. IPCC, Kanagawa

Kabinawa, I. M. G. W. T. (2014). *The Role of Government in Promoting the Development of Renewable Energy (Biodiesel) Investment Policies to Enhance Economic Growth in Indonesia*. Thesis, Universitas Gadjah Mada, Yogyakarta. [Text in Indonesian]

Kim, D.-H., H. Lee, K. Kim, S. Kim, J. H. Kim, Y. W. Ko, I. Hawes, J.-E. Oh, and J.-T. Kim (2024). Persistent Organic Pollutants in the Antarctic Marine Environment: The Influence Impacts of Human Activity, Regulations, and Climate Change. *Environmental Pollution*, **363**; 125100

Kolmasiak, C. (2024). Decarbonization of Production Systems in Foundries. *Archives of Foundry Engineering*

Lamberts-Van Assche, H., M. Lavrutich, T. Compernolle, G. Thomassen, J. J. J. Thijssen, and P. M. Kort (2023). CO_2 Storage or Utilization? A Real Options Analysis Under Market and Technological Uncertainty. *Journal of Environmental Economics and Management*, **122**; 102902

Li, B., W. Zhou, Y. Xian, and X. Guan (2023). Forecasting the Energy Demand and CO_2 Emissions of Industrial Sectors in China's Beijing-Tianjin-Hebei Region Under Energy Transition. *Environmental Science and Pollution Research*, **31**(5); 7283–7297

Liu, X., L. Yang, J. Du, H. Zhang, J. Hu, A. Chen, and W. Lv (2024). Carbon and Air Pollutant Emissions Forecast of China's Cement Industry from 2021 to 2035. *Resources, Conservation and Recycling*, **204**; 107498

Martawardaya, B., A. S. Nugroho, E. Listiyanto, D. Y. Junifta, and A. M. Pulungan (2023). Resisting the Curse of Deindustrialization: Towards Mainstreaming Green Industrialization. [Text in Indonesian]

Martins, T., A. C. Barreto, F. M. Souza, and A. M. Souza (2021). Fossil Fuels Consumption and Carbon Dioxide Emissions in G7 Countries: Empirical Evidence from ARDL Bounds Testing Approach. *Environmental Pollution*, **291**; 118093

Micieta, B., J. Markovic, and V. Binasova (2016). Advances in Sustainable Energy Efficient Manufacturing System. *MM Science Journal*; 918–926

Ministry of Environment and Forestry Republic of Indonesia (2024). Ministry of Environment and Forestry Performance Report 2023. [Text in Indonesian]

Ministry of Industry Republic of Indonesia (2024a). Ministry of Industry Government Performance Report 2023. [Text in Indonesian]

Ministry of Industry Republic of Indonesia (2024b). SIINAS Industrial Data

Ministry of National Development Planning/National Development Planning Agency and Economic Research Institute for ASEAN and East Asia (2021). Study of Indonesia's Manufacturing Sector in 2021. [Text in Indonesian]

Mutaqin, D. J., F. O. Nurhayani, and N. H. Rahayu (2022). Timber Industry Performance and Recovery Strategies Post-Covid-19 Pandemic. *Bina Widyaparwa*, **5**(1); 48–62. [Text in Indonesian]

Ningsih, R. Y., F. Goembira, P. S. Komala, and N. P. Putra (2019). Emission and Heavy Metal Content Characteristic of Densified Refused Derived Fuels of Oil Sludge and Biomass Combination as an Alternative Fuel for Cement Plant. *Indonesian Journal of Environmental Management and Sustainability*, **3**(3); 100–105

Oshita, K., T. Okumura, M. Takaoka, T. Fujimori, L. Appels, and R. Dewil (2014). Methane and Nitrous Oxide Emissions Following Anaerobic Digestion of Sludge in Japanese Sewage Treatment Facilities. *Bioresource Technology*, **171**; 175–181

Panagiotopoulou, V. C., P. Stavropoulos, and G. Chryssolouris (2022). A Critical Review on the Environmental Impact of Manufacturing: A Holistic Perspective. *International Journal of Advanced Manufacturing Technology*, **118**(1–2); 603–625

Pedersen, S. T. J., F. Duarte Santos, D. Van Vuuren, J. Gupta, R. Encarnação Coelho, B. A. Aparício, and R. Swart (2021). An Assessment of the Performance of Scenarios Against Historical Global Emissions for IPCC Reports. *Global Environmental Change*, **66**; 102199

Secretariat General of the National Energy Council (2024). Indonesia Energy Outlook 2024

Siagian, U., B. Yuwono, S. Fujimori, and T. Masui (2017). Low-Carbon Energy Development in Indonesia in Alignment with Intended Nationally Determined Contribution (INDC) by 2030. *Energies*, **10**(1); 52

Simangunsong, B. C. and R. A. Wulandari (2016). Analysis of the Competitiveness of Indonesian Pulp and Paper Products in the Global Market. *Jurnal Ilmu Teknologi Kayu Tropis*, **14**(1); 87–101. [Text in Indonesian]

Soeder, D. J. (2021). Greenhouse Gas Sources and Mitigation Strategies from a Geosciences Perspective. *Advances in Geo-Energy Research*, **5**(3); 274–285

Statistics Indonesia (2024). *Indonesia Manufacturing Industrial Directory Volume 13, 2024*. Statistics Indonesia

Veven, M. (2023). *Optimization Study of Renewable Energy Potential to Support the Energy Transition for the 2023–2033 Period (Case Study of Bengkulu Province)*. Master's thesis, Universitas Gadjah Mada, Yogyakarta, Indonesia. Master of Systems Engineering, [in Indonesian]

Victor-Gallardo, L., J. Roccard, P. Campos, C. S. Malley, E. N. Lefevre, and J. Quiros-Tortos (2022). Identifying Cross-Sectoral Policy Synergies for Decarbonization: Towards Short-Lived Climate Pollutant Mitigation Action in Costa Rica. *Journal of Cleaner Production*, **379**; 134781

Wiśniewski, P. and M. Kistowski (2020). Greenhouse Gas Emissions from Cultivation of Plants Used for Biofuel Production in Poland. *Atmosphere*, **11**(4); 394

Xiao, T. and Z. Liu (2023). Air Pollution and Enterprise Energy Efficiency: Evidence from Energy-Intensive Manufacturing Industries in China. *Sustainability*, **15**(7); 6311

Zaekhan, N. Djalal Nachrowi, D. Hartono, and T. Rosita (2022). What Drivers the Decoupling of CO_2 Emissions in the Indonesian Manufacturing Industry? An Analysis of Firm Level Factors. *International Journal of Sustainable Energy*, **41**(5); 538–555

Zhu, Y., G. Li, S. Liu, S. Yu, G. Hou, Z. Zha, Q. Zhang, S. Liu, C. Jing, and J. Chu (2024). Hollow Waveguide CO_2 Laser Sensing System for Rapid Detection of Trace Sulfur Hexafluoride (SF_6) Gas. *Infrared Physics & Technology*, **136**; 105045

