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LIFE CYCLE ASSESSMENT OF NATURAL GAS PRODUCTION IN INDONESIA

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Abstract: Indonesia is a country with a population of 270 million as of 2020, which thus requires a substantial amount of energy to support growth and development. Over the last 5 years from 2012 to 2017, natural gas production averaged 2.9 trillion standard cubic feet (Tscf) making natural gas the third primary source of energy used in Indonesia after oil and coal. With its significant use as an energy source in Indonesia, natural gas has significant impacts on the environment, such as global warming potential (GWP) during its lifetime. Thus, the study aims to evaluate the potential environmental impact per 1 MMscf of natural gas produced using the life cycle assessment method based on ISO 14040/14044 standards and investigate the most contributed impact categories and unit process to the overall impact using Principal Component Analysis (PCA). The target of the study is an offshore natural gas production site located on Makassar Strait, South Kalimantan Province, Indonesia. On the basis of the 2019 research data, the results of impact assessment are as follows: Abiotic Resource Depletion (ARD): 1.1 E+06 MJ/MMscf, Acidification Potential (AP): 1.1 E+00 kg SO_2 eq./MMscf, Eutrophication Potential (EP): 2.5 E−01 kg PO_4^{3-} eq./MMscf, Fresh Water Ecotoxicity Potential (FAETP): 8.0 E−05 kg 1,4-DCB eq./MMscf, Global Warming Potential (GWP): 1.1 E+03 kg CO^2 eq./MMscf, Human Toxicity (HT): 3.5 E+00 kg 1,4-DCB eq./MMscf, Marine Aquatic Ecotoxicity Potential (MAETP): 3.8 E+03 kg 1,4-DCB eq./MMscf, Photochemical Oxidant Potential (POP): 6.0 E−02 kg ethylene eq./MMscf and Terrestrial Ecotoxicity Potential (TETP): 9.0 E−02 kg 1,4-DCB eq./MMscf. After normalisation and PCA, most contributed impact categories are grouped with the first group of AP, EP, GWP, POP and HT which are associated with gas compressor unit and the second one is FAETP, MAETP, TETP, and also HT which are associated with produced water treatment unit.

Keywords: Sustainability, life cycle assessment, natural gas, Indonesia.

Introduction

Energy is one of main inputs that support the growth and development of a country. Therefore, Indonesia is no exception as a country with its population of 270 million as of 2020, which requires a massive amount of energy. According to data from the Ministry of Energy and Mineral Resources (2018a) of the Republic of Indonesia, energy consumption per capita is approximately 3.54 barrels of oil equivalent per year. Thus, the total energy consumption is approximately 955.8 million barrels of oil equivalent per year. To address the demand for energy and support the energy security policy, obtaining energy supply from various sources, such as fossil fuel, and renewable energy is necessary.

Moreover, data describe that energy supply is derived from oil (41.73%), coal (30.48%) and natural gas (23.37%). The remainder is sourced from renewable energy (hydropower: 2.89%, geothermal: 1.37% and biofuel: 0.165%) (Ministry of Energy and Resources, 2018a). Changes in such a composition are being planned. In the future, supply will be optimised from the renewable sector by approximately 23% and 31% in 2025 and 2050, respectively. The next potential source will be natural gas at a minimum of 22% and 24% in 2025 and 2050, respectively (Presidential Regulation, 2017). The figures demonstrate that the country's natural gas usage will undergo long-term optimisation for approximately the next 30 years.

Over the last 5 years (2012–2017), the average natural gas production reached 2.9 Tscf per year. In 2017, natural gas production levelled at approximately 7.619 MMscf per day (Ministry of Energy and Resources, 2018b). With the large amount of production and long-term plan for natural gas utilisation in Indonesia, examining the sustainability of natural gas from the environmental perspective is deemed important.

Natural gas is produced by enabling its source in subsurface reservoirs to flow to the surface into a receiving facility through drilling. When a natural gas resource is successfully discovered, a drilling well is called a production well. Prior to distribution to consumers, the gas should be further processed and conditioned. The goal of the process is to separate natural gas from other forms of hydrocarbon and impurities, such as hydrocarbon condensate, uncondensed gas, sour gas and water. Moreover, for the process conditions the gas need to be ready for purchase or disposal (Mokhatab *et al.*, 2006). Figure 1 presents the flow of natural gas processing.

The environmental impacts of activities related to natural gas production can be grouped into impacts to the air due to flaring combustion activities, release of methane gas (CH_4), outcome of combustion of electricity-generating activities and impact on water bodies due to the disposal of produced water and other wastewater (Mokhatab *et al.*, 2018).

In terms of impact to water bodies, produced water from oil and gas fields constitute the highest volume of liquid discharged during the production stage (International Association of Oil & Gas Producers [IOGP], 2020). Produced water carries many potential constituents that pollute water bodies, such as dissolved and dispersed oil, dissolved formation mineral, heavy metals, naturally occurring radioactive materials and production chemical components (Hedar & Budiyono, 2018). Table 1 lists the range of constituents and characteristics of produced water from natural gas fields.

Produced water from gas fields display characteristics that differ from those of produced water from oil fields, such as higher contents of benzene, toluene, ethylbenzene and xylene (BTEX), which make it more toxic. Moreover, it is more acidic (pH ~3.5–5.5) compared with produced water from oil fields (pH ~6–7.7). Nevertheless, the amount of produced water from offshore gas production fields are much less, which considerably lessens the total environmental impact (Jim Enez *et al.*, 2017).

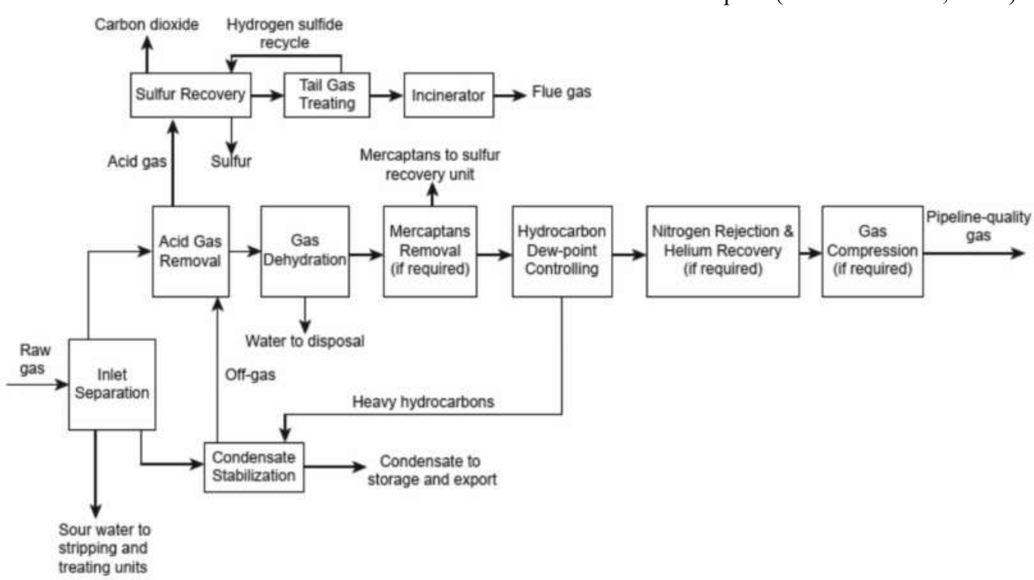


Figure 1: Typical flow of natural gas processing (Mokhatab *et al.*, 2018)

Table 1: Constituents and characteristics of produced water from natural gas

Parameter	Concentration (mg/l)	Parameter	Concentration (mg/L)
pH	4.4–7.0	Chromium	ND[a]–0.03
TDS	2,600–310,000	Copper	ND[a]–5
TSS	8–5484	Lead	<0.2–10.2
BOD	75–2870	Nickel	ND[a]–9.2
COD	2,600–120,000	Sodium	520–120,000
Arsenic	0.004–1	Benzene	<0.010–10.3
Cadmium	<0.02–1.21	Oil and grease	2.3–60

Source: Hedar & Budiyono (2018)
[a] Not detectable

In terms of impacts to air, carbon dioxide (CO_2) is the highest emitted gas in terms of mass by the oil and gas exploration and production industry (IOGP, 2020). The sources of emission are combustion of natural gas in flaring units, fuel combustion for energy generation and stripped-off CO_2 from natural gas to meet sales requirements. (IOGP, 2020) issued a report that the amount of CO_2 emitted by the oil and gas industry in 2019 is approximately 139 tonnes CO_2 per kilo tonnes of hydrocarbon production.

The second highest emission is CH_4, which is emitted by process venting in the form of fugitive emission from process equipment and incomplete combustion of hydrocarbon during production activities, such as operation of turbines and flaring of hydrocarbons (IOGP, 2020). The amount of CH_4 emission from the oil and gas industry in 2019 is approximately 1.14 tonnes CH_4 per kilo tonnes of hydrocarbon production (IOGP, 2020). Moreover, the natural gas system contributed 25% to the total CH_4 emission in the US (Energy in Depth [EID], 2019).

For an overall description of atmospheric emission from natural gas systems, Table 2 provides a list of atmospheric emissions from natural gas combined-cycle power plants in the form of greenhouse gas emission and other atmospheric emission.

In the previous years, several methods and tools were used to assess sustainability performance especially in terms of the environmental aspect. These tools can be grouped according to Maslow's hierarchy of needs. Using the pyramid approach, the basic life cycle thinking approach, which is a tool used to assess environmental impact and sustainability, is situated at the bottom of the pyramid. It is followed by a method for evaluating environmental impact, such as CO_2 emission or water footprinting. Life cycle assessment (LCA), which is used to assess multiple environmental impacts, appears next followed by resource assessment or eco-efficiency, which combines the assessments of economic and environmental aspects. Last, the life cycle sustainability assessment which uses one method to evaluate the three pillars of sustainability, namely, environmental, economic and social aspects, appears at the top of the pyramid (Ambrus *et al.*, 2018).

LCA is a compilation and evaluation of several inputs and outputs and the potential environmental impact of a product system throughout its life cycle (ISO 14040, 2006). It is distinguished from other environmental assessment tools by at least two advantages. The first is that it adopts the life cycle perspective with regard to the assessment of environmental impact in the form of matter and energy flow, which occur through all stages of the life cycle (from cradle to grave) of a product system (goods or services), such as the extraction and processing of raw materials, stages of production

Table 2: Intensity of atmospheric emission from natural gas systems

Parameter	Natural Gas Extraction	Natural Gas Transport	NGCC Power Plant
Greenhouse gas emission (g CO_2/kWh)			
CO_2	20.8	3.95	393.00
N_2O	0.2	0.00	0.00
CH_4	47.7	0.01	0.01
Other atmospheric emission (g/kWh)			
NO_x	0.482	0.0008	0.0305
SO_2	0.0059	0.0003	0.0012
PM	0.001	0.0006	0.0031

Source: Mac Kinnon *et al.* (2018)including mitigating climate change and reducing pollution in the air, has led to questions regarding the viability of continued use of natural gas. Natural gas use, particularly for electricity generation, has increased in recent years due to enhanced resource availability from non-traditional reserves and pressure to reduce greenhouse gasses (GHG)

and subsequent processing, distribution, transportation, used to disposal and recycling (Toniolo *et al.*, 2019) to include the greatest number of standards. The second step was data cleaning. The documents were selected by eliminating duplicate results and those standards not in force. The majority of the documents obtained were published by the International Organization for Standardization (ISO).

The second is that it can be used as an approach for all environment media. The relevant environmental impacts of the input (i.e., use of resources and raw materials) and output sides on the environment (i.e., air emission, wastewater and solid waste) should be considered to be included. Therefore, LCA considers many categories of impact, whether it is midpoint impact or endpoint impact (Guinée & Heijungs, 2017).

Another advantage is that LCA is already an internationally standardised method for environmental assessment. ISO 14040 and 14044 international standards were revised in 2006, which replaced the previous ISO 14040 versions of 1997–2000 (ISO 14040, 2006). The four main structures of the standards include the definition of scope and objectives, inventory analysis, environmental impact analysis and interpretation of results, which were developed at the time of harmonisation/standardisation between SETAC and ISO (Guinée & Heijungs, 2017).

Previous studies that employed LCA to evaluate natural gas as a system product are abundant. However, results varied according to the impact categories and system boundary considered. Several studies considered only one or two impacts, such as greenhouse gas emission, energy use and water consumption (Khan *et al.*, 2019)· whereas studies that focused on multiple impacts are few (Tagliaferri *et al.*, 2017b)increasing interest in shale gas is developing in many countries holding shale reserves and exploration is already taking place in some EU countries, including the UK. Any commercial development of shale gas in Europe requires a broad environmental assessment, recognizing the different European conditions and legislations. Methods: This study focuses on the UK situation and estimates the environmental impacts of shale gas using life-cycle assessment (LCA.

With regard to system boundary, the cradle-to-grave approach is the most popular method in terms of the usage stage of natural gas products for electricity generation (Cavalcanti *et al.*, 2021) or transportation (Khan *et al.*, 2019). However, several studies used this approach to investigate stages in the life cycle stage of a product of natural gas systems, such as natural gas extraction and transportation stages (Tagliaferri *et al.*, 2017a,b) use of any carbon-based fuel runs counter to mitigation of greenhouse gas emissions (GHGs. Moreover, other studies employed the gate-to-gate approach, which focuses only on the transportation stage (Di Lullo *et al.*, 2020) it is important to understand its life cycle emission intensity. A framework is developed for performing bottom-up greenhouse gas (GHG).

The current study differs from previous studies because it considers multiple categories to assess impact and focuses on the upstream side of the life cycle of natural gas, which are natural gas extraction and transportation. Furthermore, the study uses trendlines from 5 years of data to compare significant impact assessments within the timeframe. The study highlights the upstream side because different alternatives are available for the final usage of natural gas in Indonesia, such as energy source for electricity generation or raw material for fertiliser production.

With the frequent use of LCA as a tool for environmental impact assessment, practices related to LCA, in terms of energy in Indonesia, are on an increasing trend particularly over the previous 2 years. The researcher conducted a search for relevant literature on July 13, 2020, on Scopus© using the keywords 'life cycle' in the title and 'energy' for other article sections. A total of 64 studies from 2008 to 2020 were found. These studies employed LCA and were conducted in Indonesia. Out of these publications, however, studies on LCA of natural gas products as a primary source of energy in Indonesia are lacking.

Given the research gap, the current study is thus deemed important because Indonesia remains with minimum exposure to the LCA of natural gas products despite the important role of natural gas as a major energy supply. Therefore, the study aims to investigate the potential environmental impact of natural gas production by employing the LCA method based on ISO 14040/14044 standards and also to identify which of the impact categories that mostly contributed to the overall environmental impact along with the process unit associated with the impact categories using Principal Component Analysis (PCA). The study contributes to the literature by filling the research gaps related to LCA in Indonesia particularly for natural gas production.

Materials and Method

The study follows ISO 14040/14044 standards by conducting the study in four stages, namely, determination of scope and objectives, inventory analysis, impact assessment and interpretation of the results of impact assessment.

Product Description

The system product of the study is the production of natural gas in the waters of Makassar Strait, South Kalimantan Province, Indonesia. The field has two platform facilities, namely, the process platform (process quarter process) and wellhead platform connected by a bridge with a length of 60 m. The field is designed to accommodate a maximum production capacity of 120 MMscf of natural gas from production wells. Moreover, a maximum of 115 MMscf of natural gas will be exported through a subsea pipeline with a diameter of 14″ and a length of 312 km to an onshore receiving facility in East Kalimantan.

First, hydrocarbon fluid from the production well will pass through a separator unit that will separate the fluid into three phases, namely, gas, condensate and produced water. Natural gas, which is the main product, will then flow into a compressor unit to increase its pressure and a gas metering unit is used to measure the amount of gas. Then, natural gas will travel through a subsea export pipeline that will guide natural gas to onshore receiving facilities. Condensate, which is a by-product, will pass through a condensate metering unit to calculate the amount before finally being combined with natural gas to be jointly exported through a subsea export pipeline. Lastly, produced water from the separation process will undergo a treatment system that reduces oil content in the water to below the limit set in the wastewater discharge permit (Republic of Indonesia Ministry of Environment, 2010) and finally released into the environment, which is into sea.

Goal and Scope

The study aims to determine the potential environment impacts of natural gas production with a functional unit of 1 MMscf of natural gas produced. The scope of this study includes the use of the cradle-to-gate approach which covers natural gas extraction and transportation, and excludes the distribution of natural gas to consumers and its usage as previously explained. Figure 2 depicts the scope and system boundary of the study.

Dashed lines in Figure 2 illustrate that the study groups the product system into the following stages:

1. Natural gas extraction

   1.a. Production separator process unit: A processing unit that separates hydrocarbons produced from production wells (). The subsystem consists of three process units, namely, production wells, a manifold and a separator.

   1.b. Condensate production process unit: It calculates the amount of condensate production. Condensate is a by-product of the separation process. After calculating the amount of production, the condensate is recombined with gas for distribution to consumers. This subsystem consists of a condensate pump unit and a condensate metering system.

   1.c. Produced water treatment process unit: It treats water from the separation process before being released into the sea. This subsystem consists of a hydrocyclone unit and a polishing unit.

   1.d. Process unit for supporting activities: This unit supports the implementation of the four previous processing units, such as the safety aspects of production activities. The system consists of (1) electricity generation and a (2) flaring unit.

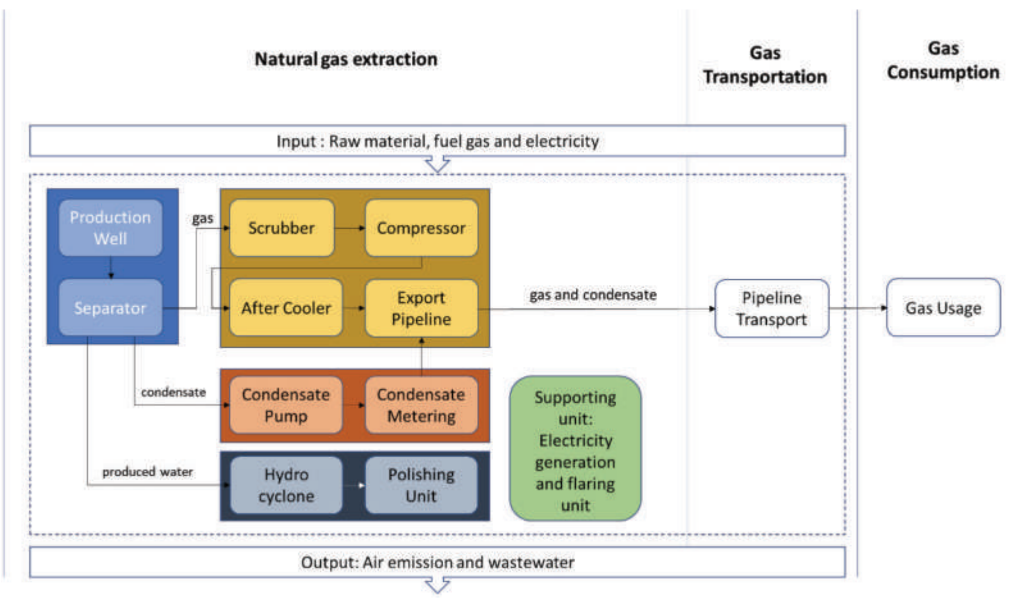


Figure 2: Scope and system boundary of the study (represented by dashed lines)

2. Gas transportation

   This unit transfers natural gas and condensate to consumers through long-distance subsea pipelines. It consists of a (1) compressor unit with supporting units, such as a suction scrubber unit, after-cooler and gas metering systems and (2) pipeline transport.

Table 3 provides a summary of the scope and objective of the study.

Table 3: Goal and scope and objective of the study

Items	Description
Product Description	Natural gas production at offshore field
Location	Makassar Strait
Objective	Identify the potential environmental impacts of natural gas production
Scope	Cradle-to-gate examination which covers natural gas extraction and transportation
Product	Natural gas
Functional unit	1 MMscf of natural gas produced

Life Cycle Inventory (LCI)

The input and output data for the study consist of data from 2015 to 2019, which are mainly from secondary sources, such as emission measurements conducted by object study. Input data consist of raw material to the process which are natural gas from production separator and condensate from condensate metering unit. While output data consist of several constituents in waste water (e.g., Arsenic, Cadmium, etc.) from produced water treatment unit and emission to air (e.g., methane [CH_4], carbon dioxide [CO_2], etc.) from electricity generation, compressor, flaring and pipeline transport unit. Calculation using emission factors is conducted in the absence of data. Descriptive statistics use of mean value, maximum value, minimum value, interquartile range and standard deviation were first used to describe data distribution and filter the inventory data from any outliers. Table 4 reports the clean dataset from the main inventory for year 2019.

The following text provides a detailed explanation of the input and output data type, sources and calculation method if required from each process unit.

1. Natural gas extraction

   1.a. Production separator process: Input and output data from this process unit which pertain to the amount of raw material (natural gas) extracted from production wells. This type of data is obtained using a production measurement instrument by the study object.

   1.b. Condensate metering process: Data from this process unit denote raw material in the form of amount of condensate as a by-product extracted from the production well. This type of data is also obtained from measurement data of the study object.

   1.c. Produced water treatment: The load of wastewater effluent produced by the water treatment process. The pollutant load of the effluent is obtained from laboratory analysis conducted by the study object. Data on the amount of effluent flow are collected from measurements also conducted by the study object.

   1.d. Supporting unit: electricity generation: The input and output data from this process unit consist of several forms of air emission, such as greenhouse gases or conventional pollutants, as a result of the combustion process in the gas turbine generator. The study object conducted laboratory analysis to determine the loads of SO_2 and NO_2. Data on other pollutants were calculated using the emission factor approach for natural gas production activities as per the regulation and guideline of the Republic of Indonesia Ministry of Environment (2012).

1.e. Supporting unit (flaring): Data obtained from this process unit also pertain to air emission of the combustion process in the unit. All pollutant loads were calculated using the emission factor approach for natural gas production activities as per the regulation and guideline of the Republic of Indonesia Ministry of Environment (2012).

2. Gas transportation

2.a. Compressor: The input and output data obtained at this stage were related to the operation of the compressor as a unit for delivering high-pressure transmission along the subsea export pipeline and its construction materials. The emission load from the operation of the compressor were measured and calculated using the same method used for the turbine generator.

2.b. Pipeline transport: The input and output data for this process unit were related to the amount of CO_2, CH_4 and N_2O emitted, which are associated with virgin steel and concrete usage during pipeline construction and installation with total length of 312 km and diameter of 14 inch. The emission factors for CO_2, CH_4 and N_2O from virgin steel and concrete as per Di Lullo *et al.* (2020) it is important to understand its life cycle emission intensity. A framework is developed for performing bottom-up greenhouse gas (GHG were used to calculate emission loads.

Table 4: Data from the main inventory per MMscf of natural gas produced

Input Output Data	**Unit**	**Statistics**			
		Minimum	**Maximum**	**Mean**	**Std. Deviation**
		Amount			
1. Natural gas extraction					
1.a. Production separator					
Natural gas	MMscf	1.01E+00	1.02E+00	1.02E+00	8.10E-04
1.b. Condensate metering					
Condensate	kg	1.15E-03	2.76E-02	1.07E-02	7.31E-03
1.c. Produced water treatment					
Arsenic	kg	3.61E-12	3.12E-08	1.58E-08	4.97E-09
Cadmium	kg	4.13E-12	3.56E-08	1.80E-08	5.68E-09
Chromium VI	kg	2.58E-11	2.23E-07	1.13E-07	3.55E-08
Chemical Oxygen Demand	kg	1.37E-07	1.18E-03	5.97E-04	1.88E-04
Copper	kg	5.16E-12	4.45E-08	2.25E-08	7.10E-09
Lead	kg	2.58E-11	2.23E-07	1.13E-07	3.55E-08
Mercury	kg	2.58E-12	2.23E-08	1.13E-08	3.55E-09
Nickel	kg	1.03E-11	8.91E-08	4.51E-08	1.42E-08
Phenol	kg	6.34E-10	5.48E-06	2.77E-06	8.73E-07
Vanadium	kg	4.13E-11	3.56E-07	1.80E-07	5.68E-08
Zinc	kg	3.09E-12	2.67E-08	1.35E-08	4.26E-09
1.d. Supporting unit (electricity generation)					

CH_4	kg	4.09E-03	6.44E-03	4.69E-03	3.26E-04
CO_2	kg	2.05E+02	3.24E+02	2.36E+02	1.65E+01
N_2O	kg	1.71E-03	2.48E-03	2.09E-03	1.18E-04
Natural gas	MMscf	3.93E-03	6.20E-03	4.51E-03	3.15E-04
NO_2	kg	2.84E-03	7.27E-01	1.50E-01	1.72E-01
PM_{10}	kg	1.22E-05	1.92E-05	1.40E-05	9.74E-07
SO_2	kg	7.04E-05	4.56E+00	2.69E-02	2.52E-01
1.e. Supporting unit (flaring)					
CH_4	kg	1.81E-06	6.92E-06	4.20E-06	9.49E-07
CO_2	kg	1.29E-02	4.94E-02	3.00E-02	6.78E-03
NO_x as NO_2	kg	2.08E-03	7.41E-01	7.72E-02	1.81E-01
2. Gas transportation					
2.a. Compressor					
CH_4	kg	9.68E-06	1.25E-05	1.13E-05	5.10E-07
CO_2	kg	4.84E+02	6.42E+02	5.67E+02	2.72E+01
N_2O	kg	1.96E-03	2.35E-03	2.09E-03	1.07E-04
Natural gas	MMscf	3.93E-03	5.31E-03	4.50E-03	2.93E-04
NO_2	kg	2.55E-03	3.60E+00	1.29E+00	1.15E+00
PM_{10}	kg	2.87E-05	3.74E-05	3.36E-05	1.55E-06
SO_2	kg	2.55E-03	3.51E-01	1.13E-01	1.17E-01

Life Cycle Impact Assessment (LCIA)

Relevant impact categories of natural gas production were selected during the LCIA. In this phase, the impact assessment methods CML 2001 model are used for characterisation and normalisation (CML-Department of Industrial Ecology, 2016). The categories are global warming potential (GWP), marine aquatic ecotoxicity potential (MAETP), fresh water ecotoxicity potential (FAETP), terrestrial ecotoxicity potential (TETP), photochemical oxidant potential (POP), acidification potential (AP), eutrophication potential (EP), abiotic resource depletion (ARD) of fossil fuel and human toxicity (HT). In particular, assessment of the GWP covers a period of 100 years as per the Intergovernmental Panel on Climate Change.

Interpretation

The results of the LCIA were first reviewed to enable the interpretation of all impact categories based on the 2019 LCI data. Then, all impact categories were examined with hotspot analysis of each process unit to determine which process units contribute the most to these impact categories. Furthermore, PCA were used using normalized LCIA result to identify which ~~of~~ impact categories contributed most to the overall environmental impact along with the process unit associated with the impact categories following methods from Onat *et al.* (2019). Required calculation of eigenvalues, eigenvectors and loading factors from the identified principal component along with the plot result were performed by RStudio software version 1.4. Interpretation is also conducted to compare the LCIA results within the 5-year LCI data. In this manner, the variation in impact results over time was determined.

Result and Discussion

LCIA Result

Table 5 provides the results for LCIA compared with the 2019 LCI data. Figure 3 illustrates the LCIA results after normalisation using the 2019 LCI data.

Table 5: LCIA results for natural gas production and transportation

Impact category	Stage							Total amount
	Natural gas extraction					Gas transport		
	PS[a]	CM[b]	PWT[c]	EG[d]	F[e]	C[f]	PT[g]	
ARD (MJ/MMscf)	1.1E+06	9.7E-01	-	5.1E+03	-	1.3E+04	-	1.1E+06
AP (kg SO_2 eq./MMscf)	-	-	-	2.4E-01	-	8.4E-01	-	1.1E+00
EP (kg PO_4^{3-} eq./MMscf)	-	-	1.4E-02	5.3E-02	1.8E-03	1.8E-01	5.7E-04	2.5E-01
FAETP (kg 1,4-DCB eq./MMscf)	-	-	8.0E-05	-	-	-	-	8.0E-05
GWP (kg CO_2 eq./MMscf)	-	-	-	2.4E+02	2.9E+01	5.8E+02	2.8E+02	1.1E+03
HT (kg 1,4-DCB eq./MMscf)	-	-	1.4E+00	4.9E-01	1.6E-02	1.7E+00	-	3.5E+00
MAETP (kg 1,4-DCB eq./MMscf)	-	-	3.8E+03	-	-	-	-	3.8E+03
POP (kg ethylene eq./MMscf)	-	-	-	1.3E-02	4.0E-04	4.5E-02	2.4E-03	6.0E-02
TETP (kg 1,4-DCB eq./MMscf)	-	-	9.0E-02	-	-	-	-	9.0E-02

[a] Production separator
[b] Condensate metering
[c] Produced water treatment
[d] Electricity generation
[e] Flaring
[f] Compressor
[g] Pipeline transport

The following text provides a detailed investigation for each impact category and analyses of the 5-year trendline.

Abiotic Resource Depletion (Fossil Fuel)

ARD is related to extraction from the fossil fuel resource in the form of natural gas as raw materials and condensate as a by-product. The production separator process unit contributes 98.39% of the impact, which is associated with the extraction of natural gas from subsurface reservoirs via the production well. The rest of the impact is derived from compressor process unit (1.16%) and from the electricity generation process unit (0.45%), which uses natural gas used as fuel source for the process units. The amount of ARD in the form of condensate is non-significant.

The amount of natural gas used for internal usage is 1.58% as a fuel source for the electricity generation and compressor units. In other words, 1.0158 MMscf of natural gas is required to

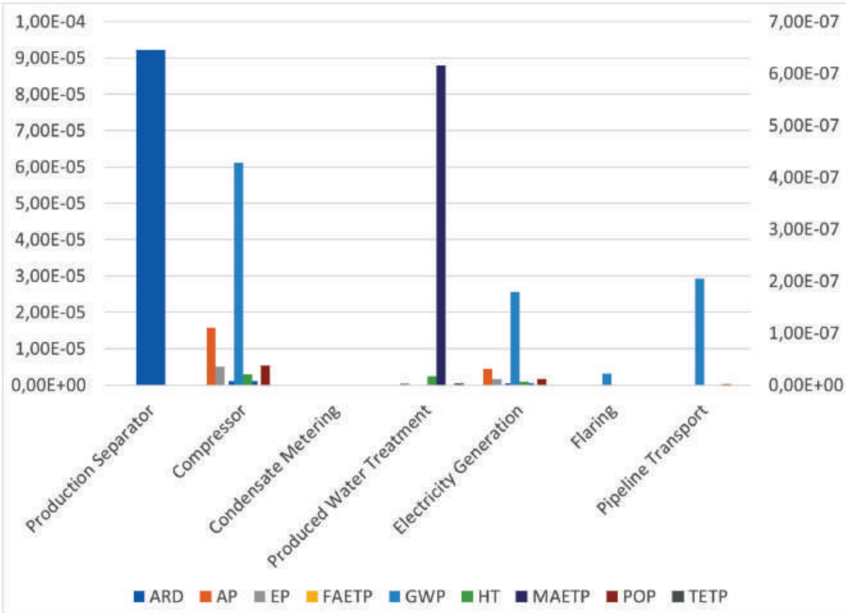


Figure 3: LCIA results after normalisation

produce 1 MMscf of natural gas from subsurface reservoirs.

Figure 4 displays the 5-year trendline and indicates that ARD from the production separator changes on a yearly basis but is non-significant. However, a slight increase of approximately 12.48% per year is observed for the compressor unit due to the increased consumption of fuel gas each year from the process unit.

Marine Aquatic Ecotoxicity Potential

A number of pollutants (i.e., arsenic, cadmium, chromium VI, copper, lead, mercury, nickel, phenol, vanadium and zinc) contained in

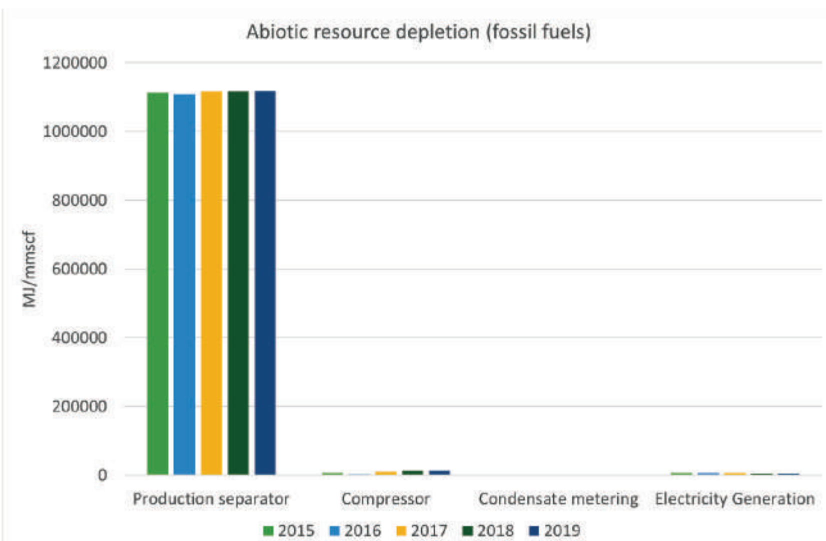


Figure 4: ARD trendline from 2015 to 2019

wastewater discharged into sea water contribute to this category. This impact is fully associated with produced water treatment because it is the only process unit that generates wastewater discharge into sea water.

Specifically, vanadium has the most contribution to this impact at 90.19% followed by nickel at 7.09%. Al-Jaser and Hamoda (2019) stated that the concentration levels of vanadium and nickel are indeed higher in produced water from oil fields compared with their natural concentrations in sea water. This finding, thus, indicates that the same tendency may occur for produced water from gas production fields.

Nickel and vanadium are oil-related metals which are present mainly in the form of organic metals in crude oil and have been regarded as indicators of petroleum hydrocarbon contamination from illegal dumping of tankers passing through the coast of Kuwait (Al-Jaser & Hamoda, 2019). The existence of nickel and vanadium in petroleum comes from the initial mechanism of hydrocarbon formation, namely through the exchange of magnesium ions with nickel or vanadium when the degradation of chlorophyll in organic matter occurs (Dembicki, 2016), thus the presence of nickel and vanadium in petroleum related material or its produced water is a common finding.

Figure 5 presents an interpretation of the 5-year trendline from 2015 to 2019. MAETP significantly increased from 255.50 kg 1,4-DCB eq./MMscf in 2016 to 5,685.46 1,4-DCB eq./MMscf in 2017.

The significant increase in MAETP from 2016 to 2017 is due to the increased generation of produced water from 14.45 tonnes in 2016 to 402.22 tonnes in 2017. An increase in the water-to-hydrocarbon ratio along with the increasing age of production wells is a common phenomenon in oil and gas production (Jim Enez *et al.*, 2017). However, a downward trend was observed for 2018 and 2019 due to decreased MAETP impact from nickel and phenol despite the upward trend of vanadium during those years.

Numerous factors influence the impact of the discharge of produced water to the sea, such as dilution in the receiving environment, volatilisation of low molecular hydrocarbon and biodegradation of organic compounds (Beyer *et al.*, 2020). By considering the concentration, relative toxicity, dispersion and bioaccumulation rate of the majority of produced water discharge, the potential for acute toxicity impact from produced water is limited. However, the impact assessment for chronic toxicity is required

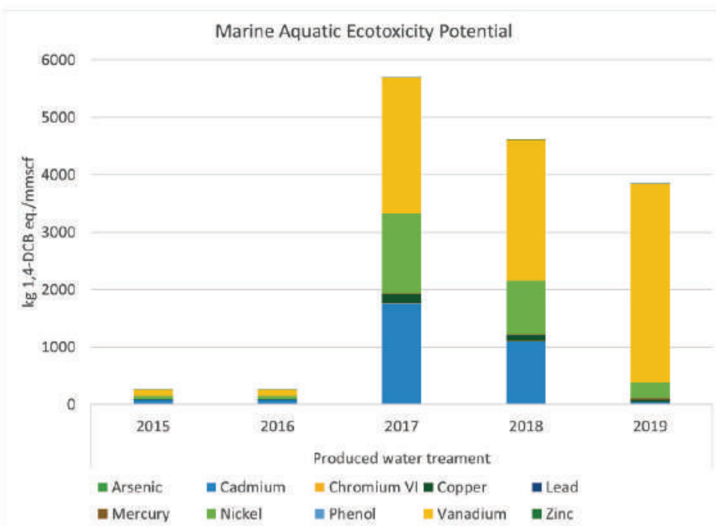


Figure 5: MAETP trendline from 2015 to 2019

because it is associated with long-term exposure to produced water (Beyer *et al.*, 2020).

With the potential impact of produced water discharge on the environment, many countries set limitations to produced water discharge to the environment, which are mostly in the form of total oil and grease (TOG) concentration in produced water (Liu *et al.*, 2021). Table 6 provides the limits of produced water discharge to the environment set by several countries.

However, measuring the impact of produced water through TOG concentration does not measure low molecular hydrocarbons, such as BTEX, which contribute to the toxicity potential impact of produced water (Schmeichel, 2017).

Global Warming Potential

GWP is related to the release of CO_2, CH_4 and N_2O to ambient air as greenhouse gas emission, which contributes to the global warming effect. The compressor unit (51.38%), pipeline transport (24.53%), electricity generation (21.53%) and flaring unit (2.56%) contribute to this impact category. Thus, the majority of the impact is associated with the gas transportation stage (Figure 6). GWP from the compressor unit is increasing by approximately 13.91% each year due to the increased amount of fuel gas.

Gas production rate naturally declines as a function of time due to resulting declining pressure in reservoirs or changing water-to-hydrocarbon ratio (Poston *et al.*, 2019).

Table 6: Limit of produced water discharge set by other countries

Country	Monthly Average TOG (mg/L)	Daily Maximum TOG (mg/L)
Nigeria, Angola, Cameroon, Thailand[a]	30	-
China[a]	20 - 45	-
Argentina, Venezuela[a]	-	15
Indonesia[b]	-	50

Sources: [a](Liu *et al.*, 2021); [b]Republic of Indonesia Ministry of Environment (2010)

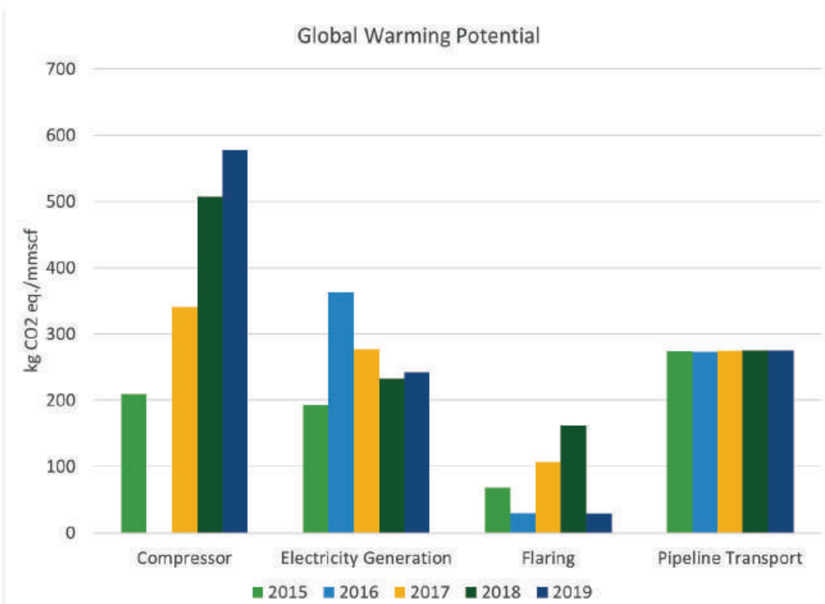


Figure 6: GWP trendline from 2015 to 2019

The reduced pressure in reservoirs increases the amount of fuel gas required by the gas compressor unit because it requires more compressing energy to maintain the same production rate. From 2017 to 2019, an increase of approximately 32% in fuel amount each year was observed because of this occurrence.

GWP in the flaring unit also experienced increments from 2016 to 2018. However, the amount decreased in 2019 due to the process efficiency initiative applied to the compressor unit, which led to a decrease in the amount of seal gas required for flaring in the compressor unit. Next to electricity generation, a yearly comparison of GWP pointed to a non-significant change, which indicated that the amount required for electricity generation is not correlated to the amount of gas produced.

In other words, GWP from natural gas production using a long-distance pipeline as a means of transport requires more attention in terms of process efficiency at the transportation stage due to the annual increment particularly from the compressor unit compared with GWP generated during the extraction stage for electricity generation and the flaring unit.

Next, the composition of gases that contribute to GWP is described (Figure 7). The results indicate that CO_2 is the largest contributor at an average of 98.74% followed by CH_4 at 1.17%. This finding is consistent with generic data from the emission inventories of other oil and gas producers (IOGP, 2020). In contrast with the GWP of greenhouse gas emission, regulations that directly limit emissions from greenhouse gases, particularly from oil and gas production activities, are not currently in place in Indonesia. Oil and gas producers in Indonesia follow the mandatory requirement to provide a yearly report of emission inventory including greenhouse gas emission (Republic of Indonesia Ministry of Environment, 2012).

Acidification Potential

AP is associated with the release of NO_2 and SO_2 to air, which act as precursors of acid rain. The source of NO_2 and SO_2 emission is the natural gas combustion process, which occurs during the operation of the turbine engine generator for electricity generation and the compressor unit for gas transportation. The compressor process unit contributes 77.9% to AP, which indicates the AP impact is largely generated during the gas transportation stage. The remaining 22.1% is attributed to electricity generation. Figure 8 describes AP trendline from 2015 to 2019.

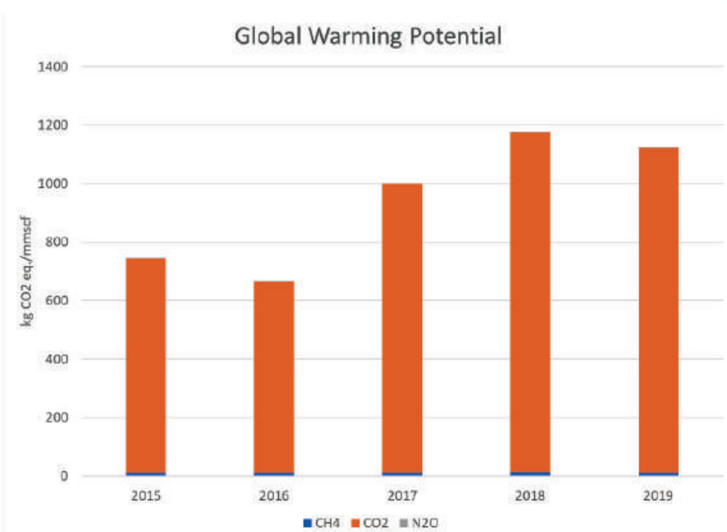


Figure 7: Greenhouse gases that contribute to GWP

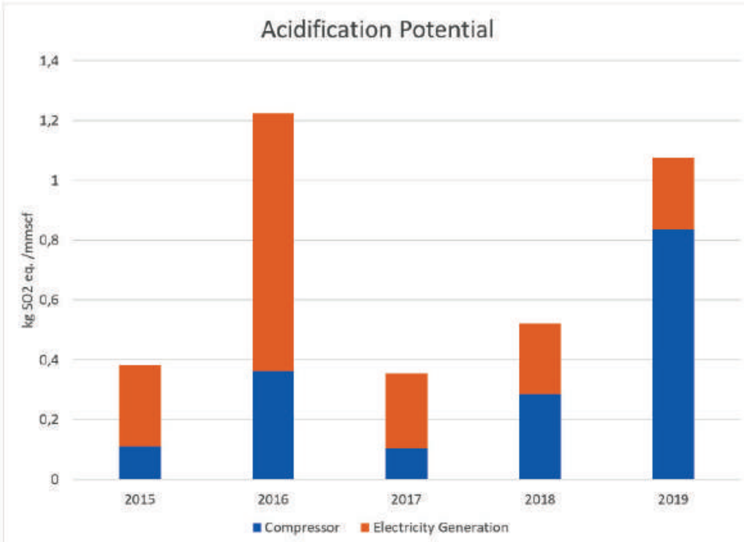


Figure 8: Acidification potential impact assessment result

Eutrophication Potential

The source of EP is NO_2 and N_2O released to ambient air and organic pollutants in the form of chemical oxygen demand to the sea. Therefore, this impact category is related to the compressor unit (72.16%), electricity generation (21.39%), produced water treatment unit (5.52%), flaring (0.7%) and pipeline transport (0.23%). The same occurrences with AP are found in EP. The compressor unit and electricity generation are the unit and process that contribute mostly to this impact category, as detailed in Figure 9.

Photochemical Oxidant Potential

POP is associated with the emission of CH_4, NO_2 and SO_2 to ambient air from the operation of the gas turbine for electricity generation and gas compression as well as emission from the flaring

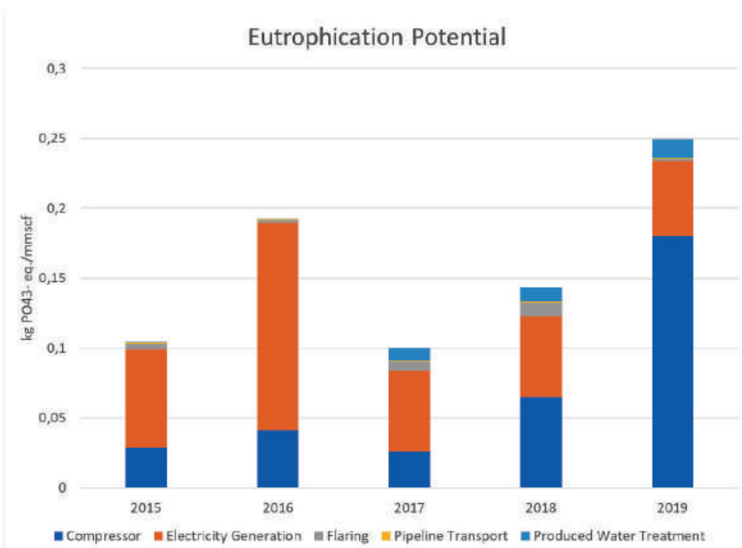


Figure 9: Eutrophication potential impact assessment result

unit. The rate of the impact associated with the compressor process unit reaches 74.10% followed by electricity generation at 21.27% using result of 2019. Figure 10 describes POP LCIA result for 2015 - 2019.

Human Toxicity

HT is correlated with the emission of NO_2, PM_{10} and SO_2 to ambient air and several pollutants, such as arsenic, cadmium, chromium VI, copper, lead, mercury, nickel, phenol, vanadium and zinc discharged to sea water. The largest contribution is associated with the compressor unit (47.14%) and produced water treatment (38.46%). On the basis of these results, HT is largely influenced by emission to air instead of wastewater discharge to the sea as described in Figure 11.

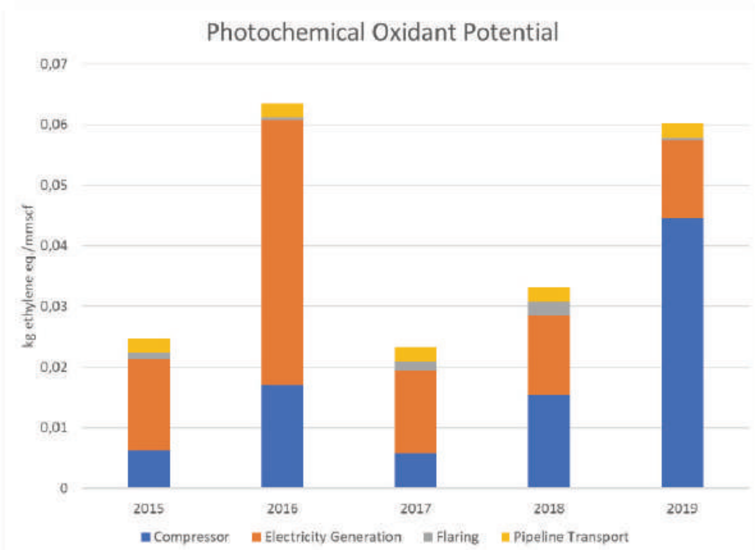


Figure 10: Photochemical oxidant potential impact assessment result

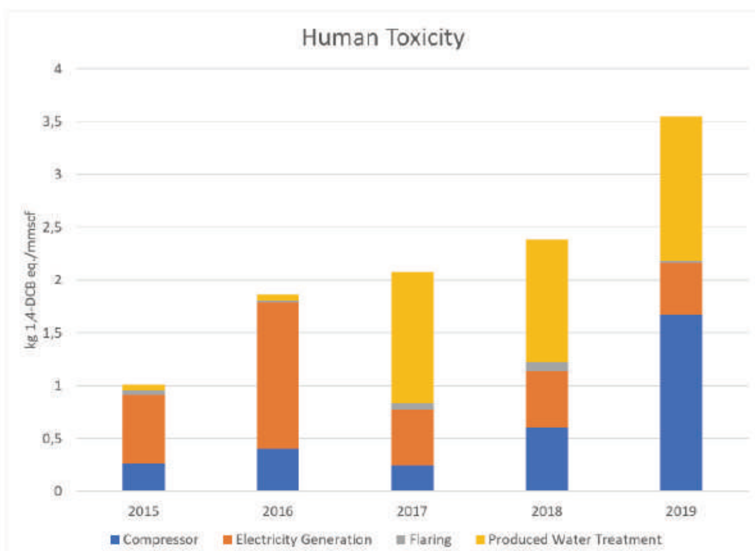
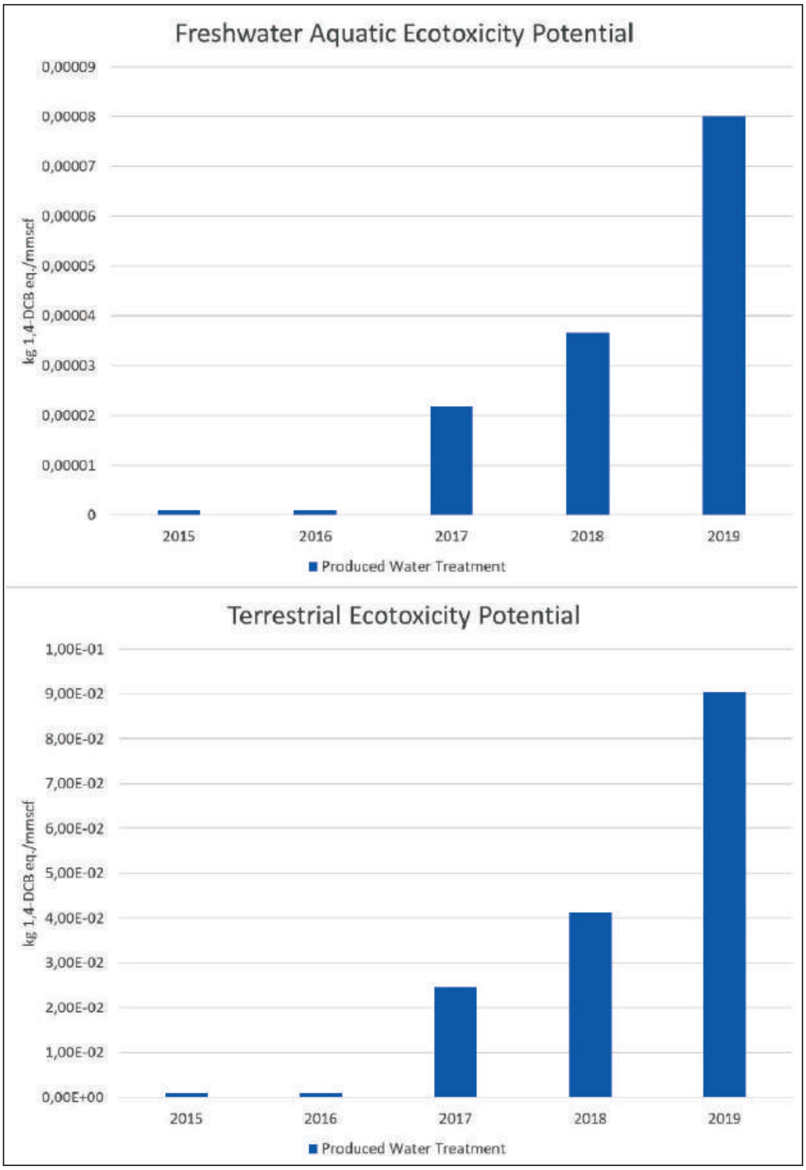


Figure 11: Human toxicity impact assessment result

Fresh Water Ecotoxicity Potential and Terrestrial Ecotoxicity Potential

The FAETP and TETP impact categories have similar characteristic in terms of correlation with the amount of pollutant contained in wastewater discharged to bodies of water or sea water. Arsenic, cadmium, chromium VI, copper, lead, mercury, nickel, phenol, vanadium and zinc are the constituents considered in the study. Mercury is the largest contributor to FAETP at 99.94%, which can even reach 100% for TETP due to the non-significant amounts of the other constituents. Figure 12a and Figure 12b show trend of FAETP and TETP from 2015 until 2019.



a.

b.

Figure 12: Impact assessment result: a. Freshwater aquatic ecotoxicity potential, b. Terrestrial ecotoxicity potential

Contribution of the Overall Process Units

Figure 13 describes the LCIA results from the 2019 data after normalisation. A further review is required on the contribution of each process unit to the overall LCIA result.

The most frequent process units that contribute to the overall impact categories is, produced water treatment at 38.22% on average: MAETP = 100%, FAETP = 100%, TETP = 100%, HT = 38.46% and EP = 5.52%. The next process unit with the largest contribution to the overall impact is the compressor unit at 35.98% on average: AP = 77.90%, POP = 74.10%, EP = 72.16%, GWP = 51.38% and HT = 47.14%.

To further justify this finding, PCA calculations were then conducted using the normalized LCIA result. Eigenvalues and variability result from PCA calculations are shown in Table 7. From the result, eigenvalues of principal component (PC) 1 and PC 2 are all greater than 1 and the cumulative variance from PC 1 and PC 2 reach 88.8% indicating that they sufficiently already contain most of the data variance, therefore, for the next analysis only PC 1 and PC 2 are considered.

Table 7: Calculation of eigenvalues

	PC 1	PC 2	PC 3
Eigenvalue	4.53	3.38	0.88
Variability (%)	50.81	37.99	9.83
Cumulative (%)	50.81	88.80	98.63

The next step, eigenvectors and loading factors were also calculated and rotated with results shown in Table 8 and illustrated in Figure 14. Five factors identified in PC 1 as the most contributed variable based on loading factors PCA result after being rotated are AP, EP, GWP, POP, and HT and furthermore, the PCA results in Figure 14 also show that these impact categories particularly AP, EP, GWP and POP have high collinearity amongst them. All of these impact categories are correlated with emission to air thus PC 1 can be seen as impact categories sourced from emission to air from this study. As previously mentioned, gas compressor is the unit process that contributed most to these five impact categories that indicate most of the impact results from this study are related with gas compressor unit. The compressor unit is part of the gas transport stage, which implies that the

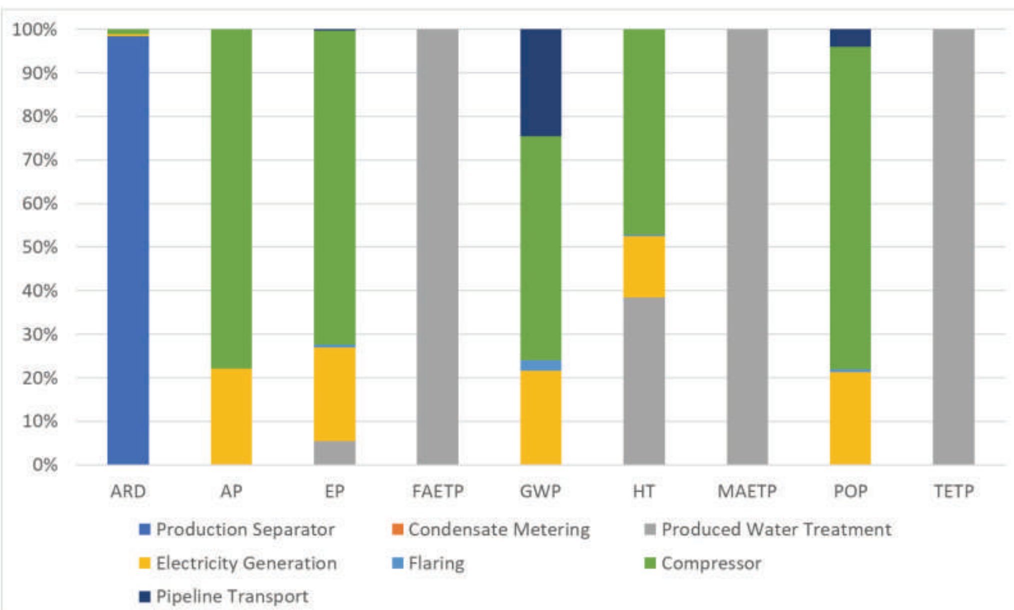


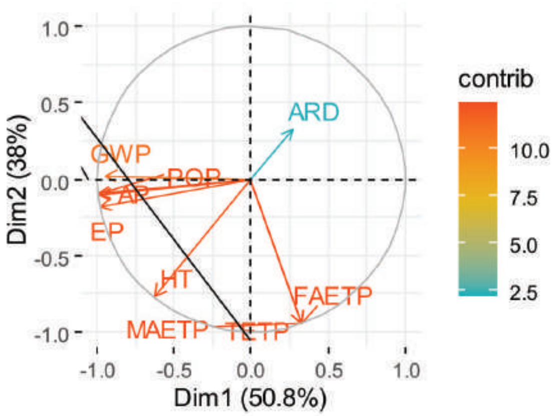
Figure 13: Overall contribution of all process units to the normalised 2019 LCIA results

transportation stage should also be considered in natural gas systems as the main contributor to the overall environmental impact in contrast with data in Table 2. Furthermore, data from Figure 6 indicate that the impact of the compressor unit increased in the following years compared with that of the other process units.

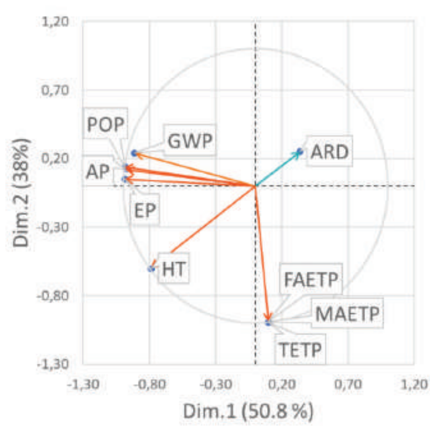
Next in PC 2, four variables identified as having contributed the most are FAETP, MAETP, TETP, and particularly HT which contributed in PC 2, although it is not as significant as the other three impact categories. All of these impacts correlated with impacts that are sourced from waste water. Thus, PC 2 can be seen as impact categories that are associated with impact to water body from this study. As previously mentioned, produced water treatment process unit is the most contributed unit process to these four impacts thus this unit was also considered as main contributor to the overall impact. This finding is alarming because the regulations implemented in Indonesia related to offshore discharge from the produced water treatment unit is only implemented for TOG content. Thus, the majority of the constituents remain unregulated *(Menteri Lingkungan Hidup* Indonesia, 2010.

Table 8: Calculation of eigenvectors and factor loadings

	Eigenvectors		**Factor Loadings**		**Factor Loadings After Rotation**	
	PC1	**PC2**	**PC1**	**PC2**	**PC1**	**PC2**
ARD	0.125	0.176	0.268	0.326	0.336	0.255
AP	-0.460	-0.058	-0.984	-0.108	-0.982	0.125
EP	-0.455	-0.097	-0.974	-0.179	-0.989	0.053
FAETP	0.152	-0.510	0.325	-0.944	0.096	-0.993
GWP	-0.442	0.012	-0.946	0.022	-0.914	0.242
HT	-0.293	-0.415	-0.626	-0.767	-0.787	-0.600
MAETP	0.152	-0.510	0.325	-0.944	0.096	-0.993
POP	-0.463	-0.051	-0.990	-0.095	-0.985	0.139
TETP	0.152	-0.510	0.325	-0.944	0.096	-0.993



a.



b.

Figure 14: a. Unrotated PCA result plot from all impact categories b. Rotated PCA result plot

Conclusions

LCA has been applied to investigate the potential environmental impact of the production of 1 MMscf natural gas, which includes natural gas extraction and transportation, using LCIA results based on the 2019 data of the study object (ARD: 1.1 E+06 MJ/MMscf, AP: 1.1 E+00 kg SO_2 eq./MMscf, EP: 2.5 E−01 kg PO_4^{3-} eq./MMscf, FAETP: 8.0 E−05 kg 1,4-DCB eq./MMscf, GWP: 1.1 E+03 kg CO_2 eq./MMscf, HT: 3.5 E+00 kg 1,4-DCB eq./MMscf, MAETP: 3.8 E+03 kg 1,4-DCB eq./MMscf, POP: 6.0 E−02 kg ethylene eq./MMscf and TETP: 9.0 E−02 kg 1,4-DCB eq./MMscf).

After normalisation and PCA, the most impact categories that contributed to the overall impact result can be divided into two groups. First group are AP, EP, GWP, POP and HT are correlated with impacts sourced from emission to air. The unit process that is mostly associated with the first group was gas compressor unit from gas transportation stage that contributed 35.98% on average to the overall environmental impact. And the second group is made of FAETP, MAETP, TETP, and HT that are associated with impacts sourced from waste water discharge. Produced water treatment unit was the unit process that is mostly associated with the second group impact categories, with overall contribution at 38.22% on average, to the environmental impact.

According to the time series of the 5-year data, an upward trend was observed for the MAETP impact due to increased water-to-hydrocarbon ratio over time and for GWP, particularly, from the compressor unit due to increasing natural gas fuel gas consumption as an effect from reduced pressure in reservoirs over time.

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