Mutiara: Multidiciplinary Scientifict Journal
Volume 2, Number 8 Agustus 2024
p-ISSN 2988-7860 ; e-ISSN 2988-7992

Life Cycle Assessment of Natural Gas Production in Java Sea-East Java Province, Indonesia

Ellyna Chairani[1], Errik Saleh[2], Novi Hanifah[3], Adrian Aman Santosa[4], Anita Putri Ayu[5], Richa Andreina[6]

[1]Universitas Indonesia, Indonesia, [2,3,4]Saka Energi Muriah Limited, Indonesia, [5],[6]PT. Harry Bambang Permady, Indonesia
Email: lynarani@gmail.com, errik.saleh@sakaenergi.com, novi.hanifah@sakaenergi.com, adrian.santosa@sakaenergi.com, anita@hbpkonsultan.com, richa@hbpkonsultan.com

KEYWORDS
natural gas; environmental impacts; kepodang east java; LCA

ABSTRACT

Energy products including natural gas play a very important role in the context of global economic, industrial, and infrastructure development. However, it is undeniable that the production process from raw material extraction to ready-to-use products has an impact on the environment. This study was conducted to evaluate the environmental impact of natural gas production in the Kepodang field, East Java Province, Indonesia. The next objective is to analyze the magnitude and significance of the impact or hotspot analysis. The characterization results for 4 main categories show: Global Warming Potential 70.02 kg CO_2 eq, Ozone Layer Depletion 1.11E-06 kg CFC-11 eq, Acidification Potential 0.65 mol H+ eq, Marine Eutrophication 0.30 kg N eq, and Freshwater Eutrophication 2.17E-03kg P eq. The results also show that throughout the life cycle of this product, the largest contributor to environmental impacts is in the downstream phase, especially the user gas metering unit process. This is due to the 200 km of pipelines for product transportation from the Central Processing Platform (CPP) to the user gate. Pipeline parameters (Ecoinvent database) refer to long-distance pipelines with high capacity. In addition, hotspots were also identified in the core phase: gas measurement and chromatography, gas turbine generators, and flare gas.

INTRODUCTION

Energy products such as crude oil, natural gas, and LNG (*Liquid Natural Gas*) are substantial in the context of the development of industry and infrastructure in Indonesia. As the highest oil and gas-producing country in Southeast Asia, this resource is relied upon to be the main driver of economic growth. The transportation sector is the massive consumer of oil, with motor vehicles and other transportation industries dependent on fossil fuels for their operations. Meanwhile, natural gas and LNG are used in various sectors, including power plants, industries, and households. Gas power plants have an important role in providing electricity for the people of Indonesia, with most of the natural gas used for electricity generation coming from domestic gas fields. Apart from that, Indonesia is also one of the biggest LNG exporters in the world that lead this LNG exports as a significant source of income for the country.

The need for natural gas as a primary energy supply in Indonesia is ranked third after coal and petroleum. And the amount of natural gas demand shows a slow increase from year to year. However, the existing natural gas supply is still unable to meet the target where natural gas is expected to replace the role of petroleum. This can be seen from the percentage value of the primary energy mix in 2023, where the role of natural gas is only 296.11 MBOE (million barrels of oil equivalent) or 16.28% of the total primary energy mix (Ministry of Energy and Mineral Resources of Republic of Indonesia, 2024).

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)

Intensive production and large consumption of fossil energy resources obviously impact on environment. Potential impacts on environment that occurred are challenges that need to be countermeassured. This is in line with the Government policy and commitment to shift has dependency on non-renewable energy. The usage of more renewable energy is also option to prevent environmental impacts.

Previous studies revealed various environmental issues related to the use of fossil (non-renewable) energy. The issues embrace global warming and climate change due to greenhouse gas emissions produced during the extraction, production, transportation, and burning of fossil energy. Activities in producing fossil energy clearly show the contribution of increasing global temperatures and extreme changes in weather patterns. Apart from that, fossil energy consumption is also associated with air pollution which damages air quality and human health, as well as habitat damage and biodiversity loss resulting from extraction and production infrastructure. There are in-depth evidences of the negative impacts of fossil energy consumption on the environment and society. This highlighted the importance of accelerating the transition to cleaner, more sustainable energy sources (Masson-Delmotte et al., 2019).

In the sector of oil and gas, the efforts to move from non-renewable to renewable energy has become the main focus in order to reduce the environmental impacts of the use of fossil energy. Another focus studied is the latest initiatives and technologies used in integrating renewable energy in oil and gas sector. For example, Huang (2023) discussed a comprehensive review of the application of floating solar panels on waters to produce electrical energy that can be used in drilling operations and offshore oil production. The results of the study show that there is a great potential in utilizing solar energy as an environmentally friendly energy source in the oil and gas industry. Furthermore, Wu et al., (2022) reviewed the use of new thermochemical energy systems driven by solar energy and biomass for the production of natural gas and electricity. The application of this new system shows potential energy savings and reduced natural gas production. This shows the important role of renewable energy technologies, such as biomass and solar energy, in reducing the carbon footprint of the oil and gas industry.

Environmental problems in this sector are an issue that is currently receiving serious attention. Significant problem raised is environmental pollution due to oil spills, which can cause damage to marine and coastal ecosystems. (Singh et al., 2020) brings out the negative impact of oil spills on biodiversity and ecosystem balance in waters around oil and gas drilling facilities. Greenhouse gas emissions from oil and gas sector activities are a major concern because of their contribution to climate change and air quality. Another study underlined that the oil and gas sector in Indonesia is one of the causes in country's global warming (Desrina, 2014). The oil and gas industry in Indonesia contributes significant greenhouse gases, pointing the need for more effective mitigation measures. Waste management is also a challenge, especially in terms of disposal of liquid waste, flue gas, and B3 waste from oil and gas installations. Another review of waste management practices in Qatar's oil and gas industry focused on characterization and processing technologies, challenges, and possible emerging opportunities. This recent research also discusses the potential for reuse (*reuse*) of the three types of waste (Shahbaz et al., 2023). Research of the environmental impact of natural gas production in South Kalimantan Province established the impact that came from an increase in natural gas consumption as an effect of decreasing pressure and an increase in the ratio of water to hydrocarbons during this time. Therefore, environmental problems in the oil and gas sector require a holistic approach involving various parties to achieve sustainable development (Muhamad et al., 2022).

Kepodang natural gas field is classified in the group of upstream industry. The location of the Kepodang field can be seen in Figure 1. There are 6 (six) active wells and the distance to the central processing platform (CPP) is 2.8 km. The total production in the year 2022 reached 5.909,77 MMSCF or 6.409.721.273 MJ. The product is transported from CPP, 200 km away to support the downstream industry as fuels at Tambak Lorok in Central Java Province.

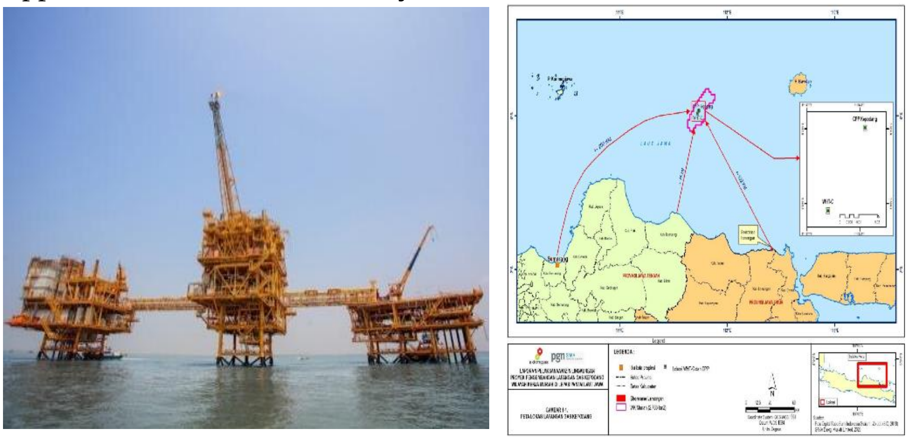


Figure 1. Natural gas production in Kepodang field, East Java

Source: SEML, 2022

This research aimed at the assessment of potential environmental impacts as the result of the production of natural gas in Kepodang field, East Java; and hotspot analysis to find out the significant issues in the entire life cycle of the product within the boundary system defined. The results of the hotspots analysis become the basis for the recommendation formulation. The recommendations will be addressed carried out by the oil company as the continuous improvement program. Standards and guidance referred include ISO 14040:2016 (Principle and Framework) and ISO 14044:2017 (Guideline); Product Category Rules (PCR) of Crude Petroleum and Natural Gas Version 1.0 2023-06-19 and Ministerial Regulation of Environment and Forestry of the Republic of Indonesia No. 1 of 2021 of Public Disclosure Program for Environmental Compliance (PROPER).

RESEARCH METHODS

This study employed the methods of life cycle assessment (LCA) European Union, (2010) which comply with international standards (these have been adopted to be Indonesian national standards). The standards include ISO 14040:2016 (Principle and Framework) and ISO 14044:2017 (Guideline). The implementation of this research also follows Product Category Rules (PCR) of Crude Petroleum and Natural Gas Version 1.0 2023-06-19; and Ministerial Regulation of Environment and Forestry of the Republic of Indonesia No. 1 of 2021 of Public Disclosure Program for Environmental Compliance (PROPER). The last guidance is referred particularly for the selection of impact categories.

The implementation of the research follows LCA frameworks that wraps 4 (four phases) as follows:

(1) defining goal and scope; (2) life cycle inventory; (3) live cycle impact assessment; (4) interpretation. Please see Figure 2.

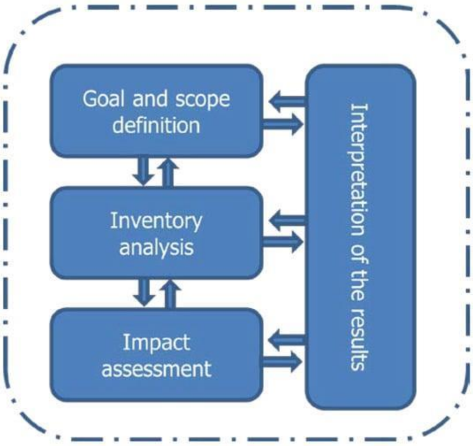


Figure 2. LCA Framework

Source: (SNI ISO 14040:2016, n.d.)

As previously described, the goal of this study is mainly to assess potential environmental impacts that are affiliated with the production of natural gas in the Kepodang field; and to analyze significant issues of find hotspots for necessary continual improvements.

The following is the detailed scope of the study:

1. The declaration unit is 1 MJ natural gas in the gas metering of customers in Tambak Lorok Central Java. Elementary flows are based on the intensity production of the Kepodang natural gas field in 2022 which total amounted to 5.909,77 MMSCF or 6.409.721.273 MJ.
2. The system boundary follows the mentioned PCR for crude oil and natural gas. The product system includes the phases of upstream (drilling and well operations); core in central processing platform - CPP (manifold, separator, fuel gas system, suction scrubber, gas dehydration system, export scrubber, Knock Out (KO) Drum, drain caisson, flare gas, gas turbine generator, gas metering and chromatograph, utilities: gas turbine compressor, accommodation vessel); and downstream gas metering (piping/ transportation of the product to Tambak Lorok). In other words, the scope of the study is cradle-to-grave. Regarding system boundaries defined, the cradle-to-grave approach is widely preferred, particularly when evaluating the use of natural gas products in electricity generation Caglayan (2022) or transportation (Khan et al., 2019). Figure 3 shows the flow process of the product and the clear system boundary of the study.
3. There are 12 impact categories assessed and the obligated methods of LCIA as required in the PCR, including 4 main impact categories stipulated in Ministerial Regulation. The more

detail impact categories and related methods applied will be described in section 3.1 Life Cycle Impact Assessment Result.

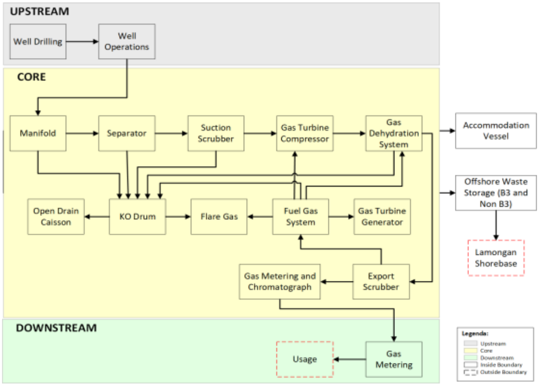


Figure 3. System boundary of the study

4. Assumptions are set as follow:
   a. Transportation of supporting materials and fuels from Lamongan ShoreBased (LSB) to upstream and core is the Royal King Ali ships with a traveled distance of 122 km.
   b. Transportation of hazardous and non-hazardous waste from Upstream and Core (CPP) to Lamongan ShoreBased (LSB) is the Royal King Ali ships with a traveled distance of 122 km.
   c. Emissions from the transportation of supporting materials, fuels, and travel of operators/personnel used database Ecoinvent after the calculation of distance traveled multiplied by the load of the material carried in the specification/type of vehicle (ton. km).
   d. Chemical supporting materials without MSDS information used similar ingredients/compositions with similar functions and created a "dummy" if there still unavailable. Dummies include Baracor 100, oxygon, DIGALITE 4200, A-02 (activator), HEC.
   e. There is no loss of natural gas from the transmitted pipe process in the distance traveled from CPP to Tambak Lorok.
   f. Accommodation vessel activities (positioned in the Kepodang field throughout the year 2022) include personnel transportation from/ to well operations (WHT-C, WHM-A), and CPP, water maker (domestic purpose), electricity supply.
   g. Emissions of drilling proses use the SimaPro database.
   h. Gas turbine generator for electricity supply in CPP is distributed in equal amounts to the manifold, separator, suction scrubber, export scrubber, gas metering & chromatograph, KO drum, open drain caisson, flare gas, and utility.

5. Data Inventory analysis

According to SNI ISO 14040:2016, data inventory covers inputs, outputs, and emissions within the system boundary and refers to the defined goal and scope. In this case, all data from the resource extraction (drilling) in the upstream up to the product in the downstream (metering at Tambak Lorok) such as main and supporting materials, chemical materials, energy, water, fuels, the product, emission to air/water/soil, and waste (hazardous and non-hazardous) are collected. The data inventory is analyzed in the declaration unit, per 1 MJ natural gas produced. The total production of the Kepodang natural gas field in 2022 amounted to 5.909,77 MMSCF or 6.409.721.273 MJ. The data inventory of the study is presented in Annex 1.

The sources of data collection are primary/specific data (estimation, calculation, and interview) and secondary/generic data (Ecoinvent, SimaPro, and literature). The results of the data source analysis can be seen in Table 2. In the upstream, the study found 59% as primary data and the rest 41% as secondary. In the core processes, there was 91% of the data collected of which 82,4% is primary/specific data and the remaining 17.6% is secondary/generic data. 67% of the primary data is from direct measurement and 24% of the primary data is from estimation/calculation. The rest, 9%, is classified as cut-off criteria. In the downstream, the study found 33% as primary data and the rest 67% as secondary.

Table 2. Summary of life cycle data source of the study

Items/ Phase	Primary	Secondary
Upstream	59%	41%
Core	82,4%	17,6%
Downstream	33%	67%

Source: Research, 2023

This research used SimaPro LCA Version 9.1.0.8 for data inventory processing and the calculation of environmental impact (classification and characterization). The summary of the life cycle data inventory is presented in phases of upstream, core, and downstream in Table 3.

Table 3. Summary of life cycle data inventory

Category of material	Component	Unit	Amount	Per declaration unit (1MJ)
Material	Raw Material from Other Processes	MJ	61.337.009.917	8,55E+00
	Raw Material	kg	21.894	3,42E-06
	Solid Support Materials	kg	47.684.334	7,44E-03
	Fluid Support Materials	kg	99.056,03	1,55E-05
	Other Supporting Materials	kg	37.149,30	5,80E-06
Water	Produced Water	L	18.284,72	2,85E-06
Energy	Electricity	kWh	18.909.494	2,95E-03
Fuel	Liquid Fuel	MJ	77.712.355	1,21E-02
Product	Natural Gas	MJ	61.207.443.910	9,55E+00
Non-Hazardous Waste	Non -Hazardous Waste	kg	8480	1,32E-06
Hazardous Waste	Solid Hazardous Waste	kg	4.324	6,75E-07
	Liquid Hazardous Waste	kg	10.526	1,74E-06
Air Emissions	Nox	kg	3.071,72	4,79E-07
	SO2	kg	897,90	1,40E-07
	PM	kg	563,32	8,79E-08
	CO	kg	717,27	1,12E-07
	NMVOC	kg	7,77	1,21E-09
	NO2	kg	200,42	3,13E-08

For more detailed data inventory can be found in Annex1.

RESULT AND DISCUSSION

LCIA Results

As required in the PCR of Crude Petroleum and Natural Gas Version 1.0 2023-06-19 International EPD System, (2023), potential impact categories should include the following: global warming potential (GWP), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP) including marine (ME)/ freshwater (FE), photochemical Oxidation (POD), abiotic depletion potential (ADP) including non-fuel (ADP NF) and fuel (ADP F), biotic depletion potential/ ecotoxicity (BDP) including marine ecotoxicity (MAETP), freshwater ecotoxicity (FAETP) and terrestrial ecotoxicity (TETP), human carcinogenic/non-carcinogenic toxicity potential (HTPC)/(TNC), water scarcity footprint (WSF), cumulative energy demand (CED) and renewable energy demand (RED). Land use change was excluded in this study as the location of the production is on the offshore area in the Java Sea). Whereas, the Ministerial Regulation No 1/2021 concerns 4 (four) main impact categories: GWP, AP, EP, and ODP. The methods for assessing the life cycle impact follow the requirement in the PCR can be seen in Table 3.

The assessment of the environmental impact of producing 1 MJ natural gas at the metering in Tambak Lorok for the mentioned 12 (twelve) categories is done in SimaPro (PRé Sustainability, n.d.). The steps of assessment include classification, characterization, and weighting run in this software.

The results of life cycle impact assessment (characterization) show that GWP 70,02 kg CO_2 eq; OPD 0,000001 kg CFC-11 eq, AP 0.65 mol H+ eq; ME 0,30 kg N eq; FE 0,002172 kg P eq; POD 0,97 kg NMVOC eq; ADP NF 0,000025 kg Sb eq; ADP F 916,53 MJ; MAETP 0,52 kg 1,4- dichlorobenzene (DB) eq; FAETP 0,33 kg 1,4- dichlorobenzene (DB) eq; TETP 78.59 kg 1.4- dichlorobenzene (DB) eq; HTPC 2,67 kg 1,4- dichlorobenzene (DB) eq; TNC 7,17 kg 1,4- dichlorobenzene (DB) eq; WSF 2,02 m^3; CED 916,54 MJ; dan RED 5,25 MJ. The impact of cradle-gate-to-grave can be seen presented in Table 4:

Table 4. Life cycle impact assessment (characterization) of Kepodang Natural Gas Per 1 MJ

No	Potential impact category	Methods of LCIA	Per MJ			Total (Cradle to Grave) 2022
			Cradle	Gate	Grave	
1	GWP kg CO_2 eq	EN 15804[1)]	9,78E-04	7,00E+01	6,21E-02	**70,02**
2	ODP kg CFC-11 eq	EN 15804[1)]	2,00E-11	1,11E-06	1,16E-09	**0,000001**
3	AP mol H+ eq	EN 15804[1)]	1,08E-05	6,48E-01	3,01E-04	**0,65**
4	**EP**					
	ME kg N eq	EN 15804[1)]	2,97E-06	3,00E-01	8,99E-05	**0,30**
	FE kg P eq		2,22E-07	2,15E-03	2,42E-05	**0,002172**
5	POD kg NMVOC eq	EN 15804[1)]	9,96E-06	9,67 E-01	3,66E-04	**0,97**
6	**ADP**					

No	Potential impact category	Methods of LCIA	Per MJ			Total (Cradle to Grave) 2022
			Cradle	Gate	Grave	
	ADP NF kg Sb eq	EN 15804[1)]	5,80E-08	2,45E-05	2,79E-07	**0,000025**
	ADP F MJ		1,70E-02	9,16E+02	6,57E-01	**916,53**
7	**BDP**					
	MAETP kg 1,4 – dichlorobenzene (DB) eq	ReCiPe 2016 (midpoint H) [2)]	1,15E-04	5,09E-01	6,84E-03	**0,52**
	FAETP kg 1,4 – dichlorobenzene (DB) eq		8,77E-05	3,24E-01	3,78E-03	**0,33**
	TETP kg 1,4 – dichlorobenzene (DB) eq		8,56E-03	7,84E+01	1,93E-01	**78,59**
8	HTPC kg 1,4 – dichlorobenzene (DB) eq	ReCiPe 2016 (midpoint H) [2)]	7,87E-05	2,63E+00	4,08E-02	**2,67**
	TNC kg 1,4 – dichlorobenzene (DB) eq	ReCiPe 2016 (midpoint H) [2)]	2,18E-03	7,11E+00	5,14E-02	**7,17**
10	WSF m^3	EN 15804[1)]	7,28E-03	1,98 E+00	3,18 E-02	**2,02**
1	CED MJ	Single issue method CED Lower Heating Values (LHV) [3)]	1,70E-02	9,16E+02	6,58E-01	**916,54**
2	RED MJ	Single issue method CED Lower Heating Values (LHV) [3)]	6,89E-04	5,21E+00	3,80E-02	**5,25**

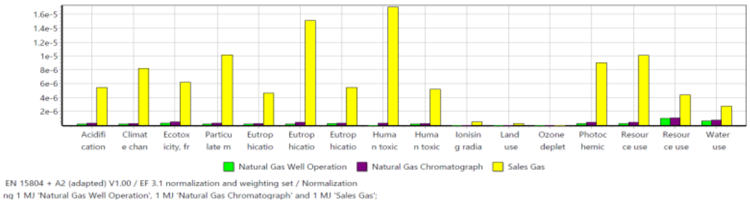
Note:
[1)] EN 15804 Method (European Platform on LCA, n.d.)
[2)] Recipe 2016 Midpoint H Method.
[3)] Lower Heating Values (LHV) Method.

ReCiPe 2016 Midpoint H method is the approach integrates both midpoint and endpoint techniques, facilitating simpler interpretation and comparison across systems (Herrando et al., 2022). Nonetheless, variations in results between the midpoint and endpoint methods may exist (Dong & Ng, 2014). Furthermore the LHV method, Study by Frischknecht (2015) presented that the 'CED standard' method and the resulting impact category indicators it computes primarily address the safeguard theme of 'energy resources' and do not encompass other environmental impacts. Accommodation vessel operates personnel transportation in the Kepodang natural gas field (CPP-Well Head Platform).

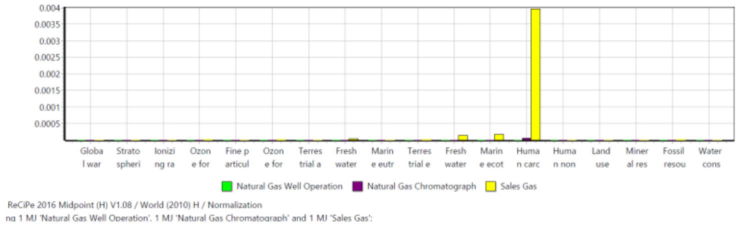
Discussions

This section discusses the result of the data inventory analysis and life cycle impact assessment. Significant issues throughout the product life cycle can be recognized in the previous Table 3. Hotspots are possibly in the form of phase, unit process, and substance which contribute at least 85% to the environmental impact (*Pareto rule*). The Pareto Principle suggests that a significant majority, typically 80%, of outcomes or consequences arise from a minority, around 20%, of inputs or causes (Dunford et al., 2014).

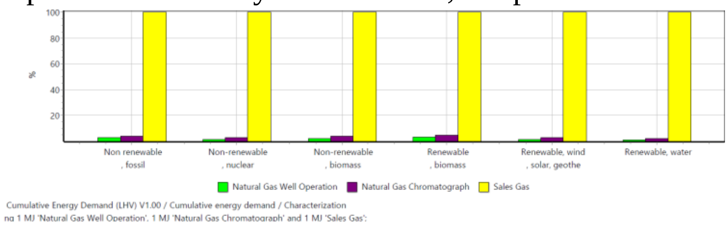
In the whole phases of product's life cycle, the most contributor to the environmental impact of the Kepodang natural gas fields is in the downstream phase, particularly the unit process of gas metering in the user/consumer (Tambak Lorok). Figures 4a, b, and c illustrate the 12 impact categories as the results of 1 MJ natural gas production throughout the product's life cycle.



4a. Impact assessment by EN 15804 method



4b. Impact assessment by ReCiPe 2016, midpoint H method



4c. Impact assessment by Single issue method CED LHV)

Figure 4. Normalization of impact assessment for 12 impact categories in upstream, core, and downstream of 1 MJ Kepodang natural gas.

The impact in downstream phase (indicated in yellow color) is the highest compared to upstream and core phases for 12 impact categories. This is due to 200 km of piping for the product transportation from the Central Processing Platform (CPP) to the user gate (Tambak Lorok, East Java). The pipe's parameter (*Ecoinvent database*) is referred to *long-distance pipe with high capacity.*

In this unit process, the use of chromium contributes 99,41% to the category impact of HTPC. HTPC is described as the potential impact on human health due to toxic materials in the form of phenol, mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), vanadium (V), and zinc (Zn). Whereas the substance of phosphate contributes 92,60% to EP FE. EP FE impact is an impact on aquatic ecosystems which is influenced by macronutrients in the form of nitrogen, phosphate, and parameters *Chemical Oxygen Demand* (COD). According to (Patterson et al., 2020), It's crucial to gain a deeper understanding of the human and ecological toxicity of OCOCs (oxygenated polycyclic aromatic hydrocarbons) resulting from petroleum biodegradation. This understanding is essential for effectively managing sites where fuel has been released, enabling informed decisions based on risk assessment.

Table 5 presents hotspot analysis and the results of which the 85% contributors are highlighted by orange color. The discussion focused on the 3 (three) hotspots of unit processes including gas metering, gas turbine generator, and flare gas. The study by (Mokhatab et al., 2018), indicated that the environmental effects stemming from natural gas production activities can be categorized into impacts on the air, primarily from combustion during flaring, methane (CH_4) emissions, and the consequences of electricity generation. Additionally, there are impacts on water bodies caused by the disposal of produced water and other wastewater.

Table 5. Hotspot analysis and result

No	Unit Proses	GWP	ODP	AP	EP ME	EP FE	POD	ADP NF	ADP F	MAETP	FAETP	TETP	HTPC	TNC	WSF	CED	RED
		kg CO_2 *eq*	kg CFC-11 *eq*	mol H+ *eq*	kg N *eq*	kg P *eq*	kg NMVOC *eq*	kg Sb *eq*	MJ	kg 1,4 – dichlorobenzene (DB) eq					m³	MJ	
1	Well Drilling	9,77E-04	1,99E-11	1,09E-05	2,93E-06	2,29E-07	9,96E-06	6,06E-08	1,71E-02	1,20E-04	9,14E-05	8,91E-03	8,06E-05	2,27E-03	7,59E-03	1,71E-02	6,85E-04
	Persentase	1,050%	1,119%	1,823%	1,668%	0,684%	1,534%	4,378%	1,534%	1,156%	1,480%	2,287%	0,159%	2,230%	4,356%	1,534%	1,143%
2	Well Operations	9,78E-04	2,00E-11	1,08E-05	2,97E-06	2,22E-07	9,96E-06	5,80E-08	1,70E-02	1,15E-04	8,77E-05	8,56E-03	7,87E-05	2,18E-03	7,28E-03	1,70E-02	6,89E-04
	Persentase	1,051%	1,125%	1,801%	1,693%	0,662%	1,535%	4,191%	1,527%	1,109%	1,421%	2,198%	0,155%	2,138%	4,179%	1,527%	1,150%
3	Manifold	1,77E-03	3,47E-11	1,46E-05	4,10E-06	5,33E-07	1,46E-05	6,09E-08	2,53E-02	2,02E-04	1,36E-04	1,10E-02	6,06E-04	2,82E-03	7,60E-03	2,53E-02	1,17E-03
	Persentase	1,902%	1,957%	2,429%	2,336%	1,589%	2,247%	4,40%	2,273%	1,949%	2,195%	2,813%	1,193%	2,764%	4,364%	2,273%	1,957%
4	Seperator	1,77E-03	3,48E-11	1,46E-05	4,11E-06	5,34E-07	1,46E-05	6,10E-08	2,53E-02	2,02E-04	1,36E-04	1,10E-02	6,07E-04	2,82E-03	7,61E-03	2,53E-02	1,17E-03
	Persentase	1,904%	1,960%	2,433%	2,341%	1,591%	2,250%	4,406%	2,276%	1,952%	2,198%	2,817%	1,195%	2,768%	4,370%	2,276%	1,960%
5	Suction Scrubber	1,77E-03	3,48E-11	1,46E-05	4,11E-06	5,34E-07	1,46E-05	6,11E-08	2,54E-02	2,03E-04	1,36E-04	1,10E-02	6,08E-04	2,82E-03	7,62E-03	2,54E-02	1,18E-03
	Persentase	1,907%	1,963%	2,438%	2,345%	1,594%	2,254%	4,412%	2,279%	1,955%	2,201%	2,821%	1,197%	2,772%	4,376%	2,279%	1,963%
6	Gas Turbine Compressor	1,87E-03	3,68E-11	1,57E-05	4,43E-06	5,65E-07	1,56E-05	6,45E-08	2,68E-02	2,14E-04	1,44E-04	1,16E-02	6,41E-04	2,98E-03	8,06E-03	2,68E-02	1,25E-03
	Persentase	2,014%	2,074%	2,615%	2,525%	1,684%	2,411%	4,657%	2,408%	2,064%	2,324%	2,979%	1,263%	2,927%	4,626%	2,408%	2,079%
7	Gas Dehydration System	1,88E-03	3,69E-11	1,57E-05	4,43E-06	5,65E-07	1,57E-05	6,45E-08	2,68E-02	2,14E-04	1,44E-04	1,16E-02	6,41E-04	2,98E-03	8,06E-03	2,69E-02	1,25E-03
	Persentase	2,015%	2,078%	2,616%	2,526%	1,685%	2,413%	4,658%	2,412%	2,064%	2,325%	2,980%	1,263%	2,928%	4,626%	2,412%	2,081%
8	Export Scruber	1,88E-03	3,69E-11	1,57E-05	4,44E-06	5,66E-07	1,57E-05	6,46E-08	2,69E-02	2,14E-04	1,44E-04	1,16E-02	6,42E-04	2,99E-03	8,07E-03	2,69E-02	1,25E-03
	Persentase	2,018%	2,081%	2,621%	2,530%	1,687%	2,417%	4,664%	2,415%	2,067%	2,328%	2,983%	1,265%	2,932%	4,633%	2,415%	2,084%
9	Gas Metering & Chromatograph	1,88E-03	3,70E-11	1,58E-05	4,45E-06	5,67E-07	1,57E-05	6,46E-08	2,69E-02	2,15E-04	1,44E-04	1,16E-02	6,43E-04	2,99E-03	8,08E-03	2,69E-02	1,25E-03
	Persentase	2,021%	2,084%	2,626%	2,535%	1,690%	2,421%	4,670%	2,418%	2,070%	2,331%	2,988%	1,267%	2,936%	4,640%	2,418%	2,087%
10	Fuel Gas System	1,91E-03	3,76E-11	1,60E-05	4,52E-06	5,76E-07	1,60E-05	6,57E-08	2,74E-02	2,18E-04	1,46E-04	1,18E-02	6,54E-04	3,04E-03	8,21E-03	2,74E-02	1,27E-03
	Persentase	2,054%	2,118%	2,668%	2,575%	1,717%	2,460%	4,747%	2,458%	2,104%	2,369%	3,036%	1,287%	2,984%	4,715%	2,458%	2,123%
11	Gas Turbine Generator	7,13E-03	1,42E-10	7,85E-05	2,29E-05	2,21E-06	7,09E-05	2,39E-07	1,06E-01	8,05E-04	5,45E-04	4,37E-02	2,37E-03	1,13E-02	3,22E-02	1,06E-01	5,43E-03
	Persentase	7,660%	8,029%	13,093%	13,084%	6,599%	10,929%	17,267%	9,480%	7,769%	8,826%	11,222%	4,675%	11,089%	18,476%	9,480%	9,069%
12	Flare Gas	3,81E-03	7,58E-11	3,90E-05	1,13E-05	1,17E-06	3,61E-05	1,29E-07	5,59E-02	4,32E-04	2,92E-04	2,34E-02	1,28E-03	6,05E-03	1,70E-02	5,59E-02	2,79E-03
	Persentase	4,097%	4,273%	6,497%	6,438%	3,498%	5,563%	9,305%	5,020%	4,167%	4,722%	6,018%	2,520%	5,937%	9,738%	5,020%	4,665%
13	KO Drum	3,33E-03	6,66E-11	3,67E-05	1,07E-05	1,03E-06	3,32E-05	1,12E-07	4,93E-02	3,76E-04	2,55E-04	2,04E-02	1,11E-03	5,28E-03	1,50E-02	4,93E-02	2,54E-03
	Persentase	3,581%	3,753%	6,120%	6,116%	3,085%	5,109%	8,071%	4,431%	3,632%	4,126%	5,246%	2,185%	5,184%	8,637%	4,431%	4,239%
14	Gas Metering	6,21E-02	1,16E-09	3,01E-04	8,99E-05	2,42E-05	3,66E-04	2,79E-07	6,57E-01	6,84E-03	3,78E-03	1,93E-01	4,08E-02	5,14E-02	3,18E-02	6,58E-01	3,80E-02
	Persentase	66,724%	65,385%	50,221%	51,286%	72,235%	56,458%	20,172%	59,069%	65,943%	61,154%	49,612%	80,376%	50,408%	18,265%	59,070%	63,400%

Source: hotspot analysis and result, 2023

The 4 (four) mandatory impact categories required in the Ministerial Regulation (Ministrial Regulation of Environment and Forestry Republic of Indonesia, 2021) are GWP, AP, EP, and ODP can be elaborated as follows:

1. The contributions to the Global Warming Potential include the unit processes of flare gas, gas turbine generator, KO drum, and gas metering. The substance of carbon dioxide contribution amounted 89%.
2. The impact category of Acidification Potential has the highest contributors from flare gas, gas turbine generator, KO drum, fuel gas system, gas metering and chromatograph, and gas metering. The substances of nitrogen oxide and sulfur dioxide contributions are 50% and 43% respectively.
3. Eutrophication Potential has the highest contributors from flare gas, gas turbine generator, KO drum, fuel gas system, gas metering and chromatograph, and gas metering. The majority (91%) contributor is nitrogen.

4. The contributions to Ozone Layer Depletion Potential include the unit processes of flare gas, gas turbine generator, KO drum, and gas metering. The substance of methane amounted 85% (Sriwahyuni, 2023).

Besides, the consumption of barium contributes 79,51% to the Abiotic Depletion Potential non-fossil in well operation. ADP NF is defined as non-fossil fuel abiotic decline, which is the depletion or reduction in the amount of non-renewable natural resources in nature which is measured based on the amount of energy extracted. This liquid chemical supporting material also becomes a significant substance in contributing the same category impact in Gas Turbine Generator.

In the implementation of this study, missing data existed. According to the Standards of LCA, missing data within the scope boundary should be set up and described clearly. The treatment done for this missing data is as follows:

1. Emission from upstream processes uses the SimaPro database
2. The cut-off for the amount of supporting materials consumed is smaller than 1% (resided glycol liquid, produced water, sand).
3. Supporting material grease & sealant, and waste domestic in accommodation vessels are categorized as limitations.

In conducting the research some limitations were found that can be explained below:

1. There are missing supporting materials: grease & sealant in the unit process of work over-well operations.
2. Transportation of all supporting materials, fuels, and waste (hazardous and non-hazardous) is carried to the Royal King Ali ships with a traveled distance of 122 km from Lamongan Shorebased (LSB) to upstream and core.
3. Due to the small amount of materials (<1%), the cut-off was applied for reside glycol liquid (at export scrubber), produced water (at the manifold, fuel gas system, suction scrubber, and gas dehydration system), and sand (separator).

Accommodation vessel is used for personnel vehicles in offshore.

CONCLUSION

This research has been conducted following the defined objectives and scope (cradle to grave) for natural gas products produced with a declaration unit of 1 MJ natural gas at Tambak Lorok Gas Metering. The study objectives to assess the impact assessment for 1 MJ of natural gas in the user's metering as follow: GWP 70.02 kg CO_2 eq; OPD 0.000001 kg CFC-11 eq; AP 0.65 mol H+ eq; ME 0.30 kg N eq; FE 0.002172 kg P eq; POD 0.97 kg NMVOC eq; ADP NF 0.000025 kg Sb eq; ADP F 916.53 MJ; MAETP 0.52 kg 1,4- dichlorobenzene (DB) eq; FAETP 0.33 kg 1,4- dichlorobenzene (DB) eq; TETP 78.59 kg 1,4- dichlorobenzene (DB) eq; HTPC 2.67 kg 1,4- dichlorobenzene (DB) eq; TNC 7.17 kg 1,4- dichlorobenzene (DB) eq; WSF 2.02 m^3; CED 916.54 MJ; and RED 5.25 MJ. Hotspot analysis highlighted that the most contributing unit process is Gas metering due to the piping transportation 200km distance traveled from CPP to Tambak Lorok. Other hospots also found in gas metering chromatograph, gas turbine generator, and flare gas.

The contributions to the Global Warming Potential include the unit processes of flare gas, gas turbine generator, KO drum, and gas metering. The cause of the substance is carbon dioxide by 89%. The impact category of Acidification Potential has the highest contributors from flare gas, gas turbine generator, KO drum, fuel gas system, gas metering and chromatograph, and gas metering. The cause of the substance is nitrogen oxide at 50% d The substantial causes are nitrogen oxide at 50% and sulfur dioxide at 43%. Eutrophication Potential has the highest contributors from flare gas, gas turbine generator, KO drum, fuel gas system, gas metering and chromatograph, and gas metering. The cause of the substance is nitrogen at 91%. The contributions to Ozone Layer Depletion Potential include the unit processes of flare gas, gas turbine generator, KO drum, and gas metering. The cause of the substance is methane 85%. The challenge faced in the research implementation was data availability which has been described in the limitation. Therefore, a strong recommendation is highlighted for the company as this is also a part of the study goal in supporting the national LCA big database.

The results of this research show the environmental impacts resulting from natural gas production and significant issues (hotspots) that require efforts to improve better environmental performance. Recommendations can be addressed is the improvement of data and documentations quality, for example Material Safety Data Sheet (MSDS) information, tools information.

BIBLIOGRAPHY

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.

Desrina, R. (2014). Pemanasan Global Akibat Kegiatan di Sektor Minyak dan Gas Bumi. *Lembaran Publikasi Minyak Dan Gas Bumi*, *48*(2), 63–72.

Dong, Y. H., & Ng, S. T. (2014). Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong. *The International Journal of Life Cycle Assessment*, *19*, 1409–1423.

Dunford, R., Su, Q., Tamang, E., & Wintour, A. (2014). The pareto principle. *The Plymouth Student Scientist*, *7*(2), 140–148.

Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., & Balouktsi, M. (2015). Cumulative energy demand in LCA: the energy harvested approach. *The International Journal of Life Cycle Assessment*, *20*, 957–969.

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*, 115402.

Huang, G., Tang, Y., Chen, X., Chen, M., & Jiang, Y. (2023). A comprehensive review of floating solar plants and potentials for offshore applications. *Journal of Marine Science and Engineering*, *11*(11), 2064.

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.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., & Pidcock, R. (2019). Global warming of 1.5 C. *An IPCC Special Report on the Impacts of Global Warming Of*, *1*, 93–174.

Mokhatab, S., Poe, W. A., & Mak, J. Y. (2018). *Handbook of natural gas transmission and processing: principles and practices*. Gulf professional publishing.

Muhamad, R., Sari, H. H., & Ellyna, C. (2022). Life cycle assessment of natural gas production in Indonesia. *Journal of Sustainability Science and Management*, *17*(2), 136–157.

Patterson, T. J., Kristofco, L., Tiwary, A. K., Magaw, R. I., Zemo, D. A., O'Reilly, K. T., Mohler, R. E., Ahn, S., Sihota, N., & Devine, C. E. (2020). Human and aquatic toxicity potential of petroleum biodegradation metabolite mixtures in groundwater from fuel release sites. *Environmental Toxicology and Chemistry*, *39*(8), 1634–1645.

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.

Singh, H., Bhardwaj, N., Arya, S. K., & Khatri, M. (2020). Environmental impacts of oil spills and their remediation by magnetic nanomaterials. *Environmental Nanotechnology,*

Monitoring & Management, *14*, 100305.
Sriwahyuni, S. (2023). The Process of Reforming of Environmental Aspect with The Sustainable Management for Indonesia's Environmental Law. *Eduvest–Journal of Universal Studies*, *3*(3).