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Study of The Calculation of The Potential Environmental Impact of Crude Oil Production on The Crude Oil and Gas Explore Industry in Sumatra Using The Life Cycle Assessment Method

Ervando Tommy Al-Hanif[1]*, Purnomo Adi Saputro[1], Isaaf Faadhilah[2], Masyiswa Fatika Sari[1], Damai Sinar Pertiwi[1], Alifah Al Farida[1]

[1]Department of Geography, Faculty of Social and Political Sciences, Universitas Negeri Semarang, Indonesia
[2]PT Sinergi Enviro Nusantara, Indonesia

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Abstract

The energy or oil and gas industry is one of the largest contributing sources in Indonesia because of the high demand for oil and gas fuel. Still, it produces emissions and waste that have the potential to damage the surrounding environment. This research aims to analyze the identification of potential environmental impacts from the petroleum and natural gas industry in Sumatra using the life cycle assessment method so that it can provide recommendations for improvements in reducing environmental impacts in the petroleum and gas industry. This research uses the life cycle assessment (LCA) SNI ISO 14040:2016 concerning Life Cycle Assessment - Principles and Framework and SNI ISO 14044:2017 concerning Life Cycle Assessment - Requirements and Alloys using SIMAPRO Developer 9.4.0.2 software. The results are as follows: 1) The oil and gas industry has conducted a life cycle assessment study according to SNI ISO 14040:2016 and 14044:2017 standards, involving 100% of its petroleum products. 2) The data quality is adequate for life cycle impact assessment, with the data collected reaching 100% completeness. 3) The results of the environmental impact assessment cover 12 relevant impact categories, providing a comprehensive picture of the impacts produced by the oil and gas industry on the environment; 4) the main focus on essential issues can be directed at core processes or production within the scope of the oil and gas industry. 5) Efforts to improve the environment can be focused on the processing unit, which is an important issue, namely diesel-based generator emissions from the power plant process unit. 6) The sensitivity analysis results show that changes in emission values in the power plant process unit do not significantly affect the resulting potential impacts. Hence, this emission value is not sensitive based on the collection method. 7) Recommendations are given based on important issues that have been identified.

*Address: Sekaran, Gunungpati, Semarang
Email: ervandotommy@mail.unnes.ac.id
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INTRODUCTION

Indonesia is one of the countries that contributes to the pollution of emissions in the air, namely emissions. According to the Ministry of Energy and Mineral Resources, in 2022, there will be greenhouse gas (GHG) emissions of 1,334 tons of CO_2e, with the energy sector contributing 453.2 Tons of CO_2e The energy or oil and gas industry is one of the largest contributors in Indonesia because of the high demand for oil and gas fuel. Until 2025, fossil fuels such as gas will still be used. The need for fuel in the transportation sector in Indonesia is a fairly high dependency. This dependence is based on economic growth in Indonesia [1] [2][3]. An increase in increased fuel distribution activity marks this growth. Indonesia's oil and gas industry produces emissions and waste, both directly and indirectly, and can potentially damage the surrounding environment. This pollution can be in the form of air, water, and soil pollution.[4][5] [6]

Seeing this phenomenon, evaluating the environmental impact of the oil and gas industry is necessary. Based on the regulation of the Minister of Environment No. 1 of 2021 concerning the Company Performance Rating Assessment Program and Environmental Management using an impact calculation approach through the Life Cycle Assessment method or *Life Cycle Assessment*. ISO 14040 also specifically describes *Life Cycle Assessment* in conducting environmental impact analysis. Life *Cycle Assessment* is one method of assessing the impact on the environment by using the *Software* Simapro Developer 9 . LCA is used to identify and calculate impacts in the process of production, distribution, and other supporting facilities based on the use of energy sources, the use of natural resources, emissions discharged into the environment, Hazardous solid and Non-Hazardous Solid competitions produced. Then, from the identification results, an evaluation and improvement will be carried out based on existing conditions [7][1]. The function of LCA is to analyze the potential environmental impacts arising from an activity by knowing the *Input* used in each process and the *Output* results of the review of existing processes.[8]

As explained above regarding the background of the problem, the formulation of the problem in this study is: How to identify potential environmental impacts of the oil and gas industry in Sumatra using the *life cycle assessment method,* and; What is the most significant impact so that it can provide recommendations for improvements in reducing the impact on the environment in the oil and gas industry?

METHOD

This research uses the *Life Cycle Assessment* (LCA) method with reference to SNI ISO 14040: 2016 concerning Life Cycle Assessment - Principles and Framework and SNI ISO 14044: 2017 concerning Life Cycle Assessment-Requirements and Alloys[12]. Use *Software* SIMAPRO Developer 9.4.0.2. The stages in this method are purpose and scope, inventory analysis, impact assessment, and interpretation [1] [9] [10].

The research subjects that have been reflected in the focus of the study are determined deliberately. Research subjects become sources of inventory data that will be processed using the LCA method and produce various information needed during the research process. Data sources required in data inventory:[11] The energy use of each process; Use clean water from each process; GHG emissions, wastewater, hazardous waste, and non-hazardous waste are generated in each process.

Data analysis in this study refers to SNI ISO 14040: 2016 concerning Life Cycle Assessment - Principles and Framework and SNI ISO 14044: 2017 concerning Life Cycle Assessment-Requirements and Alloys using *SIMAPRO Developer 9.4.0.2* software.

The LCA study begins by determining a model that describes the mass flow and energy used throughout the system so that data that can be used to build a model is needed. The stages carried out in this step are: Create a flow chart based on the system constraints that have been created; Collect data from all production activities along the system; Calculate the environmental load adjusted to the function unit of each activity

Furthermore, the impact assessment calculation method was carried out using SimaPro software Developer version 9.4.0.2. Impact assessment for the *upstream and* downstream processes *will use databases available* on *SimaPro software, such as* Ecoinvent, *Agri-footprint, USLCI, and* so on. In addition, in the impact assessment calculation, the characterization factor of each assessment method will use the characterization factor and methods available in the *SimaPro* software.

Impact categories are selected based on the impacts determined based on the Minister of Environment and Forestry Number 1 Regulation of 2021 concerning the Company Performance Rating Assessment Program in Environmental Management, namely 5 main impact categories and 7 secondary impact categories. In addition, it is also based on *the Draft Product Category Rules* (PCR) of Crude oil and natural gas) UN CPC 12 for product category 1201 12010. The twelve (12) impact categories mentioned above were analyzed using five impact assessment methods: IPCC *2021 GWP100, CML-IA Baseline, ReCiPe 2016 Midpoint (H), AWARE, and Cumulative Energy Demand*.

RESULTS AND DISCUSION

The life cycle venti results of this study are operational activities including the process of land transformation, production of supporting materials, *and workover* and well services *as the Upstream Process* (Cradle*), then the process of collecting and processing the oil itself through collection stations and supporting utilities such as power plants and water treatment as the Core process (Gate*). Then, the petroleum delivery process is carried out and will be further processed in the *company's refinery unit*, including the Downstream Process (*Grave*).

In detail, the implementation is as *Upstream Process,* Core *Process, and* Downstream Process. *The upstream Process* is carried out with the following details:

The manufacturing process of supporting chemicals included in it are solvents, emulsifying agents, and reverse demulsifying agents. Although this supporting chemical is a liquid, in simulation, the calculation is carried out using mass units based on the density of the substance.

The manufacturing process of liquid fuel, namely diesel, which is used as an energy source in petroleum production, is measured in liters, but in simulated calculations, it is adjusted in units of mass calculated based on density.

The land use transition from forest to operational area, including well sites and station facilities, is measured in square meters.

Well management activities, fluid extraction services (including petroleum mixtures and produced water), and natural gas extraction are measured in the MMSCF quantitative reference for gas and barrels for oil. Solvents support fluid extraction from certain wells as supporting chemicals, which aim to facilitate the process of petroleum extraction in the subsoil.

The core process is implemented with the following details:

The fluid flow process through the manifold occurs after fluid extraction from active wells. This fluid flows through the manifold for measurement before the next step, separation, or processing at the *gathering station*.

The process of transporting fluid through truck vehicles is used when the fluid has low pressure and does not allow it to flow through pipelines or *manifolds*. This fluid is directly sent to the *main gathering station* to follow the processing process

The initial separation process at the *gathering station* was carried out on a small scale. At this location, initial separation is carried out to reduce the moisture content in petroleum using *reverse demulsifier* chemicals. After the initial separation, the oil is sent to the main gathering station for processing.

The processing process at *the main gathering station*, as the main collection center on a large scale, focuses on separating the water content from petroleum to meet the quality standards set for sales. Here, the fluid undergoes continuous circulation and is handled with the help of chemical *demulsifiers* and *reverse demulsifiers*. Oil is processed until it reaches a less than 0.5% water level before distribution.

Virtual ports or artificial terminals are used to collect oil that has undergone treatment and meets the requirements with a water content of less than 0.5%. At this artificial terminal, the loading and unloading process fills the tanker that will carry oil to the *Refinery Unit* through shipping through maritime routes.

The downstream Process is carried out with the following details:

The process of distributing petroleum from *the virtual port* to the *Refinery Unit* is carried out through tankers that use diesel fuel as their power source. The travel distance reaches 115 km in every single shipment. The delivery process is carried out 29 times in 1 year.

At the *refinery*: petroleum processing into diesel fuel (ADO) is carried out in the *Refinery Unit*. Of the total production flow carried out by the *Refinery Unit*, approximately 0.1738 barrels of diesel fuel (ADO) are produced from each barrel of petroleum.

Consumption: The utilization of diesel fuel (ADO) in the transportation sector, especially in vehicles with a higher weight, impacts greenhouse gas emissions. These gases include CO2, CH4, and N2O.

Total inventory summary data is presented in full, starting from raw material *inputs*, energy use, water use, use of supporting materials and other materials, and *outputs* including products, air emissions produced, liquid waste generated, Hazardous waste, and non-hazardous waste. Inventory calculation will be used to calculate impact and analyze important issues. Below are Tables 4 and 5 summaries of inventory data.

Table 1. Summary of *Cradle-to-Grave Process Inventory Data*

Kategori	Nama	Jumlah	Satuan	Jumlah/Unit Fungsi	Satuan	Persentase (%)	Proses Kontribusi Terbesar
Input							
Material	Fluida	10.844.593,62	Barrel	5,54E+00	Barrel/GJ	100,00%	Work Over and Well Services
		63.621.276,55	GJ	3,25E+01	GJ/GJ		
	Gas	59.636,96	mmscf	3,05E-02	mmscf/GJ	100,00%	Work Over and Well Services
		65.311.552,72	GJ	3,34E+01	GJ/GJ		
Energi Bahan Bakar Cair	Solar	3.121.424,00	liter	1,60E+00	liter/GJ	100,00%	Pembangkit Listrik
Energi Bahan Bakar Gas	Gas	59.636,96	mmscf	3,05E-02	mmscf/GJ	100,00%	Heater Main Gathering Station
		65.311.552,72	GJ	3,34E+01	GJ/GJ		
Energi Listrik	Listrik	9.326.573,00	kWh	4,77E+00	kWh/GJ	100,00%	Pembangkit Listrik
Bahan Kimia/ Pendukung	Solvent	17.997,33	liter	9,20E-03	liter/GJ	38,73%	Work Over and Well Services
	Demulsifier	26.236,84	liter	1,34E-02	liter/GJ	56,46%	Main Gathering Station
	Reverse Demulsifier	2.239,24	liter	1,14E-03	liter/GJ	4,82%	Gathering Station
Air	Air Terproduksi	874.277,90	m3	4,47E-01	m3/GJ	100,00%	Main Gathering Station
Lahan	Lahan digunakan	2.834.012,00	m2	1,45E+00	m2/GJ	100,00%	Work Over and Well Services
Output							
Produk	Minyak	324.059,62	Barrel	1,66E-01	Barrel/GJ	100,00%	Main Gathering Station
		1.956.007,68	GJ	1,00E+00	GJ/GJ		
Emisi Udara GRK	CO_2	8.298,12	Ton	4,24E-03	Ton/GJ	99,98%	Pembangkit Listrik
	CH_4	0,64	Ton	3,26E-07	Ton/GJ	0,01%	Pembangkit Listrik
	N_2O	1,00	Ton	5,10E-07	Ton/GJ	0,01%	Pembangkit Listrik
Emisi Udara Konvensional	SO_x	16,28	Ton	8,32E-06	Ton/GJ	5,79%	Pembangkit Listrik
	NO_x	247,60	Ton	1,27E-04	Ton/GJ	88,02%	Pembangkit Listrik
	PM	17,41	Ton	8,90E-06	Ton/GJ	6,19%	Pembangkit Listrik
Emisi Fugitif	nmVOC	22,33	Ton	1,14E-05	Ton/GJ	12,71%	Manifold
	CH_4	81,81	Ton	4,18E-05	Ton/GJ	46,57%	Manifold
	TOC	71,54	Ton	3,66E-05	Ton/GJ	40,72%	Manifold
Limbah Cair	Air Terinjeksi	1.672.764,91	m3	8,55E-01	m3/GJ	99,98%	Water Injection Well
	Limbah Domestik	382,30	m3	1,95E-04	m3/GJ	0,02%	Gathering Station
Beban Pencemaran Air	Minyak dan Lemak	0,0011	Ton	5,48E-10	Ton/GJ	4,23%	Gathering Station
	TOC	0,011	Ton	5,51E-09	Ton/GJ	42,53%	Gathering Station
	BOD	0,0023	Ton	1,15E-09	Ton/GJ	8,91%	Gathering Station
	COD	0,0082	Ton	4,18E-09	Ton/GJ	32,25%	Gathering Station
	TSS	0,0025	Ton	1,27E-09	Ton/GJ	9,84%	Gathering Station
	Ammonia	0,0006	Ton	2,90E-10	Ton/GJ	2,24%	Gathering Station
Limbah B3	Residu Produksi	2,03	Ton	1,04E-06	Ton/GJ	28,37%	Work Over and Well Services

Table 2. Grave Inventory Data Summary *(Downstream)*

Proses Pengiriman dan Pengolahan Minyak Bumi di *Refinery Unit*					
Kategori	**Nama**	**Jumlah**	**Satuan**	**Catatan**	**Referensi**
Input					
Bahan Baku	Minyak Bumi	324.059,62	barrel		
Bahan Bakar Cair	Solar	318.135,72	liter	Bahan bakar yang dibutuhkan kapal tanker untuk distribusi minyak ke *Refinery Unit*	IPCC Guidelines 2006
Output					
Produk	Bahan Bakar Diesel (ADO)	56.310,08	barrel	Output produk bahan bakar solar (ADO) dari berbagai turunan produk lainnya, dengan 1 barrel minyak bumi menghasilkan sekitar 0,1738 barrel solar (ADO). Sehingga berdasarkan total produk minyak bumi PT Pertamina Hulu Energi Kampar, dapat menghasilkan 56.310,08 barrel atau sekitar 8.953.301,95 liter solar (ADO) (1 barrel = 159 liter)	Laporan Kajian LCA PT Pertamina RU II Sungai Pakning 2021
		8.953.301,95	liter		
Emisi Udara GRK	CO_2	847,51	ton	Emisi udara yang dihasilkan kapal tanker dari konsumsi bahan bakar	IPCC Guidelines 2006
	CH_4	0,08	ton		
	N_2O	0,02	ton		
Potensi Dampak	Potensi pemanasan global	7,11E-02	Kg CO2 ek / liter	Penyesuaian karakterisasi atau perhitungan dampak 1 ton produk bahan bakar solar (ADO)	Laporan Kajian LCA PT Pertamina RU II Sungai Pakning 2021
	Potensi penipisan lapisan ozon	6,19E-09	Kg CFC11 ek / liter		
	Potensi hujan asam	7,32E-03	Kg SO2 ek / liter		
	Potensi eutrofikasi	1,12E-01	Kg PO4 ek / liter		
	Photochemical oxidation	3,01E-06	Kg C2H4 ek / liter		
	Abiotic depletion	1,93E-09	Kg Sb ek / liter		
	Abiotic depletion (fossil fuels)	2,35E+00	MJ / liter		
	Terrestrial ecotoxicity	1,32E-03	Kg 1,4-DCB ek / liter		
	Freshwater ecotoxicity	2,47E-05	Kg 1,4-DCB ek / liter		
	Marine ecotoxicity	6,63E-05	Kg 1,4-DCB ek / liter		
	Human toxicity (karsinogenik)	9,73E-05	Kg 1,4-DCB ek / liter		
	Human toxicity (non karsinogenik)	2,46E-02	Kg 1,4-DCB ek / liter		
	Water footprint	5,01E-05	m3 / liter		
	Land use change	3,81E-04	m2a crop ek / liter		
	Cumulative energy demand (Non renewable)	2,49E+00	MJ / liter		
	Cumulative energy demand (Renewable)	1,66E-04	MJ / liter		

Table 3. Solar Use Process

Proses Penggunaan Solar (ADO) oleh Konsumen (*End-of-Life phase*)					
Kategori	**Nama**	**Jumlah**	**Satuan**	**Catatan**	**Referensi**
Input					
Bahan Bakar Cair	Solar	8.953.301,95	liter		
Output					
Emisi Udara GRK	CO_2	23.851,60	ton	Emisi udara yang dihasilkan dari konsumsi bahan bakar	IPCC Guidelines 2006
	CH_4	1,61	ton		
	N_2O	0,19	ton		

The results of the life cycle impact assessment carried out in the LCA study will be divided into two, according to the unit of function, where the unit of petroleum function or per GJ of petroleum will be included in the results of the calculation of the impact that is the scope of the company or *cradle-to-gate*. The 2nd function unit, an impact assessment based on function units per liter of diesel product (ADO) used by consumers or downstream processes, will be included in the *cradle-to-grave calculation*.

In this study, a *Life Cycle Assessment* was carried out, divided based on function units, namely per GJ of petroleum for the company's scope (cradle-to-gate) *and per liter of diesel product (ADO) for the scope of* cradle-to-grave. The impact assessment results on the company scope can be found in Table 4 for the overall overview, Table 5 for the impact of upstream processes, and Table 6 for the impact of core processes. This assessment details the impact of 1 GJ of petroleum, which is part of the total petroleum production 2021 of 324,059.62 barrels or equivalent to 1,956,007.68 GJ.

Table 4. Results of Life Cycle Impact Assessment of 1 GJ of Petroleum Products

No	Kategori Dampak	Indikator Kategori	Proses Hulu	Proses Inti	Total *Cradle to Gate*
Dampak Primer					
1	Potensi pemanasan global	Kg CO_2 ek / GJ	1,12E+00	5,30E+00	6,42E+00
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	9,99E-07	2,14E-10	1,00E-06
3	Potensi hujan asam	Kg SO_2 ek / GJ	8,07E-03	7,33E-02	8,14E-02
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	1,01E-03	1,66E-02	1,76E-02
Dampak Sekunder					
5	*Photochemical oxidation*	Kg C2H4 ek / GJ	4,08E-04	5,84E-04	9,92E-04
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:				
	a. *Abiotic depletion*	Kg Sb ek / GJ	1,14E-06	1,98E-09	1,15E-06
	b. *Abiotic depletion (fossil fuels)*	MJ / GJ	6,17E+04	1,73E-02	6,17E+04
7	Potensi terjadi penurunan biotik, terdiri dari:				
	a. *Terrestrial ecotoxicity*	Kg 1,4-DCB ek / GJ	2,67E+00	1,61E-03	2,68E+00
	b. *Freshwater ecotoxicity*	Kg 1,4-DCB ek / GJ	9,17E-03	1,09E-03	1,03E-02
	c. *Marine ecotoxicity*	Kg 1,4-DCB ek / GJ	1,57E-02	1,33E-03	1,70E-02
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / GJ	2,92E-02	1,07E-04	2,94E-02
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / GJ	2,85E-01	3,93E-03	2,88E-01
10	*Water footprint*	m3 / GJ	5,45E-02	-1,87E-01	-1,86E-01
11	*Land use change*	m2a crop ek / GJ	5,45E-01	2,06E-05	5,45E-01
Dampak Pemakaian Energi					
12	*Cumulative energy demand*, terdiri dari:				
	a. *Non renewable*	MJ / GJ	6,60E+04	1,86E+02	6,60E+04
	b. *Renewable*	MJ / GJ	2,07E-01	1,26E-04	2,08E-01

Table 5. Results of Upstream Process Life Cycle Impact Assessment 1 GJ Petroleum

No	Kategori Dampak	Indikator Kategori	Proses Hulu (Total)	Transformasi Lahan	Produksi Bahan Bakar Pendukung	Produksi Bahan Kimia Pendukung	Proses Ekstraksi di Work Over dan Well Services
Dampak Primer							
1	Potensi pemanasan global	Kg CO_2 ek / GJ	1,12E+00	0,00E+00	7,54E-01	4,81E-02	5,34E-01
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	9,99E-07	0,00E+00	9,98E-07	9,77E-10	1,31E-10
3	Potensi hujan asam	Kg SO_2 ek / GJ	8,07E-03	0,00E+00	7,90E-03	1,67E-04	1,96E-06
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	1,01E-03	0,00E+00	9,68E-04	3,88E-05	7,09E-07
Dampak Sekunder							
5	*Photochemical oxidation*	Kg C2H4 ek / GJ	4,09E-04	0,00E+00	3,17E-04	2,38E-05	6,72E-05
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:						
	a. Abiotic depletion	Kg Sb ek / GJ	1,14E-06	0,00E+00	9,48E-07	1,96E-07	9,76E-10
	b. Abiotic depletion (fossil fuels)	MJ / GJ	6,17E+04	0,00E+00	7,60E+01	1,50E+00	6,16E+04
7	Potensi terjadi penurunan biotik, terdiri dari:						
	a. Terrestrial ecotoxicity	Kg 1,4-DCB ek / GJ	2,67E+00	0,00E+00	2,59E+00	7,87E-02	6,90E-04
	b. Freshwater ecotoxicity	Kg 1,4-DCB ek / GJ	9,17E-03	0,00E+00	8,36E-03	8,06E-04	1,16E-05
	c. Marine ecotoxicity	Kg 1,4-DCB ek / GJ	1,57E-02	0,00E+00	1,46E-02	1,08E-03	1,99E-05
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / GJ	2,92E-02	0,00E+00	2,78E-02	1,46E-03	1,09E-05
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / GJ	2,85E-01	0,00E+00	2,66E-01	1,96E-02	2,68E-04
10	*Water footprint*	m3 / GJ	5,45E-02	0,00E+00	1,82E-02	3,63E-02	3,19E-05
11	*Land use change*	m2a crop ek / GJ	5,45E+01	5,44E+01	7,00E-02	3,67E-04	1,09E-05
Dampak Pemakaian Energi							
12	*Cumulative energy demand*, terdiri dari:						
	a. Non renewable	MJ / GJ	6,69E+04	0,00E+00	8,09E+01	1,60E+00	6,69E+04
	b. Renewable	MJ / GJ	2,07E-01	0,00E+00	1,94E-01	1,30E-02	5,57E-05

Table 6. Results of Life Cycle Impact Assessment Core Process 1 GJ Petroleum 1

No	Kategori Dampak	Indikator Kategori	Core (Total)	Pengaliran Fluida di Manifold	Pemisahan di Gathering Station	Produksi di Main Gathering Station
Dampak Primer						
1	Potensi pemanasan global	Kg CO_2 ek / GJ	5,30E+00	5,30E-01	1,46E-01	2,34E-01
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	2,14E-10	0,00E+00	8,29E-11	1,25E-10
3	Potensi hujan asam	Kg SO_2 ek / GJ	7,31E-02	0,00E+00	1,13E-06	2,17E-06
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	1,66E-02	0,00E+00	6,53E-07	8,09E-06
Dampak Sekunder						
5	*Photochemical oxidation*	Kg C2H4 ek / GJ	5,84E-04	1,07E-04	2,04E-05	4,66E-05
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:					
	a. Abiotic depletion	Kg Sb ek / GJ	1,98E-09	0,00E+00	6,04E-10	1,14E-09
	b. Abiotic depletion (fossil fuels)	MJ / GJ	1,73E-02	0,00E+00	6,59E-03	1,02E-02
7	Potensi terjadi penurunan biotik, terdiri dari:					
	a. Terrestrial ecotoxicity	Kg 1,4-DCB ek / GJ	1,61E-03	0,00E+00	4,30E-04	8,88E-04
	b. Freshwater ecotoxicity	Kg 1,4-DCB ek / GJ	1,50E-03	0,00E+00	6,02E-06	8,41E-05
	c. Marine ecotoxicity	Kg 1,4-DCB ek / GJ	1,33E-03	0,00E+00	9,34E-06	1,27E-04
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / GJ	1,07E-04	0,00E+00	6,59E-06	3,61E-05
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / GJ	3,93E-03	0,00E+00	1,60E-04	2,66E-03
10	*Water footprint*	m3 / GJ	-1,17E+01	0,00E+00	-4,94E-03	-3,31E-03
11	*Land use change*	m2a crop ek / GJ	2,06E-05	0,00E+00	7,06E-06	1,33E-05
Dampak Pemakaian Energi						
12	*Cumulative energy demand*, terdiri dari:					
	a. Non renewable	MJ / GJ	1,86E-02	0,00E+00	7,04E-03	1,09E-02
	b. Renewable	MJ / GJ	1,25E-04	0,00E+00	3,42E-05	7,49E-05

Table 7. Results of Life Cycle Impact Assessment Core Process 1 GJ Petroleum 2

No	Kategori Dampak	Indikator Kategori	Core (Total)	Penerimaan Minyak di Virtual Port	Pembangkit Listrik	Water Injection Well
Dampak Primer						
1	Potensi pemanasan global	Kg CO_2 ek / GJ	5,30E+00	0,00E+00	4,39E+00	0,00E+00
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	2,14E-10	0,00E+00	6,30E-12	0,00E+00
3	Potensi hujan asam	Kg SO_2 ek / GJ	7,31E-02	0,00E+00	7,33E-02	0,00E+00
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	1,66E-02	0,00E+00	1,66E-02	0,00E+00
Dampak Sekunder						
5	*Photochemical oxidation*	Kg C2H4 ek / GJ	5,84E-04	0,00E+00	4,02E-04	0,00E+00
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:					
	a. Abiotic depletion	Kg Sb ek / GJ	1,98E-09	0,00E+00	2,36E-10	0,00E+00
	b. Abiotic depletion (fossil fuels)	MJ / GJ	1,73E-02	0,00E+00	5,63E-04	0,00E+00
7	Potensi terjadi penurunan biotik, terdiri dari:					
	a. Terrestrial ecotoxicity	Kg 1,4-DCB ek / GJ	1,61E-03	0,00E+00	2,88E-04	0,00E+00
	b. Freshwater ecotoxicity	Kg 1,4-DCB ek / GJ	1,50E-03	0,00E+00	9,93E-04	0,00E+00
	c. Marine ecotoxicity	Kg 1,4-DCB ek / GJ	1,33E-03	0,00E+00	1,18E-03	0,00E+00
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / GJ	1,07E-04	0,00E+00	6,41E-05	0,00E+00
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / GJ	3,93E-03	0,00E+00	1,11E-03	0,00E+00
10	*Water footprint*	m3 / GJ	-1,17E+01	0,00E+00	4,13E-05	-1,17E+01
11	*Land use change*	m2a crop ek / GJ	2,06E-05	0,00E+00	3,01E-07	0,00E+00
Dampak Pemakaian Energi						
12	*Cumulative energy demand*, terdiri dari:					
	a. Non renewable	MJ / GJ	1,86E-02	0,00E+00	6,23E-04	0,00E+00
	b. Renewable	MJ / GJ	1,25E-04	0,00E+00	1,80E-05	0,00E+00

Within the scope of the *cradle-to-grave process,* an impact assessment is carried out based on downstream products produced by the *Refinery Unit,* namely 1 liter of diesel (ADO) out of a total of 8,953,301.95 liters. The results of the impact assessment can be seen in Table 8.

Table 8. Cradle-to-Grave *Life Cycle Impact Assessment* per 1 liter of diesel (ADO)

No	Kategori Dampak	Indikator Kategori	Total Cradle to Gate	Distribusi Minyak ke *Refinery Unit*	Pengolahan di Refinery Unit dan Distribusi ke Konsumen	Penggunaan Produk	Total per liter ADO
Dampak Primer							
1	Potensi pemanasan global	Kg CO2 ek / liter	2,44E-01	1,66E-02	7,11E-02	4,68E-01	8,00E-01
2	Potensi penipisan lapisan ozon	Kg CFC11 ek / liter	3,79E-08	0,00E+00	6,19E-09	0,00E+00	4,41E-08
3	Potensi hujan asam	Kg SO2 ek / liter	3,09E-03	0,00E+00	7,32E-03	0,00E+00	1,04E-02
4	Potensi eutrofikasi	Kg PO4 ek / liter	6,69E-04	1,20E-07	1,12E-01	2,42E-06	1,13E-01
Dampak Sekunder							
5	*Photochemical oxidation*	Kg C2H4 ek / liter	3,77E-05	9,34E-09	3,01E-06	7,89E-08	4,09E-05
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:						
	a. Abiotic depletion	Kg Sb ek / liter	4,35E-08	0,00E+00	1,95E-09	0,00E+00	4,55E-08
	b. Abiotic depletion (fossil fuels)	MJ / liter	2,34E+03	0,00E+00	2,35E+00	0,00E+00	2,35E+03
7	Potensi terjadi penurunan biotik, terdiri dari:						
	a. Terrestrial ecotoxicity	Kg 1,4-DCB ek / liter	1,02E-01	0,00E+00	1,32E-03	0,00E+00	1,03E-01
	b. Freshwater ecotoxicity	Kg 1,4-DCB ek / liter	3,90E-04	0,00E+00	2,47E-05	0,00E+00	4,14E-04
	c. Marine ecotoxicity	Kg 1,4-DCB ek / liter	6,47E-04	0,00E+00	6,65E-05	0,00E+00	7,13E-04
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / liter	1,11E-03	0,00E+00	9,75E-05	0,00E+00	1,21E-03
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / liter	1,10E-02	0,00E+00	2,46E-02	0,00E+00	3,55E-02
10	*Water footprint*	m3 / liter	-7,06E-01	0,00E+00	5,01E-05	0,00E+00	-7,06E-01
11	*Land use change*	m2a crop ek / liter	2,07E+00	0,00E+00	3,81E-04	0,00E+00	2,07E+00
Dampak Pemakaian Energi							
12	*Cumulative energy demand*, terdiri dari:						
	a. Non renewable	MJ / liter	2,54E+03	0,00E+00	2,49E+00	0,00E+00	2,54E+03
	b. Renewable	MJ / liter	7,88E-05	0,00E+00	1,64E-04	0,00E+00	8,05E-03

After completing the impact assessment for the entire impact category, the next step is identifying the critical issues. This identification will be based on analyzing inventory data, determining the processes that contribute the most, and establishing the life cycle stages that influence the environmental impact categories in the product system being analyzed.

Identifying important issues in this study is limited to the processes covered in the oil and gas industry research scope. The process involves the extraction of fluid from nature and the core process, which includes the fluid drainage process unit in the *manifold, separation in the gathering station, production in the* main gathering station, *oil reception in the* virtual port, *injection process in the water injection well*, and power generation. This approach is taken to maintain the priority focus of impact on the main production process units within the company's operational areas.

Important issues identified from inventory data, with emphasis on processes that contribute the most based on *the Pareto Rules,* are presented in Table 9.

An analysis of important issues based on process units that most contribute to environmental impact has been carried out for all categories of environmental impacts related to operations in oil and gas industries. It covers fluid extraction from natural and core processes, such as fluid jetting process units in *manifolds*, separation in gathering stations, production in main gathering stations, *oil reception in* virtual ports, and injection processes in *water injection wells* and power plants, by the Pareto Principle.

Table 9. Important Issues Based on Inventory Data

Kategori	Nama	Persentase (%)	Proses Kontribusi Terbesar
Input			
Material	Fluida	100,00%	Work Over and Well Services
	Gas	100,00%	Work Over and Well Services
Energi Bahan Bakar Cair	Solar	100,00%	Pembangkit Listrik
Energi Bahan Bakar Gas	Gas	100,00%	Heater Main Gathering Station
Energi Listrik	Listrik	100,00%	Pembangkit Listrik
Bahan Kimia/ Pendukung	Solvent	38,73%	Work Over and Well Services
	Demulsifier	56,46%	Main Gathering Station
	Reverse Demulsifier	4,82%	Gathering Station
Air	Air Terproduksi	100,00%	Main Gathering Station
Lahan	Lahan digunakan	100,00%	Work Over and Well Services
Output			
Produk	Minyak	100,00%	Main Gathering Station
Emisi Udara GRK	CO2	99,98%	Pembangkit Listrik
	CH4	0,01%	Pembangkit Listrik
	N2O	0,01%	Pembangkit Listrik
Emisi Udara Konvensional	Sox	5,79%	Pembangkit Listrik
	Nox	88,02%	Pembangkit Listrik
	PM	6,19%	Pembangkit Listrik
Emisi Fugitif	nmVOC	12,71%	Manifold
	CH4	46,57%	Manifold
	TOC	40,72%	Manifold
Limbah Cair	Air Terinjeksi	99,98%	Water Injection Well
	Limbah Domestik	0,02%	Gathering Station
Beban Pencemaran Air	Minyak dan Lemak	4,23%	Gathering Station
	TOC	42,53%	Gathering Station
	BOD	8,91%	Gathering Station
	COD	32,25%	Gathering Station
	TSS	9,84%	Gathering Station
	Ammonia	2,24%	Gathering Station
Limbah B3	Residu Produksi	28,37%	Work Over and Well Services
	Majun Bekas	7,99%	Main Gathering Station
	Sludge Tangki	0,42%	Main Gathering Station
	Oli Bekas	51,34%	Pembangkit Listrik
	Lampu TL Bekas	0,17%	Main Gathering Station
	Filter Bekas	11,71%	Pembangkit Listrik
Limbah Padat Non B3	Pipa Bekas	6,20%	Work Over and Well Services
	Kardus Bekas	6,60%	Main Gathering Station
	Besi Bekas	30,65%	Pembangkit Listrik
	Kayu Bekas	34,17%	Main Gathering Station
	Sampah Kertas	5,33%	Main Gathering Station
	Sampah Plastik	9,10%	Main Gathering Station
	Sampah Organik	7,94%	Main Gathering Station

In Table 9, the contribution percentages of each process unit are shown for the total potential impact of each impact category. Additional information in the table description includes a special explanation, where the green information with a minus number (-) indicates that the process positively impacts the environment. For example, when a process such as Process A has an impact of -40%, it illustrates that the process positively or contributes positively to the environment by returning the substance to nature.

Table 10. Analysis of Important Issues by Process Unit

Unit Proses	Proses	GWP	ODP	AP	EP	POCP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]						[illegible]							[illegible]	
	[illegible]														[illegible]
[illegible]	[illegible]					[illegible]									
[illegible]	[illegible]														
	[illegible]		[illegible]					[illegible]	[illegible]						
[illegible]	[illegible]														
	[illegible]		[illegible]					[illegible]	[illegible]						
	[illegible]														
	[illegible]									[illegible]	[illegible]				
	[illegible]										[illegible]				
[illegible]															
[illegible]	[illegible]											[illegible]			
[illegible]		[illegible]		[illegible]	[illegible]	[illegible]									
	[illegible]	82,78%		[illegible]	[illegible]	[illegible]									
	[illegible]								[illegible]	[illegible]	[illegible]				
	[illegible]							[illegible]		[illegible]	[illegible]				
[illegible]	[illegible]												[illegible]		

Based on Table 10, all impact categories are quantified. Percentages, then the interpretation of all impact categories is carried out as follows:

Global Warming Potential

According to the data in Table 8, the processing unit that predominantly provides the potential impact of global warming is the power generation unit. The process of causing such impacts is mainly related to the emissions generated from generators in the operational functions of generating units. The power plant process unit is the main facility that produces the electricity needed in production operations using diesel-based fuel. The impact contribution of this process unit reaches 4.39E+00 kg CO2 ek per GJ, representing a percentage of 82.78% of the total global warming impact generated by the entire production system.

Ozone Layer Depletion Potential

According to Table 8, the process unit that most significantly exerts the potential impact associated with ozone layer depletion is the *sludge* treatment process by a third party. *This sludge* is produced as a by-product of the oil separation and production process at the gathering station *and* main gathering station. The gathering station is the initial unit in oil processing that separates oil from water content. In contrast, the main gathering station is the main production process that sets the quality standards of oil products.

The sludge processing process of residual production by third parties resulting from the separation process and oil production at the *gathering station and main gathering station* contributed an impact of 8.26E-11 kg CFC11 ek per GJ and 1.16E-10 kg CFC11 ek per GJ, respectively with percentages of 38.50% and 54.10%.

Acid Rain Potential

From the data listed in Table 8, the processing unit that dominates the most in causing the potential impact of acid rain is the **power generation unit**. The processes responsible for such impacts are mainly related to emissions generated from generators in the operational functions of generating units. The power plant process unit is the main facility to produce the electricity needed in production operations using diesel-based fuel. The impact contribution of this process unit reaches 7.33E-02 kg SO2 ek per GJ, which dominates with a percentage of 99.99% of the total impact of acid rain produced by the entire production system.

Eutrophication Potential

Based on the data in Table 8, the processing unit that most significantly exerts the potential impact associated with eutrophication is the power generation unit. The processes responsible for such impacts are primarily related to emissions generated from generators in the operational functions of generating units. The processing unit of the power plant serves as the main facility for generating the electricity needed in production operations using diesel-based fuel. The impact contribution of this process unit reached 1.66E-02 kg PO4 ek per GJ, dominating with a percentage of 99.99% of the total eutrophication impact generated by the entire production system.

Photochemical Formation Potential

According to the information contained in Table 8, the process units that most significantly exert potential impacts related to photochemical formation are power generation units and fluid drainage processes in ***manifolds***. The processes that cause this impact are mainly related to the emissions generated from generators in the process units of power plants and the fugitive emissions derived from *manifolds*. The power plant process unit is the main facility for generating electricity in production operations using diesel-based fuel. Meanwhile, the manifold process unit *is part of the fluid drainage process in* manifold pipes *from the extraction process to the initial separation at the* gathering station.

The impact contribution of these two process units is 4.02E-04 kg C_2H_4 ek per GJ for power generation units and 1.07E-04 kg C_2H_4 ek per GJ for fluid jetting units in *manifolds*. The contribution percentage reached 68.72% and 18.27%, respectively, to the total impact of photochemical formation produced by the entire production system.

Potential Decline in Abiotic Fossils

According to the data in Table 8, the process unit that most significantly exerts the potential impact associated with fossil abiotic decline is the "*Work Over and Well Services" process unit*, with the largest contribution coming from the process of extracting fluids (petroleum and natural gas) from the ground. This process unit is part of extracting fluid from underground, which serves as an initial or upstream stage in the oil and gas industry operations. The impact contribution of this process unit reached 6.16E+04 MJ per GJ, which dominates with a percentage of 99.99% to the total impact of fossil abiotic decline produced by the entire production system.

Non-Fossil Abiotic Decline Potential

From the information listed in Table 8, the most dominant processes in providing potential non-fossil abiotic impacts are *sludge processing* of production residues by third parties, resulting from oil separation and production process units at the *gathering station and* main gathering station, as well as processing used oil from power plant process units. A gathering station is an initial process unit in oil processing to separate oil from water content. In contrast, a main *gathering station* is the main production or processing process that sets oil product quality standards. The power plant process unit is the main facility for generating electricity in production operations using diesel-based fuel [13]. The sludge processing process of residual production by third parties from the separation process and oil production at the gathering station and *main gathering station*, as well as the processing of used oil from the power plant process unit, each contributed an impact of 5.95E-10 kg Sb ek per GJ, 8.34E-10 kg Sb ek per GJ, and 1.93E-10 kg Sb ek per GJ. The contribution percentages are 30.10%, 42.22%, and 9.78%, respectively, to the total non-fossil abiotic impact generated by the entire production system.

Potential Reduction in Biotic/Ecotoxicity

From the information contained in Table 8, the most dominant processes in providing potential impacts related to biotic decline are *sludge processing* of production residues by third parties, resulting from oil separation and production process units at the *gathering station and* main gathering station*, as well as scrap iron processing from power plant process units. A* gathering station is an initial process unit in oil processing to separate oil from water content. In contrast, *a main gathering station* is the main production or processing process that sets oil product quality standards. The power plant process unit is the main facility for generating electricity in production operations using diesel-based fuel.

The sludge processing of residual production by third parties from the separation process and oil production at *the gathering station and main gathering station*, as well as scrap iron processing from the power plant process unit, each contributed an impact of 4.19E-04 kg 1.4-DCB ek per GJ, 5.87E-04 kg 1.4-DCB ek per GJ, *and* 2.17E-03 kg 1.4-DCB ek per GJ, respectively. The contribution percentage is 11.67%, 16.36%, and 60.37%, respectively, to the total impact of biotic decline produced by the entire production system.

Potential Toxicity to Human Carcinogenic

According to the information contained in Table 8, the most dominant processes in providing potential toxicity impacts on carcinogenic humans are third-party processing of used oil, resulting from the oil separation and production process unit at the *main gathering station*, as well as scrap iron processing and scrap oil from the power plant process unit. The main *gathering station* process is the main production or processing process, where the oil products produced in this process unit must meet specified standards. The process-generating unit is the main facility for producing electricity in production operations using diesel-based fuel.

The process of processing oil residual production by third parties from the separation process unit and oil production at the *main gathering station*, scrap iron processing, and used oil from the power plant process unit each contributed an impact of 2.22E05 kg 1.4-DCB ek per GJ, 3.65E-05 kg 1.4-DCB ek per GJ, and 2.72E-05 kg 1.4-DCB ek per GJ, respectively. The contribution percentages are 20.81%, 20.77%, and 25.43%, respectively, to the total impact of toxicity to carcinogenic humans produced by the entire production system.

Potential Toxicity to Non-Carcinogenic Humans

According to the information contained in Table 8, the most dominant processes in providing potential non-carcinogenic human toxicity impacts are the processing of used oil and used plastics by third parties, produced by the oil separation and production process unit at the *main gathering station*, and the processing of scrap iron and used oil from the power plant process unit. The *main gathering station* process is the main production or processing process, where the oil products produced in this process unit must meet specified standards. The process-generating unit is the main facility for producing electricity in production operations using diesel-based fuel.

The processing of oil and plastic used from production by third parties from the oil separation and production process unit at the *main gathering station*, scrap iron processing, and used oil from the power plant process unit each contributed an impact of 2.31E-04 kg 1.4-DCB ek per GJ, 1.83E-03 kg 1.4-DCB ek per GJ, 8.17E-04 kg 1.4-DCB ek per GJ, and 2.82E-04 kg 1.4-DCB ek per GJ. The contribution percentages were 5.87%, 46.53%, 20.77%, and 7.17% to the total non-carcinogenic human toxicity impact generated by the entire production system.

Water Scarcity Footprint

According to the data in Table 8, the most dominant process unit in providing the potential impact of water scarcity traces is the water *injection well* process unit, which is part of injecting produced water back into the soil. *Water injection wells* return water produced from the production process or oil separation into the soil. The water injection positively impacts the environment, as it returns the substance, that is, water, back to nature. This positive impact is seen in the water scarcity footprint value of -1.87E+01 m3 per GJ and contributes 100% to the total water scarcity footprint impact generated by the entire production system.

Land Use

According to the information in Table 8, the most dominant process unit in providing potential land use impacts is the use of production land. The oil and gas industry carries out the production process or industrial activities in one of the districts in Sumatra by transforming and expanding land that was originally a forest into wells and production stations, with a total area of around 2,508,675.00 m2. From the land transformation activities carried out, a land use contribution of 5.44E+01 m2a crop oak per GJ was recorded and contributed 100% to the total land use impact generated by the entire production system.

Cumulative Energy Demand Non-Renewable

According to the data contained in Table 8, the most dominant process unit in providing the potential impact *of cumulative energy demand non-renewable* is the Work Over and Well Services *process unit*, with the main contribution coming from the process of extracting fluids (petroleum and natural gas) from the ground. This process unit is the initial or upstream stage in the series of oil and gas industry activities, where petroleum and natural gas substances are taken from the ground. This processing unit contributed an impact of 6.16E+04 MJ per GJ, with a contribution percentage of 99.99%, which was caused by taking the natural substance.

Cumulative Energy Demand Renewable

According to the data contained in Table 8, the most dominant process unit in providing the potential impact *of renewable cumulative energy demand* is the Work Over and Well Services *process unit*, with the main contribution coming from the process of extracting fluids (petroleum and natural gas) from the ground. This process unit is the initial or upstream stage in the series of oil and gas industry activities, where petroleum and natural gas substances are taken from the ground. This processing unit contributes an impact of 5.02E-05 MJ per GJ, with a contribution percentage of 100% due to the process of taking the natural substance.

In the analysis of the last important issue (*hotspot*), this study also pays attention to the stages of the life cycle, namely upstream processes, core processes, and downstream processes, to identify the contribution of each life cycle stage to the petroleum production process in one of the oil and gas industries. The evaluation of important issues is carried out based on the production process covering the scope of one of the oil and gas industries, especially related to 1 GJ of petroleum products for the *cradle-to-gate scope and 1 liter of diesel fuel (ADO) to involve the cradle-to-grave scope*. The scope of the *cradle-to-grave* includes the *unit refinery* process and the consumer use of the product. This analysis aims to determine the life cycle stages that most contribute to oil and gas companies' petroleum production process.

In this study, evaluation was carried out through completeness checks, sensitivity checks, uncertainty checks, and consistency checks. Completeness checking is carried out by verifying that all data requirements are met to meet the objectives and scope of this study. Priority in data selection for this study is given to primary data. If primary data is unavailable, data collection will be carried out by the procedures described in the Data Collection Procedure.

Table 11. Analysis of Important Issues Basle-to-Gate 1 GJ Scope of Petroleum

No	Kategori Dampak	Indikator Kategori	Proses Hulu	Proses Inti
Dampak Primer				
1	Potensi pemanasan global	Kg CO_2 ek / GJ	1,12E+00	5,30E+00
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	9,99E-07	2,14E-10
3	Potensi hujan asam	Kg SO_2 ek / GJ	8,07E-03	7,33E-02
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	1,01E-03	1,66E-02
Dampak Sekunder				
5	*Photochemical oxidation*	Kg C2H4 ek / GJ	4,08E-04	5,84E-04
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:			
	a. *Abiotic depletion*	Kg Sb ek / GJ	1,14E-06	1,98E-09
	b. *Abiotic depletion (fossil fuels)*	MJ / GJ	6,17E+04	1,73E-02
7	Potensi terjadi penurunan biotik, terdiri dari:			
	a. *Terrestrial ecotoxicity*	Kg 1,4-DCB ek / GJ	2,67E+00	1,61E-03
	b. *Freshwater ecotoxicity*	Kg 1,4-DCB ek / GJ	9,17E-03	1,09E-03
	c. *Marine ecotoxicity*	Kg 1,4-DCB ek / GJ	1,57E-02	1,33E-03
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / GJ	2,92E-02	1,07E-04
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / GJ	2,85E-01	3,93E-03
10	*Water footprint*	m3 / GJ	5,45E-02	-1,87E+01
11	*Land use change*	m2a crop ek / GJ	5,45E+01	2,06E-05
Dampak Pemakaian Energi				
12	*Cumulative energy demand*, terdiri dari:			
	a. *Non renewable*	MJ / GJ	6,69E+04	1,86E-02
	b. *Renewable*	MJ / GJ	2,07E-01	1,26E-04

Table 12. Analysis of Important Issues Based on the Scope *of Cradle-to-Grave* 1 liter of Diesel Fuel (ADO)

No	Kategori Dampak	Indikator Kategori	Proses Hulu	Proses Inti	Proses Hilir
Dampak Primer					
1	Potensi pemanasan global	Kg CO_2 ek / liter	4,24E-02	2,01E-01	5,56E-01
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / liter	3,79E-08	8,12E-12	6,19E-09
3	Potensi hujan asam	Kg SO_2 ek / liter	3,06E-04	2,78E-03	7,32E-03
4	Potensi eutrofikasi	Kg PO_4 ek / liter	3,82E-05	6,30E-04	1,12E-01
Dampak Sekunder					
5	*Photochemical oxidation*	Kg C2H4 ek / liter	1,55E-05	2,22E-05	3,10E-06
6	Potensi terjadi penurunan abiotik (*fossil* dan *non fossil*), terdiri dari:				
	a. *Abiotic depletion*	Kg Sb ek / liter	4,35E-08	7,50E-11	1,93E-09
	b. *Abiotic depletion (fossil fuels)*	MJ / liter	2,34E+03	6,58E-04	2,35E+00
7	Potensi terjadi penurunan biotik, terdiri dari:				
	a. *Terrestrial ecotoxicity*	Kg 1,4-DCB ek / liter	1,01E-01	6,10E-05	1,32E-03
	b. *Freshwater ecotoxicity*	Kg 1,4-DCB ek / liter	3,48E-04	4,13E-03	2,47E-05
	c. *Marine ecotoxicity*	Kg 1,4-DCB ek / liter	5,97E-04	5,04E-05	6,63E-05
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB ek / liter	1,11E-03	4,05E-06	9,73E-05
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB ek / liter	1,08E-02	1,49E-04	2,46E-02
10	*Water footprint*	m3 / liter	2,07E-03	-7,08E-01	5,01E-05
11	*Land use change*	m2a crop ek / liter	2,07E+00	7,83E-07	3,81E-04
Dampak Pemakaian Energi					
12	*Cumulative energy demand*, terdiri dari:				
	a. *Non renewable*	MJ / liter	2,54E+03	7,04E-04	2,49E+00
	b. *Renewable*	MJ / liter	7,88E-03	4,78E-06	1,66E-04

In the data quality assessment in the Data Quality Assessment, it was revealed that all data collected reached a completeness level of 100%. Specifically, primary data account for 70% of direct measurement results, while 30% comes from calculations or estimates. The collected data involves all the important potential issues of the company's operations, ensuring that the results of the interpretation of lifecycle impact assessments are reliable.

Table 13. Data Completeness

Jenis Data	Ketersediaan Data		
	Ada-Lengkap	Tidak Ada-Diestimasi	Tidak Ada-Tidak Dicakup
Proses dalam lingkup PT Pertamina Hulu Energi Kampar			
Bahan Baku	100%	0%	0%
Listrik	100%	0%	0%
Bahan Bakar Cair	100%	0%	0%
Bahan Kimia/Pendukung	100%	0%	0%
Bahan Bakar Gas	100%	0%	0%
Air	100%	0%	0%
Lahan	100%	0%	0%
Produk	100%	0%	0%
Emisi Udara	100%	0%	0%
Limbah Cair	100%	0%	0%
Limbah B3	100%	0%	0%
Limbah Non-B3	100%	0%	0%
Total	**100%**	**0%**	**0%**

Sensitivity checks are carried out to assess the extent of data importance and their impact on the impact assessment results. This study's focus of sensitivity checks is directed at one of the main focus data, namely emissions produced by solar-based generators from power plant process units. In addition to being the main focus, one oil and gas industry company has involved an inventory of air emissions from each process using calculation methods that have been recognized as standards or received company approval.

Therefore, data derived from the calculation process has the potential to deviate. In analyzing sensitivity, modifications were made to air emission data by reducing by 20% and 10% and adding by 10% and 20%. This is done to evaluate the extent of sensitivity of the impact assessment results to changes in *hotspot* values, which is the main focus of attention in this analysis.

Table 14. Generator Air Emission Data from Power Plant Process Units

Uji Sensitivitas	Satuan	*Baseline*	-20%	-10%	10%	20%
Emisi dari generator pembangkit listrik						
Emisi CO2	ton	8298,12	6638,49	7468,30	9127,93	9957,74
Emisi CH4	ton	0,64	0,51	0,57	0,70	0,76
Emisi N2O	ton	1,00	0,80	0,90	1,10	1,20
Emisi Sox	ton	16,28	13,03	14,65	17,91	19,54
Emisi Nox	ton	247,60	198,08	222,84	272,36	297,12
Emisi Partikulat	ton	17,41	13,92	15,66	19,15	20,89

From the results of modifying the number of streams for sensitivity checks to *hotspots* and data capture methods, the following sensitivity check results are obtained.

The results of sensitivity analysis showed that variations in *emission hotspot* values from generators in power plants and modifications to the calculation method did not produce a significant impact. Despite a change of +/- 20%, the difference in potential impact is less than 20%. Thus, it can be concluded that the emission data from the generator and the emission inventory calculation method have achieved an adequate and reliable level of representativeness for environmental impact assessment. Just as is done in other research, from the results of the interpretation, it is known that all impact categories studied have important issues [14].

Table 15. Sensitivity Check Results

No	Kategori Dampak	Indikator Kategori	*Baseline*	-20%	-10%	20%	10%
1	Potensi pemanasan global	Kg CO_2 ek / GJ	5,64	4,76	5,20	6,08	6,52
		% Beda		-15,57%	-7,79%	7,79%	15,57%
2	Potensi penipisan lapisan ozon	Kg CFC_{11} ek / GJ	3,45E-10	3,45E-10	3,45E-10	3,45E-10	3,45E-10
		% Beda		0,00%	0,00%	0,00%	0,00%
3	Potensi hujan asam	Kg SO_2 ek / GJ	0,073	0,059	0,066	0,081	0,088
		% Beda		-19,00%	-9,00%	9,00%	19,00%
4	Potensi eutrofikasi	Kg PO_4 ek / GJ	0,017	0,013	0,015	0,018	0,020
		% Beda		-18,99%	-8,99%	8,99%	18,99%
5	*Photochemical oxidation*	Kg C_2H_4 ek / GJ	0,0007	0,0006	0,0006	0,0007	0,0007
		% Beda		-12,33%	-6,16%	6,16%	12,33%
6	Potensi terjadi penurunan abiotik (fossil dan non fossil), terdiri dari:						
	a. Abiotic depletion	Kg Sb ek / GJ	2,95E-09	2,95E-09	2,95E-09	2,95E-09	2,95E-09
		% Beda		0,00%	0,00%	0,00%	0,00%
	b. Abiotic depletion (fossil fuels)	MJ / GJ	61642,41	61642,41	61642,41	61642,41	61642,41
		% Beda		0,00%	0,00%	0,00%	0,00%
7	Potensi terjadi penurunan biotik, terdiri dari:						
	a. Terrestrial ecotoxicity	Kg 1,4-DCB / GJ	0,002	0,002	0,002	0,002	0,002
		% Beda		0,00%	0,00%	0,00%	0,00%
	b. Freshwater ecotoxicity	Kg 1,4-DCB / GJ	0,001	0,001	0,001	0,001	0,001
		% Beda		0,00%	0,00%	0,00%	0,00%
	c. Marine ecotoxicity	Kg 1,4-DCB / GJ	0,001	0,001	0,001	0,001	0,001
		% Beda		0,00%	0,00%	0,00%	0,00%
8	*Human toxicity* (karsinogenik)	Kg 1,4-DCB / GJ	0,000	0,000	0,000	0,000	0,000
		% Beda		0,00%	0,00%	0,00%	0,00%
9	*Human toxicity* (non karsinogenik)	Kg 1,4-DCB / GJ	0,004	0,004	0,004	0,004	0,004
		% Beda		0,00%	0,00%	0,00%	0,00%
10	*Water scarcity footprint*	m^3 / GJ	-18,660	-18,660	-18,660	-18,660	-18,660
		% Beda		0,00%	0,00%	0,00%	0,00%
11	*Land use change*	m^2a crop ek / GJ	0,000	0,000	0,000	0,000	0,000
		% Beda		0,00%	0,00%	0,00%	0,00%
12	*Cumulative energy demand*, terdiri dari:						
	a. Non renewable	MJ / GJ	66855,03	66855,03	66855,03	66855,03	66855,03
		% Beda		0,00%	0,00%	0,00%	0,00%
	b. Renewable	MJ / GJ	0,000	0,000	0,000	0,000	0,000
		% Beda		0,00%	0,00%	0,00%	0,00%

Uncertainty checks become relevant when there are data with a high degree of uncertainty, low data quality, or assumptions involved in the calculation, so an examination is needed to assess the impact of such uncertainty on the reliability of Life *Cycle Impact Assessment* (LCIA) results. However, in the context of this study, uncertainty checks are not carried out because all data in the inventory is primary data or the result of routine monitoring. Therefore, the data is of good quality and representative of the actual condition of the company, eliminating the need for uncertainty checks.

Consistency checks are conducted to verify that assumptions, methods, and data have been consistently applied throughout the study and by the definition of objectives and scope that have been previously set to conclude. This consistency check process involves qualitative evaluation of several aspects, including consistency of data quality with the purpose and scope of the study, consistent application of regional and/or temporal differences, consistent application of allocation rules and system boundaries, and consistent application of impact assessments.

Table 16. Consistency Checks

No	Pemeriksaan	Hasil
1	Sumber Data	Seluruh data inventori memiliki sumber data yang sama
2	Akurasi Data	Seluruh data inventori memiliki akurasi yang sama karena berasal dari sumber yang sama
3	Umur Data/Cakupan Waktu	Seluruh data primer inventori yang menjadi lingkup salah satu perusahaan minyak dan gas, skenario *cradle-to-gate* berasal dari data aktual perusahaan pada tahun 2021. Sedangkan untuk skenario *grave* karena melibatkan proses *refinery* di luar jangkauan salah satu perusahaan minyak dan gas, data yang digunakan adalah tahun 2020
4	Cakupan Teknologi	Seluruh data primer inventori merupakan data aktual perusahaan untuk proses inti yang mana memiliki teknologi yang sama
5	Cakupan Geografis	Seluruh data primer inventori berasal dari data aktual perusahaan yang sama
6	Metodologi	Kajian ini ini telah dilakukan sesuai dengan persyaratan SNI ISO 14040:2016 dan SNI ISO 14044:2017
7	Tujuan dan Lingkup, Tujuan Penerapan, Batasan Sistem, Sistem Produk	Kajian ini ditujukan untuk pemangku kepentingan internal dan eksternal dengan tujuan menghitung potensi dampak lingkungan dari proses produksi listrik. Ruang lingkup dan batasan sistem produk disesuaikan dengan kondisi aktual perusahaan dan telah disesuaikan dengan tujuan yang ingin dicapai. Hal ini sudah konsisten pada seluruh tahapan kajian dan konsisten untuk seluruh produk yang dikaji
8	Penentuan Unit Fungsi	Unit fungsi yang digunakan konsisten dalam seluruh kajian, yaitu 1 GJ minyak bumi yang diproduksi untuk lingkup *cradle-to-gate* dan 1 liter bahan bakar solar (ADO) untuk lingkup *cradle-to-grave*.
9	Pemilihan Data	Pemilihan data yang diprioritaskan dalam kajian ini adalah data primer dari perusahaan. Jika data primer tidak tersedia, pengumpulan data akan dilakukan sesuai prosedur pengumpulan data pada Prosedur Pengumpulan Data
10	Level Agregasi	Agregasi yang dilakukan adalah vertikal-horizontal dan konsisten untuk seluruh produk yang dikaji
11	Prosedur Kalkulasi	Seluruh produk memiliki prosedur kalkulasi yang sama
12	Penilaian Dampak	Kategori dampak yang dikaji konsisten dengan tujuan dan lingkup hingga interpretasi dan kesimpulan. Hal ini sudah konsisten untuk seluruh produk yang dikaji
13	Interpretasi	Interpretasi hasil yang dilakukan sesuai dengan tujuan yang hendak dicapai pada kajian
14	Penggunaan Istilah dan Definisi	Penggunaan istilah dan definisi di seluruh laporan konsisten sesuai SNI ISO 14044:2017

CONCLUSION

Based on the LCA analysis that has been carried out on each process unit of the oil and gas industry, several significant conclusions can be drawn as follows:

The oil and gas industry has carried out a life cycle assessment study according to SNI ISO 14040: 2016 and 14044: 2017 standards, involving 100% of its products, namely petroleum. This assessment covers the scope of *cradle-to-grave using 2021 company* data for cradle-to-gate scenarios*, and* 2020 *refinery unit* data for grave scenarios. The function units analyzed are 1 GJ of petroleum and 1 liter of diesel fuel (ADO) for *grave scenarios*.

The quality of the data used is adequate for lifecycle impact assessment, with the data collected reaching 100% completeness. Specific/primary data consists of 70% of direct measurement results and 30% of calculations or estimates.

The results of the environmental impact assessment cover 12 relevant impact categories, providing a comprehensive picture of the impact generated by the oil and gas industry on the environment.

Based on the identification of important issues (hotspots*), it was revealed that the main focus on important issues* can be directed at core processes or production within the scope of the oil and gas industry. Therefore, improvement program recommendations can be drafted by companies based on these *hotspot findings*. In the context of petroleum production, *hotspots* come from the emission process of solar-based generators in power generation process units.

Environmental improvement efforts can be focused on process units that are an important issue, namely solar-based generator emissions from power plant process units.

Sensitivity checks are carried out by modifying the emission values produced by the generator. This is done considering that the inventory of emissions is carried out using the company's internal calculations. The sensitivity analysis results showed that changes in emission values in the power plant process unit did not significantly affect the results of the potential impact generated. Thus, it can be concluded that this emission value is not sensitive based on the collection method.

Potential for global warming, Potential ozone layer depletion, Potential acid rain, Potential for eutrophication, Photochemical oxidation, Potential for abiotic decline (fossil and non-fossil), consisting of Abiotic depletion and Abiotic depletion (fossil fuels), Potential for abiotic decline, consisting of Terrestrial ecotoxicity; Freshwater ecotoxicity; and Marine ecotoxicity, Human toxicity (carcinogenic), Human toxicity (non-carcinogenic), Water footprint, Land use change, Cumulative energy demand, consisting of Non-renewable and Renewable

From the interpretation results, it is known that all impact categories studied have important issues (hotspots) in core process or production units within the scope of the oil and gas industry caused by diesel-based generators from power generation process units with a characterization value for global warming potential of 6 .42E+00 Kg CO_2 ek / GJ, Potential for ozone layer depletion of 1.00E-06 Kg CFC11 ek / GJ, Potential for acid rain of 8.14E-02 Kg SO_2 ek / GJ, Potential for eutrophication of 1.76E-02 Kg PO_4 ek / GJ, Photochemical oxidation of 9.92E-04 Kg C_2H_4 ek / GJ, Potential for abiotic depletion (fossil and non-fossil), consisting of: Abiotic depletion of 1.15E-06 Kg Sb ek / GJ and Abiotic depletion (fossil fuels) of 6.17E+04 MJ / GJ, Potential for biotic decline, consisting of: Terrestrial ecotoxicity of 2.68E+00 Kg 1.4-DCB ek / GJ; Freshwater ecotoxicity of 1.03E-02 Kg 1.4-DCB ek / GJ; and Marine ecotoxicity of 1.70E-02 Kg 1.4-DCB ek / GJ, Human toxicity (carcinogenic) of 2.94E-02 Kg 1.4-DCB ek / GJ, Human toxicity (non-carcinogenic) of 2.88E -01 Kg 1.4-DCB ek / GJ, Water footprint of -1.86E+01 m3 / GJ, Land use change of 5.45E+01 m2a crop ek / GJ, Cumulative energy demand, consisting of: Non-renewable amounting to 6.69E+04 MJ / GJ and Renewable amounting to 2.08E-01 MJ / GJ.

Recommendations are given based on important issues that have been identified, namely in the power plant process unit. Recommendations Based on *Hotspots* are as follows:

Developing a program to optimize the operation of G-3412 and G-398 generator sets by utilizing related gas or wet gas from PRM-26 and MRB-01 production wells aims to reduce dependence on diesel fuel in production operational power plants. Substituting diesel with this gas can significantly reduce emissions from combustion in power plants.

Modification and maintenance of the recover pit, with the addition of nets, is expected to reduce the amount of dirt entering, optimize the performance of suction pumps, and effectively reduce energy use, with a positive impact on emissions from the use of diesel in power plants.

Using heat generated by generator blowers for *water heaters* through *heat recovery steam* generators aims to increase the efficiency of electricity use. By harnessing this heat, the use of electricity in production can be minimized, resulting in fuel savings, and reducing emissions from power plants.

REFERENCES

A. Kholil, M. Budihardjo, F. Muhammad and K. Karno, "Life Cycle Assessment of Fuel Distribution Process at PT Pertamina (Persero) Fuel Terminal Parepare," Journal of Environmental Sciences, vol. 20, no. 3, pp. 685-695, 4 Jul 2022.

A. Setyono and B. Kiono, "From Fossil Energy to Renewable Energy: A Portrait of Indonesia's Oil and Gas Conditions in 2020 – 2050," Journal of New and Renewable Energy, vol. 2, no. 3, pp. 154-162, 21 Oct 2021.

Kholiq I, "Utilization of Alternative Energy as Renewable Energy to Support [Internet] Fuel Substitution," [Online]. Available: http://ejurnal.itats.ac.id/iptek/article/view/12/12. [Accessed 20 April 2023].

A. S. Bilqis, A. Bakhtiar and K. Kunci, "Determination of the Number of Tank Car Needs in the Fuel Distribution Process at Pt Pertamina (Persero) Integrated Terminal Semarang [Internet]," 2021. [Online]. Available: https://ejournal3.undip.ac.id/index.php/ieoj/article/download/33672/26784. [Accessed 20 Apr 2023].

Sulistyono, "Oil And Gas Industry Business Activities Related To Environmental Sustainability Impacts And Responsibilities," Swara Patra: PPSDM Migas Scientific Magazine, vol. 5, no. 2, pp. 23-30, 31 Dec 2015.

F. Cici, "Life Cycle Assessment on Paper Product Distribution Transportation," Industry, vol. 11, no. 2, pp. 98-105, 14 Sep 2021.

P. F. Lubis, L. Hakim and A. Nugroho, "Application Of Life Cycle Assessment To Patchouli Oil Industry in Aceh Jaya Regency," Scientific Journal of Agricultural Students, vol. 4, no. 1, pp. 363-371, 2019.

D. Astuti, "Potential Analysis Of Environmental Impact Of Sugarcane Plantation Using Life Cycle Assessment (Lca) Approach," Journal of R&D: Media Information on Research, Development, and Science and Technology, vol. 15, no. 1, pp. 51-64, 2019.

K. Siregar, A. A. R. Setiawan, E. I. Wiloso, T. Miharza, and I. Sofia, "IDN-LCI: The conceptual framework of the Indonesian life cycle inventory database to support the life cycle assessment," IOP Conference Series: Earth and Environmental Science, vol. 542, no. 1, p. 012044, Jul 1, 2020.

H. M. Al Zarkani, T. Mezher, and M. El-Fadel, "Life cycle assessment in the petroleum industry: A systematic framework towards improved environmental performance," Journal of Cleaner Production, vol. 408, p. 137196, 1 July 2023.

A. Muhyinsyah, J. A. Witono, and E. Santoso, "Life cycle assessment of natural gas and crude oil: a case study in PT Pertamina Hulu Mahakam–BSP Site," IOP Conference Series: Earth and Environmental Science, vol. 753, no. 1, p. 012037, 1 May 2021.

Badan Standarisasi Nasional. SNI ISO 14044:2017 – Penilaian Daur Hidup Persyaratan dan Panduan.2017.BSN RI, Jakarta

Hall, G.M. and Howe, J., 2012. Energy from waste and the food processing industry. Process Safety and Environmental Protection, 90(3), pp.203-212

Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, J.F. and Stolten, D., 2018. Life Cycle Assessment of hydrogen transport and distribution options. Journal of cleaner production, 199, pp.431-443