



Assessing Global Warming Potential (GWP) of the Production of Oil and Natural Gas in Pangkah Block Field, Indonesia

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ABSTRACT

The production of oil and natural gas is the main source of economic activity and a vital component of the global energy system. However, a major contributor to greenhouse gas emissions that directly cause anthropogenic climate change is the production process. This study looks at the effects of oil and gas production in Indonesia's Ujung Pangkah field on the environment, specifically on global warming potential (GWP) fossil fuels, along the whole supply chain, from the extraction of raw materials to the products' transit (distribution). Life cycle assessment (LCA) in accordance with ISO 14040:2016, ISO 14044:2017, and the Product Category Rules (PCR) of Crude Petroleum and Natural Gas Version 1.0 2023-06-19 is the methodology used in this study. The software SimaPro 9.1.0.8 was used to do the life cycle impact assessment. Cradle to grave is the system boundary established for this study, encompassing both direct emissions from operations and indirect emissions from energy use. According to the paper's conclusion, the characterisation results for oil, gas, and LPG's Global Warming Potential (IPCC 2021 GWP100 VI.02) are 0,06910 kg CO₂ eq, 0,07494 kg CO₂ eq, and 0.7786 kg CO₂ eq, respectively. The results also show that, during the course of the product's life cycle, the core stream phase as a utility—specifically, the unit processes of diesel generator & emergency WHP-A and diesel generator & emergency WPN—contributes the most to the environmental impact. This is because pertadex diesel is used as fuel for the power in the living quarters and offshore (WHP-A) in WPN. Diesel consumed in diesel electric producing is the parameter of the Pertadex (Ecoinvent database)

INTRODUCTION

Indonesia was a major net exporter of (crude) oil in the past and was a member of the Organization of the Petroleum Exporting Countries (OPEC) from 1962 to 2008 and again from 2015 to 2016. Nevertheless, the country is currently facing the challenges of diminishing oil output, aging resources, and the shift to being a net importer of crude oil. For the past 20 years, Indonesia's oil production has been steadily declining. From more than 1.5 million barrels per day (bpd) in the 1990s to about 703,000 bpd in 2023, crude oil production has decreased, according to data from SKK Migas (the Special Task Force for Upstream Oil and Gas Business Activities).

Crude oil, natural gas, and LNG (Liquid Natural Gas) are examples of energy products that are significant in the context of national development, particularly in the infrastructure and industry sectors. Since motor vehicles and other transportation-related businesses rely on fossil fuels to function, the transportation sector is a major user of oil. On the other hand, Indonesia continues to be a significant participant in the worldwide market for liquefied natural gas (LNG). Being one of the largest LNG exporters globally, the nation depends heavily on LNG export revenue. Power plants, businesses, and homes are just a few of the sectors that use natural gas and LNG. Since domestic gas fields supply the majority of the natural gas needed to generate electricity, gas power plants play a significant role in supplying electricity to Indonesians.

After coal and petroleum, natural gas is Indonesia's third most important energy source. Additionally, the demand for natural gas is gradually rising annually. Nevertheless, the current supply of natural gas is still insufficient to reach the goal, which is for natural gas to take the place of petroleum. According to the Ministry of Energy and Mineral Resources of the Republic of Indonesia (2024), natural gas's share of the primary energy mix in 2023 is a mere 296.11 MBOE (million barrels of oil equivalent), or 16.28% of the total.

Table 1. Primary Energy Mix in 2023

No	Primary energy	MBOE	%
1	Petroleum	548,99	30,18
2	Coal	736,00	40,46
3	Natural Gas	296,11	16,28
4	Renewable Energy	238,12	13,09
Total		1.819,22	100,00

Source: (Ministry of Energy and Mineral Resources of Republic of Indonesia, 2024)

The environment is clearly impacted by the intensive production and extensive use of fossil fuels. Activities related to exploration, production, distribution, and consumption will undoubtedly have negative long-term effects on the ecosystem. Potential environmental effects that may have happened are difficulties that require countermeasurement. This is consistent with the government's objective to reduce reliance on non-renewable energy sources.

Another way to avoid negative effects on the environment is to use more renewable energy.

LITERATURE RIVIEW

Research has established the profound environmental consequences associated with fossil (non-renewable) energy use, notably contributing to global warming, climate change, and extreme weather phenomena through greenhouse gas emissions across extraction, production, transport, and combustion stages. Additionally, fossil fuel reliance exacerbates air pollution, poses risks to human health, and accelerates habitat degradation and biodiversity loss. These findings reinforce the imperative to expedite the transition toward cleaner, more sustainable energy systems (Masson-Delmotte et al., 2018).

This industry's environmental issues are a topic that is currently getting a lot of attention. Environmental pollution from oil spills, which can harm coastal and marine ecosystems, is a significant issue brought up. The detrimental impacts of such spills on biodiversity and ecological balance close to extraction sites are highlighted by Singh et al. (2020). Moreover, greenhouse gas emissions from sector activities are a critical driver of climate change and air quality decline. Research further identifies the industry as a significant contributor to Indonesia's global warming trajectory (Desrina R, 2014). Indonesia's oil and gas sector is a major source of greenhouse gas emissions, highlighting the urgent need for stronger mitigation efforts. Waste management, particularly for liquid waste, flue gases, and hazardous waste, remains a significant challenge. A recent study on Qatar's oil and gas industry (Shahbaz et al., 2023) examines waste characterization, processing technologies, challenges, and emerging opportunities, including the potential for waste reuse.

The correlation among the products assessed, impact category selected-GWP, and the method to analyze the magnitude and significance of the impact in this research can be explained below. The Global Warming Potential (GWP) is a crucial measure developed by the Intergovernmental Panel on Climate Change (IPCC) to standardize the climate impact of various greenhouse gases relative to carbon dioxide (CO₂) over a given period, typically 100 years. While CO₂ from burning fossil fuels is the most abundant anthropogenic GHG, others, like methane (CH₄), are far more potent per molecule. Oil and natural gas constitute a dominant share of the world's energy mix. Their extraction, processing, transportation, and final combustion release a suite of GHGs that contribute to atmospheric warming. Life Cycle Assessment (LCA) has been widely recognized as a quantitative method for assessing the environmental impact of a product or service throughout its life cycle (SNI ISO 14040:2016, n.d.). In the context of oil and natural gas, the application of LCA enables the measurement of environmental impacts from upstream to downstream stages, including the identification of critical stages that contribute the most to the total environmental burden. Thus, LCA serves not only as an evaluation tool, but also as a basis for developing impact reduction strategies in the energy industry (SNI ISO 14044:2017, n.d.). The Life Cycle Assessment analysis of oil and gas in this journal

is carried out with a cradle-to-grave approach, to measure potential environmental impacts to obtain/ identify hotspots due to natural gas production activities. This study is expected to be able to mitigate the impact and develop more environmentally friendly solution.

Pangkah field is classified in the group of upstream industry (Figure 1). There are 35 (thirty five) active wells with 4 (four) Well Head Processing (WHP) that called as WHP-A (15 well slots); WHP-B (20 well slots); WHP-C and WHP-D (both 5 well slots), all the following WHPs with distribution pipes and the distance from WHP-B to onshore platform facilities (OPF) is 46 km. The total production of natural as in the year 2023 reached 9.904.550.318,62 MJ; crude oil amounted 15.271.856.025,57 MJ; and LPG: 866.164.879,75 MJ. The products are distributed through transmission pipes to PLN Nusantara Power (natural gas) and LPG distributor; and temporary receiver in tanker ship.



Figure 1. Natural Gas production in Pangkah field, Indonesia Source: SIPL, 2024

In order to identify the major problems in the product's whole life cycle within the specified boundary system, this study used hotspot analysis and the assessment of a specific environmental impact category, namely the global warming potential (GWP), as a result of the oil and gas production in Indonesia's Ujung Pangkah field. The development of the recommendations is based on the findings of the hotspot analysis. The oil business will implement the suggestions as part of its ongoing improvement initiative. The Product Category Rules (PCR) of Crude Petroleum and Natural Gas Version 1.0 2023-06-19, ISO 14040:2016 (Principle and Framework), and ISO 14044:2017 (Guideline) are among the standards and guidelines cited.

METHODOLOGY

This study used life cycle assessment (LCA) techniques from the European Union (2010) in accordance with its worldwide standards, which have been adapted as national standards in Indonesia. Among the standards are ISO 14044:2017 (Guideline) and ISO 14040:2016 (Principle and Framework). The Product Category Rules (PCR) of Crude Petroleum and Natural Gas Version 1.0 2023-06-19 are also followed in the execution of this study. This PCR was adopted primarily to verify the study's scope, not to claim ecolabel type III (environmental product declaration) or EPD. The research is implemented using

life cycle assessment (LCA) frameworks, which are divided into four phases: (1) aim and scope definition; (2) life cycle inventory; (3) life cycle impact assessment; and (4) interpretation. Refer to Figure 2.

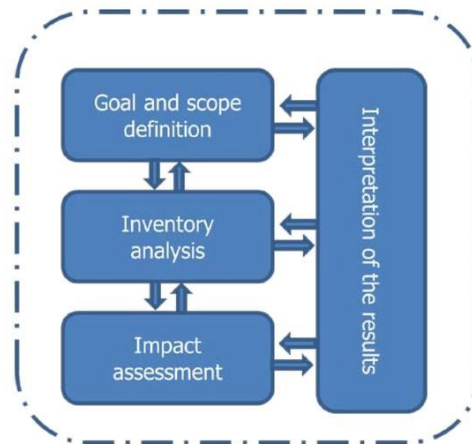


Figure 2. LCA Framework Source: (SNI ISO 14040:2016, n.d.)

As previously stated, this study's primary objective is to evaluate the possible environmental effects of global warming potential (GWP) fossil fuels linked to the oil and gas production in the Block of Pangkah field. It also aims to identify hotspots for ongoing improvements.

The following is the detailed scope of the study:

1. The declaration unit are 1 MJ of crude oil at the temporary receiver of tanker ship; 1 MJ of natural gas in the gas metering of customers in PLN Nusantara Power; and 1 MJ of LPG at the Maspion Distributor. Elementary flows are based on the intensity production of the Ujung Pangkah Block field in 2023 for the products of crude oil is amounted 15.271.856.025,57 MJ; natural gas which amounted to 9.904.550.318,62 MJ; and LPG is 866.164.879,75 MJ
2. The system boundary follows the mentioned PCR for Natural Gas and natural gas. The product system includes the phases of upstream (drilling and well service); core in (manifold, separator, gas lift, hydrocarbon receiving and separation, gas sweetening, gas dehydration (gas processing facilities), gas dehydration (LPG facilities), gas compression & cryogenic processing, LPG fractionation, LPG sphere tank, oil treating process, gas compressor, Natural Gas tank, produced water treatment, water well injection to WHP-B, collection vessel, caisson overboard, acid disposal system, and produced water treatment (oil treating facilities), utilities such as (gas turbine generator and compressor offshore, diesel generator WHP-A and diesel generator WPN, offshore waste storage from all WHP and WPN, flaring offshore, gas turbine generator and emergency diesel onshore, heating medium system, onshore waste storages, fire water system and water utility, and flaring onshore); and downstream temporary receiver (piping/ transportation of the product to PLN Nusantara Power). To put it another way, the study's scope

is cradle to tomb. The cradle-to-grave method is frequently used to define system boundaries, particularly when evaluating the use of fossil resources for transportation (Khan et al., 2019) or electricity generation (Caglayan & Caliskan, 2022). The product's flow process and the study's distinct system boundaries are depicted in Figure 3.

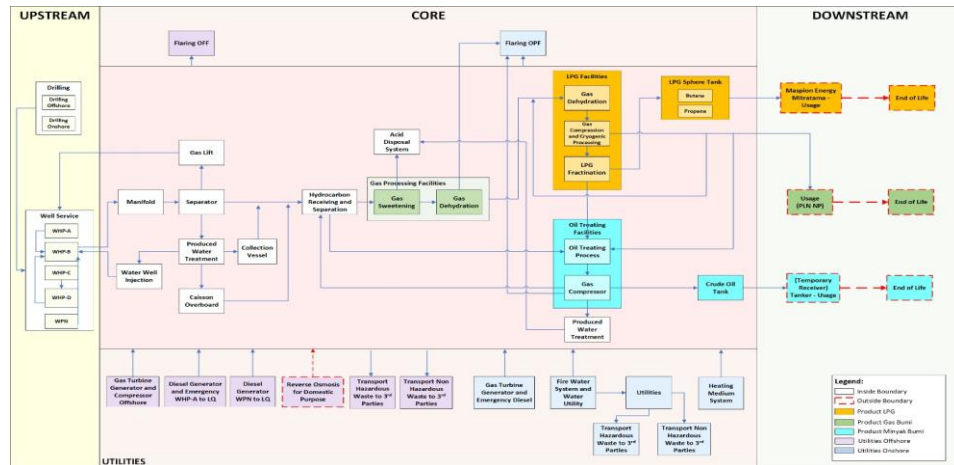


Figure 3. System Boundary of the Study

3. Assumptions are set as follow:
 - a. Transportation of supporting materials and fuels in the upstream and core stream in the offshore and West Pangkah (WPN) using the vessel mode by calculating the distance from Lamongan ShoreBased (LSB).
 - b. Transportation of all AUP support materials and fuels is by Royal King Ali (RKA) vessel located at LSB at a distance of 17,3 km. There are 3 (three) vessels used alternately from LSB to AUP considered to have the same specifications.
 - c. After calculating the distance traveled multiplied by the amount of the cargo carried in the vehicle type and specification (in tons per kilometer), the database Ecoinvent was used to calculate emissions from the transportation of fuels, supporting materials, and personnel.
 - d. Emissions (including hazardous and non-hazardous waste) of well drilling both onshore West Pangkah (WPN) and offshore use the SimaPro/ ecoinvent database.
 - e. The type of material used per well for well intervention activities in WHP-B and WHP-A in 2023 is considered the same as the material requirements for well intervention activities in WHP-C and WHP-D.
 - f. Monitoring and inspection transportation to each WHP using S Grace and S Hermes vessels (fuel usage in 2023).
 - g. Acid gas that enters, none of which is absorbed by produced water.
 - h. Calculation of product converted to MJ using heating value.
 - i. There are 2 (two) gas flare units in the OPF that considered to be 1 (one) unit because its can not be separated from the input and output emissions.

- j. There is no electrical energy use in the WPN onshore drilling process unit except for the living quarter generated by the diesel generator-set.

Data Inventory Analysis

SNI ISO 14040:2016 states that data inventory refers to the specified aim and scope and includes inputs, outputs, and emissions within the system boundary. Here, all information is gathered from the upstream resource extraction (drilling) to the downstream product (distribution of the products), including primary and secondary materials, chemical materials, energy, water, fuels, the product, emissions to the air, water, and soil, and waste (both hazardous and non-hazardous). The declaration unit analyzes the data inventory according to 1 MJ of crude oil at the tanker's temporary receiver, 1 MJ of gas (sales) at the user gate, and 1 MJ of LPG distributor (Maspion) gate. The study's data inventory is shown below.

Table 3. Summary of Life Cycle Data Inventory

Category of Material	Component	Unit	Amount	Per declaration unit (1MJ)
Material	Raw Material from Other Processes: Fluida Natural Gas	MJ	285.339.461.140,45	1,10E+01
	Raw Material from Other Processes: Produced Water	L	13.972.763.259,22	5,37E-01
	Fluid Support Material	Ton	1.883.302,51	7,23E-05
	Solid Support Material	Ton	22.893,31	8,79E-07
	Other Supporting Material	Ton	3,40	1,30E-10
Water	Water	L	7.928.176.702,55	3,04E-01
Energy	Electricity	kWh	46.243.082,60	1,78E-03
Fuel	Fuel	L	670.952,53	2,58E-05
Product	Crude oil, Gas (sales), LPG	MJ	9.904.550.318,62	3,80E-01
Co-Product	Water	L	17.385.106.083,60	6,68E-01
Co-Product	Electricity	kWh	97.295.297,32	3,74E-03
Emissions to Air	i-Butane	Ton	1,26E-04	4,84E-15
	i-Pentane	Ton	4,37E-05	1,68E-15
	Nitrogen	Ton	1,06E-03	4,08E-14
	Component	Unit	Amount	Per declaration unit (1MJ)
	Methane	Ton	4,20E-02	1,61E-12
	Ethane	Ton	6,59E-03	2,53E-13
	Propane	Ton	1,04E-03	3,97E-14
	Nitrogen, total	Ton	2,20E-05	8,45E-16
	Carbon dioxide	Ton	1,13E-04	4,34E-15
	Hydrogen sulfide	Ton	3,90E-05	1,50E-15

NO2	Ton	5,69E-13	2,18E-23
SO2	Ton	3,14E-13	6,28E-24
PM	Ton	1,75E-13	8,71E-24
CO	Ton	3,30E-16	1,27E-26
O2	Ton	5,00E-17	1,92E-27
Treated water	L	7.965.559.264,76	3,06E-01
Solid Hazardous Waste	Ton	319,36	1,23E-08
Liquid Hazardous Waste	Ton	1.340.541,33	5,15E-05
Non Hazardous Waste	Ton	19,102	7,33E-10

Primary/specific data (estimation, computation, and interview) and secondary/generic data (Ecoinvent, SimaPro, and literature) are the sources of the data. Upstream processes accounted for 53% of the primary/specific data obtained in this study, whereas core processes accounted for 75%. Additionally, direct measurement accounts for 68% of the key data from the core process, with the remaining 7% coming from estimation and calculation. The analysis discovered that 33% of the downstream data was secondary and 67% was primary.

SimaPro LCA Version 9.1.0.8 was utilized in this study to process the data inventory and calculate the environmental effect (classification and characterization). Table 3 displays the life cycle data inventory summary in upstream, core, and downstream stages.

RESULT

Life Cycle Impact Assessment (LCIA) Results

According to PRé Sustainability (n.d.), SimaPro is used to evaluate the environmental impact of creating 1 MJ of crude oil at the tanker's temporary receiver, 1 MJ of gas (sales) at the user gate, and 1 MJ of LPG distributor (Maspion) gate. This software performs the classification, characterization, and weighting steps of the assessment process.

According to life cycle impact assessment (characterization) data, the fossil fuel GWP (GWP) for oil, gas, and LPG products is 0,06910 kg CO₂ eq, 0.7786 kg CO₂ eq, and 0,07494 kg CO₂ eq, respectively. Table 4 and Graph 1 show the effects of the phases in cradle-gate-to-grave as follows:

Table 4. Life Cycle Impact Assessment for Global Warming Potential (fossil) of Crude oil, Sales Gas, and LPG, Pangkah Block Field (IPCC 2021 GWP100 characterization)

No	Product	Units	Per MJ			Total (Cradle to Grave) 2024
			Cradle	Gate	Grave	
1	Crude oil	kg CO ₂ eq	2,19E-02	2,36E-02	2,36E-02	0,06910
2	Sales Natural Gas	kg CO ₂ eq		2,65E-02	2,65E-02	0.7786
3	LPG	kg CO ₂ eq		2,76E-02	2,83E-02	0,07494

Table 4 indicates that among the phases of the products' life cycle, operations in the gate for crude oil and sales natural gas share the same amount to the their total GWP (fossil). However, in the production of LPG, the phase of grave contributes the highest to the total impact on GWP (fossil).

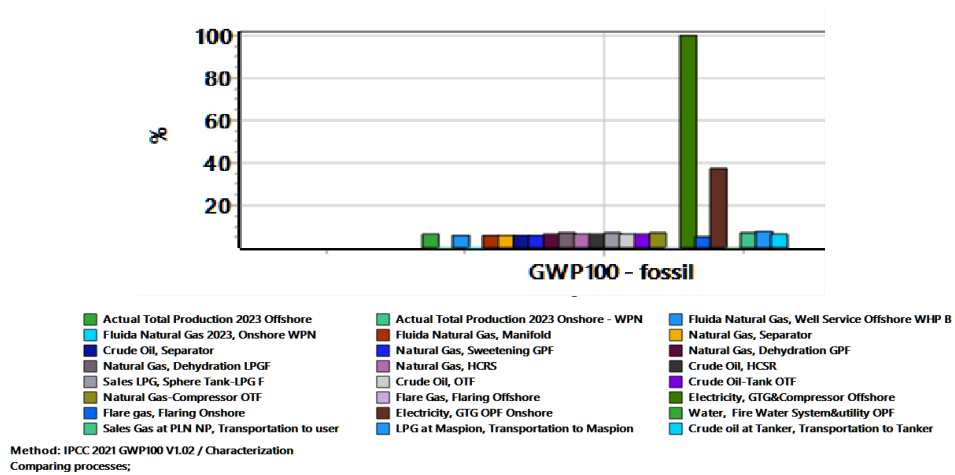


Figure 4. Impact Assessment Result on GWP 100 (Fossil) in All Process Units of the Study Source: LCIA Result, 2024

Figure 4 indicates the clearly that the process unit of electricity in the GTG (diesel generator) and Compressor at the offshore is the highest contributor to the GWP (fossil), followed by the electricity in the GTG OPF (diesel generator) at onshore.

DISCUSSION

The results of the life cycle impact assessment and data inventory analysis are covered in this section. The preceding Table 4 identifies significant concerns across the product life cycle. Phases, unit processes, and substances that account for at least 85% of the environmental impact are examples of hotspots (Pareto rule). According to the Pareto Principle, a minority of inputs or causes – roughly 20% – cause a significant majority of outcomes or consequences, usually 80% (Dunford et al., 2014).

The downstream phase, specifically the unit process of diesel generator & emergency WHP-A and diesel generator & emergency WPN, contributes the most to GWP across all product life cycle stages. Compared to the upstream and core stages, the downstream phase has the greatest impact on GWP. Nevertheless, the main activity that contributes the most to the GWP (fossil) is the production of electricity for both WPN and offshore (WHP-A) at the living quarter. This is because Pertadex is used as the generator's fuel. Diesel consumed in diesel electric producing is the parameter for Pertadex (Ecoinvent database).

Table 5 details each process unit's contribution from birth to death and displays the findings of a hotspot analysis band, with the 85% contributors indicated in orange. Diesel generator & emergency WHP-A (67%) and diesel





generator & emergency WPN (33%), two (two) hotspots of unit processes, were the main topics of discussion. Additionally, the contribution of carbon dioxide was 89.10 percent.

Table 5. Impact Assessment Result (Charachterisation) on GWP 100 Fossil in All Processes Unit

No	Unit Process Unit	GWP kg CO ₂ eq	Percentage
1	Drilling Offshore	2,46E-02	0,0012%
2	Drilling Onshore	3,04E-04	0,00001%
3	Well Service Offshore	2,19E-02	0,0011%
4	Well Service Onshore	1,06E-04	0,00001%
5	Manifold	2,19E-02	0,0011%
6	Separator	4,40E-02	0,0022%
7	Gas Lift	2,20E-02	0,0011%
8	Hydrocarbon Receiving & Separation	6,96E-02	0,0034%
9	Gas Sweetening	2,28E-02	0,0011%
10	Gas Dehydration GPF	2,50E-02	0,0012%
11	Gas Dehydration LPGF	2,53E-02	0,0012%
12	Gas Compression & Cryogenic	5,29E-02	0,0026%
13	LPG Sphere Tank	2,76E-02	0,0014%
14	LPG Fractionation	2,73E-02	0,0013%
15	Oil Treating Process	4,72E-02	0,0023%
16	Crude Oil Tank	2,36E-02	0,0012%
17	Gas Compressor	2,56E-02	0,0013%
18	Collection Vessel	3,45E-02	0,0017%
19	Caisson Overboard	5,09E-02	0,0025%
20	Produced Water Treatment Offshore	2,32E-02	0,0011%
21	Water Well Injection	2,84E-03	0,0001%
22	Flaring Offshore	4,84E-04	0,00002%
23	GTG & Compressor Offshore	3,73E-01	0,0184%
24	Diesel Generator & Emergency WHP-A	1,36E+03	67%
25	Diesel Generator & Emergency WPN	6,70E+02	33%
26	Acid Disposal System	4,03E-01	0,0198%
27	Produced Water Treatment OPF	5,54E-03	0,0003%
28	Flaring OPF	1,89E-02	0,0009%
29	GTG OPF	1,39E-01	0,0069%
30	Fire Water System & Water Utility	7,57E-04	0,0000%

No	Unit Process Unit	GWP kg CO ₂ eq	Percentage
31	Heating Medium System	1,48E-01	0,0073%
32	Utilities	1,481E-01	0,00729%
33	Transportation of Sales Gas to User	2,65E-02	0,0013%
34	Transportation of Sales LPG to User	2,83E-02	0,0014%
35	Transportation of Crude Oil to Tanker	2,36E-02	0,0012%

Note:

-  Crude oil
-  Sales gas (natural)
-  LPG
-  Hotspot

There were missing data points in this study's implementation. Missing data within the scope boundary should be put up and documented in detail in accordance with the LCA Standards. The following is how this missing data is being treated: emission from upstream processes using the SimaPro database; the PCR's cut-off condition was set at less than 1%, which also applied to the quantity of supporting materials used (cotton waste/majun); dummy data was land data prior to land use change; and because it is less than 1% and virtually nonexistent in 2023, the usage of fuel for emergency diesel generator sets, both onshore and offshore, is included in the cut-off criteria. This study also marked some limitations that should be consider in the interpretation of the study result. They consist of: (1) system boundary cradle to grave (distribution/transportation of products to the user/ receiver) meaning exclude the usage process and end of the life of the products; (2) impact categories GWP100 of this study only consider GWP fossil in kg CO₂ eq and exclude GWP biogenic and land transformation; (3) emission data on the onshore and offshore drilling process was not measured and utilized ecoinvent/ SimaPro database; onshore land use for West Pangkah offshore drilling and OPF in Maspion Industrial Estate previously was reclaimed pond land and created a dummy input; (4) supporting materials in the form of grease & sealant for work over activites in the well service process unit are not available and exluded from material input; (5) this study was conducted partly according to related PCR as none of its goals to declare the ecolabel type 3 (environmental product declaration); (6) the study consider process units of diesel genset at WPN and offshore (AUP) for living quarter electricity because of the use of Pertadex fuel which was presume as the main hotspots for the entire production activity.

CONCLUSIONS

This research has been conducted following the defined goals and scope (cradle to grave) for three products (crude oil, natural (sale) gas, LPG) with declaration units of 1 MJ crude oil at the temporary receiver in tanker ships, 1 MJ natural gas at the user gas metering, and 1 MJ LPG at the distributor gate. The study result in assessing GWP fossil of the three products (crude oil, natural (sales) gas, and LPG found respectively 0,06910 kg CO₂ eq; 0,07494 kg CO₂ eq; and 0.7786 kg CO₂ eq. Hotspot analysis highlighted that the most contributing unit process is diesel generator & emergency WHP-A and diesel generator & emergency WPN due to the use of Pertadex as fuels for the electricity in WPN and offshore (WHP-A) at the living quarter.

The diesel generator and emergency WHP-A and diesel generator and emergency WPN unit processes contribute to the potential for global warming. The cause of the substance are carbon dioxide which amounted 89,10%. The availability of data presented a barrier for the research's implementation, as detailed in the restriction. Therefore, as this is also part of the study purpose in supporting the national LCA huge database, a strong recommendation is highlighted for the company. Enhancing the quality of data and documentation, such as Material Safety Data Sheet (MSDS) and tool information, is also crucial. Equally important, efforts must be made to improve fuel types for improved environmental performance in order to solve major difficulties (hotspots), especially the usage of diesel (Pertadex).

REFERENCES

- A. (2022). A global gridded inventory of methane emissions from oil and gas systems based on national reports to the UNFCCC. *Earth System Science Data*, 14(2), 979–1006. <https://doi.org/10.5194/essd-14-979-2022>
- Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., ... & Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*, 361(6398), 186-188. <https://doi.org/10.1126/science.aar7204>
- BP. (2022). Statistical Review of World Energy 2022. BP p.l.c. Retrieved from <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>
- Caglayan, H., & Caliskan, H. (2022). Life cycle assessment based exergoenvironmental analysis of a cogeneration system used for ceramic factories. *Sustainable Energy Technologies and Assessments*, 52, 102078. <https://doi.org/10.1016/j.seta.2022.102078>
- Desrina R. (2014). Contribution of Oil and Gas Sector Activities to Global Warming *Lembaran Publikasi Minyak Dan Gas Bumi*, 48(2), 63–72.
- Dunford, R., Su, Q., & Wintour, A. (2014). The Pareto Principle. In *The Plymouth Student Scientist* (Issue 7).
- E. J., ... & Tans, P. P. (2016). Upward revision of global fossil fuel methane emissions based on isotope database. *Nature*, 538(7623), 88–91. <https://doi.org/10.1038/nature19797>
- European Platform on LCA. (n.d.). EN 15804. Retrieved August 1, 2024, from <https://eplca.jrc.ec.europa.eu/LCDN/EN15804.html>
- European Union. (2010). *International Reference Life Cycle Data System (ILCD) Handbook*.
- Frischknecht, R., Wyss, F., Knöpfel, S., Lützkendorf, T., & Balouktsi, M. (2015). Cumulative energy demand in LCA: the energy harvested approach. *The International Journal of Life Cycle Assessment*, 20. <https://doi.org/10.1007/s11367-015-0897-4>
- GIIGNL. (2022). *The LNG Industry: GIIGNL Annual Report 2022*. International Group of Liquefied Natural Gas Importers.

- Herrando, M., Elduque, D., Javierre, C., & Fueyo, N. (2022). Life Cycle Assessment of solar energy systems for the provision of heating, cooling and electricity in buildings: A comparative analysis. *Energy Conversion and Management*, 257. <https://doi.org/10.1016/j.enconman.2022.115402>
- Howarth, R. W. (2019). Ideas and Perspectives: Is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences*, 16(15), 3033-3046.
- IEA. (2023). Emissions from Oil and Gas Operations in Net Zero Transitions. Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The*
- International Energy Agency (IEA). (2021). *Indonesia Energy Policy Review 2021*. Paris: IEA. International Energy Agency (IEA). (2022). *Methane Tracker 2022*. Paris: IEA.
- International Energy Agency (IEA). (2023). *Methane Tracker 2023*. Retrieved from <https://www.iea.org/reports/methane-tracker-2023>
- International EPD System. (2023). *PRODUCT CATEGORY RULES (PCR) CRUDE PETROLEUM AND NATURAL GAS PRODUCT CATEGORY CLASSIFICATION: UNCPC 120*. www.environdec.com.
- IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Kementerian ESDM (ESDM). (2021). *Handbook of Energy & Economic Statistics of Indonesia 2021*. Ministry of Energy and Mineral Resources of the Republic of Indonesia.
- Khan, M. I., Shahrestani, M., Hayat, T., Shakoor, A., & Vahdati, M. (2019). Life cycle (well- to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. *Applied Energy*, 242, 1738–1752. <https://doi.org/10.1016/j.apenergy.2019.03.196>
- Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (2018). *Global warming of 1.5°C: Summary for Policymakers*. IPCC - The Intergovernmental Panel on Climate Change.
- Ministry of Energy and Mineral Resources (ESDM), Republic of Indonesia. (2022). *Handbook of Energy & Economic Statistics of Indonesia 2022*.

- Ministry of Energy and Mineral Resources of Republic of Indonesia. (2024). Energy and Mineral Sector Performance Achievement in 2023.
- Ministry of Environment and Forestry (KLHK), Republic of Indonesia. (2016). First Biennial Update Report (BUR) Under the United Nations Framework Convention on Climate Change (UNFCCC).
- Ocko, I. B., & Hamburg, S. P. (2022). Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, 22(14), 9349–9368. <https://doi.org/10.5194/acp-22-9349-2022>
- Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. (For GWP values of CH₄). <https://www.ipcc.ch/report/ar6/wg1/>
- PRé Sustainability. (n.d.). SimaPro Guideline-Sustainability. Retrieved August 1, 2024, from <https://pre-sustainability.com/>
- Putra, R. Y., Saputra, B., & Kurniawan, A. (2022). "Carbon Capture and Storage (CCS) Development in Indonesia: Potential and Challenges." *Journal of Earth Energy Science, Engineering, and Technology*, 5(2), 55-62.
- Sandoval, D. , S. B. , & K. A. (2020). Life cycle assessment of Natural Gas extraction and refining processes. *Journal of Cleaner Production*. <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.120620>
- Scarpelli, T. R., Jacob, D. J., Grossman, S., Lu, X., Qu, Z., Sulprizio, M. P., ... & Randles, C.
- Schwietzke, S., Sherwood, O. A., Bruhwiler, L. M. P., Miller, J. B., Etiope, G., Dlugokencky,
- Shahbaz, M., Rashid, N., Saleem, J., Mackey, H., McKay, G., & Al-Ansari, T. (2023). A review of waste management approaches to maximise sustainable value of waste from the oil and gas industry and potential for the State of Qatar. *Fuel*, 332, 126220. <https://doi.org/https://doi.org/10.1016/j.fuel.2022.126220>
- Siregar, S., Ridwan, M. K., & Prakoso, A. (2018). "Optimization of Energy Consumption in Mature Oil Field Operations: A Case Study in South Sumatra." *Journal of Earth Energy Engineering*, 7(2), 45-54.

SNI ISO 14040:2016. (n.d.). SNI ISO 14040-2016: Environmental Management-Life Cycle Assessment-Principles and Framework.

SNI ISO 14044:2017. (n.d.). SNI ISO 14044-2017: Environmental Management-Life Cycle Assessment-Requirements and Guidelines.

U.S. Energy Information Administration (EIA). (2022). How much carbon dioxide is produced when different fuels are burned?. Retrieved from <https://www.eia.gov/tools/faqs/faq.php?id=73&t=11>

U.S. Environmental Protection Agency (EPA). (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks.

United Nations Framework Convention on Climate Change (UNFCCC). (2021). Indonesia's Updated Nationally Determined Contribution (NDC).

World Bank. (2023). Global Gas Flaring Reduction Partnership (GGFR) Report. World Bank Group. Retrieved from <https://www.worldbank.org/en/programs/gasflaringreduction>

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasackers, J. D., Sadavarte, P., ... & Hamburg, S. P. (2020). Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Science Advances*, 6(17), eaaz5120