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Environmental Impacts Potential of Natural Gas Production Through Life Cycle Assessment

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Abstract. Life cycle assessment (LCA) is a methodology used to evaluate potential environmental impacts in various industry sectors, including the oil and gas industry to quantify the environmental impacts and determine the processes that have significant impacts along their production cycle. This environmental impact study adheres to ISO 14040:2016 and 14044:2017 standards, using the ReCiPe methodology within a gate-to-gate scope to analyze potential environmental impacts of 1 MMSCFD natural gas production. The impact categories analyzed in this study are Global Warming Potential (GWP), Particulate Matter Formation (PM), Ozone Formation (OF), and Terrestrial Acidification (TA). The results of this study identified several activities and processes in production cycle that can be categorized as hotspots: (1) Emissions from the Waste Heat Boiler and Thermal Oxidizer process to oxidize acid and permeate gas, (2) Emissions from the electricity generator unit, (3) Emissions from the compressor unit, and (4) Emissions from flaring activities related to safety operations. The quantified impacts of each category are GWP (3,555 kg CO₂-eq), PM (0.52 kg PM₁₀-eq), OF (3.36 kg NOₓ-eq), and TA (1.72 kg SO₂-eq). This study maps the environmental impacts of natural gas production cycle, helping to identify further improvements for reducing potential environmental impacts.

Keywords: Environmental impact; Gate-to-gate; LCA; Natural gas; ReCiPe

1. Introduction

The process of industrialization or the adoption of other technologies undeniably requires energy resources to achieve its objectives. In 2022, global energy consumption reached 178,899 TWh (approximately 644.05 EJ), representing an 800% increase over roughly one millennium (1920s; 18,770 TWh or 67,572 EJ), and a fourfold increase from the previous period (1820 - 1920s) (Smil, 2016; The Energy Institute, 2023). The extensive use of fossil fuels, which accounted for 77% of total energy consumption, significantly drove this rise from 1920 to 2022. This heavy reliance on fossil fuels has substantially contributed to global emission increases, with 70% of emissions originating from fossil fuel-related activities (Friedlingstein et al., 2022).

Indonesia, one of the largest producers and consumers of fossil fuels, particularly oil and natural gas in Southeast Asia (The Energy Institute, 2023), experienced a 193% increase in emissions from 1990 to 2019, reaching approximately 933 MtCO₂-eq per year (Climate Transparency, 2022). These emissions are primarily driven by energy activities (65%) that utilize fossil fuels. To curb emissions and combat global warming, Indonesia ratified the Paris Agreement through Law No. 16/2016, committing to reduce GHG emissions by 29% (business as usual) or 41% (with international assistance) by 2030. Furthermore, Government Regulation No. 79 of 2014 on Indonesia's National Energy Policy targets a reduction in fossil fuel utilization to
77% (25% oil, 22% natural gas, and 30% coal) by 2025 and to 69% (20% oil, 24% natural gas, and 25% coal) by 2050, aiming for a 10% reduction in fossil fuel supply within three years and an 18% reduction within a decade.

One of the largest producers of oil and natural gas in Indonesia also seeks to contribute to the optimization and efficiency of its production process to minimize environmental impacts potential (Fatriansyah et al., 2023a; Baskoro and Riastuti, 2024). The main activities in the form of product processing certainly have environmental impacts potential. Life Cycle Assessment (LCA) methodology used as an evaluation of the environmental impact potential of each production life cycle process within gate-to-gate scope (Arba and Thamrin, 2022; Muhamad et al., 2022). This study follows ISO 14040:2016 and 14044:2017 standards, aiming to comprehensively quantify significant environmental impacts (hotspots) to implement optimization and efficiency measures as effectively as possible.

2. Methods

LCA is a method for assessing the environmental impact of a system through quantitatively analyzing the environmental aspects of a product throughout all stages of its life cycle (Lee and Inaba, 2004; Fatriansyah et al., 2023b). The implementation of LCA refers to the frameworks set out in ISO 14040:2016 and ISO: 14044:2017. Based on these standards, there are some stages in conducting a LCA study as shown in Figure 1.

![Figure 1 LCA Stages Framework According to ISO 14040](image)

2.1 Goal and Scope

LCA guides the subsequent steps of the study by defining the system boundary (life cycle model). The purpose and scope of the LCA must be clearly outlined, specifying (a) the purpose of the LCA application, (b) the reason for conducting the LCA assessment, (c) LCA methods, assumptions, and impact limitations, and (d) the intended audience and other needs relevant to the study. The objective of this study is to evaluate the potential environmental impacts of natural gas production activities and to identify the activities that have a significant quantified impact throughout the production life cycle.

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Figure 2 shows the natural gas production process at the Bunsa field along with its supporting activities. Wells A, B, C, D and E are production wells that extract petroleum, a raw product, which is then transported to Bunsa field for further processing. This extraction activities along with others such infrastructure, transportation, pipeline, custody meter, and distribution line are not the main process in natural gas production. Therefore, these are not included in the study scope.

The scope of this study is gate-to-gate which the natural gas production process begins when the natural resource from the production wells enters the Bunsa field, then a separation process is carried out to separate the gas from the condensate and produced water. The gas will then go through a hydrogen sulfide and carbon dioxide removal process (e.g. Amine System) accompanied by water content reduction through a dehydration process (e.g. adsorption by Triethylene Glycol/TEG) before finally flowing into the distribution pipeline.

The operation of the Waste Heat Boiler-Thermal Oxidizer (WHB-TOX) and flaring is closely related to the treatment of waste gas from the production process, while the generator serves as an electricity producer for field needs, using part of the natural gas as fuel. As for other byproducts, such as condensate, they will be stabilized before being transported to the storage terminal. Produced water (PW) will be treated and then injected into injection wells. These processes are included within the scope of the analysis.

The functional unit used in this study is 1 million standard cubic feet per day (MMSCFD) for natural gas; and scope in gate-to-gate which assess the life cycle consists of natural resources input, all the way to natural gas production process.

Figure 2 System boundary use in Bunsa site LCA study

2.2 Life cycle inventory

This stage involves data collection and calculations to quantify the inputs and outputs of materials and energy associated with the product system in the LCA study (Lee and Inaba, 2004). Inventory analysis conducted on Emission data, Produced Water (PW) quantity, Water usage, Fuel consumption, Supporting Material (e.g. Ethylene Glycol/EG, Methyldiethanolamine/MDEA), Electricity produced (in MJ) are all gathered from primary source.

Natural resource accounted for this study are petroleum consists of gas, condensate and PW mixture that transferred directly from production well. These natural resources are an estimation which refer process flow diagram (PFD) and Mass Balance document; using the actual
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daily average production data which recorded at Custody Meter. The process along production life cycle is intended to achieve the natural gas and condensate sales characteristics, which the supporting material (EG and MDEA) consisted of liquid is converted to mass unit (kg) following the database used; adjusting to operational data on PFD and HMB. Produced water contributed to 97% of all Wastewater, which all PW are injected to Injection Wells.

Table 1 displays the Life Cycle Inventory for producing 1 MMSCFD of Natural Gas and Figure 3 shows the flow diagram of natural resource processing at the Bunsa Site within each process unit. Each process unit consists of several treatment units with their own pressure and temperature characteristics. According to Karn and Demiroglu (2023), these two parameters, along with others, affect the volume of a gas according to the ideal gas law (Karn and Demiroglu, 2023). In this study, the input and output of gas from each process unit are calculated from the actual average daily production based on the ratio according to each treatment unit design in the PFD and HMB. Therefore, there are some process units where the input and output with the same units (e.g., gas flow in MMSCFD and fuel gas in MMSCFD) do not balance due to: 1) each process unit includes several treatment units; for the purposes of the flow diagram, they are combined, resulting in some processing steps not being captured in detail, and 2) differences in pressure, temperature, mole of gas characteristics due to treatment process in each process unit.

The energy consumption in Bunsa Site mainly used in WHB-TOX for MDEA and EG regenerator reboiler unit, fuel gas in flaring to maintain its flame, drive turbines (generator) for energy production and fuel gas for compressor unit. The energy produced from generator is used to power electrical equipment either production process utility or domestic use; this energy production usage is not included in this study as its outside system boundary.

Waste produced in Bunsa Site production process are not included in this flow diagram. Although, this waste which consisted of hazardous waste and domestic waste are managed properly with the support from third parties. The emission for each process unit is an estimated calculation by emission factors, in accordance with Site emissions database.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Resources</td>
<td>MMSCFD</td>
<td>1.04</td>
</tr>
<tr>
<td>Supporting Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDEA</td>
<td>kg</td>
<td>0.76</td>
</tr>
<tr>
<td>EG</td>
<td>kg</td>
<td>0.72</td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>MJ</td>
<td>2,158,842</td>
</tr>
<tr>
<td>Fuel Gas</td>
<td>MMSCFD</td>
<td>0.067</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Use</td>
<td>M3</td>
<td>0.14</td>
</tr>
<tr>
<td>Produced Water</td>
<td>kg</td>
<td>1,529</td>
</tr>
<tr>
<td>Product</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sales Gas</td>
<td>MMSCFD</td>
<td>1.00</td>
</tr>
<tr>
<td>Condensate</td>
<td>bbls</td>
<td>5.83</td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>kgCO₂</td>
<td>3.637</td>
</tr>
<tr>
<td>CH₄</td>
<td>kgCH₄</td>
<td>4.07</td>
</tr>
<tr>
<td>N₂O</td>
<td>kgN₂O</td>
<td>1.96</td>
</tr>
<tr>
<td>SO₂</td>
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</tr>
<tr>
<td>NOₓ</td>
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</tr>
<tr>
<td>PM</td>
<td>kgPM</td>
<td>0.17</td>
</tr>
</tbody>
</table>

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3. Results and Discussion

3.1. Life cycle impact assessment

The general impact assessment resulted from consecutive steps such classification and characterization (Wu and Su, 2020). This study only classifies the impacts for global warming potential/GWP (kgCO$_2$-eq), particulate matter formation/PM (kgPM$_{2.5}$-eq), ozone formation/OF (kgNO$_x$-eq), terrestrial acidification/TA (kgSO$_2$-eq) since these data are provided specifically for substance concentration. The detailed data of each impact category are shown in below subsections.

3.1.1 Particulate matter formation

The total PM for natural gas production is estimated to be 0.52 kg PM$_{2.5}$-eq per 1 MMSCFD natural gas produced. The creation of particulate matter begins with the release of NO$_x$, NH$_3$, SO$_2$ which is then converted into secondary aerosols by atmospheric chemistry into the atmosphere, or primary PM emission (van Zelm et al., 2016). Figure 4 shows that the hotspot originates from the Inlet-Separation stage.

At this stage, a compressor unit is utilized to meet the required suction pressure for the subsequent stage. Fuel gas serves as the primary source of fuel to power the compressor. Figure 3 illustrates that the fuel gas volume for this stage is the most substantial at 0.03 MMSCFD in comparison to the other stages. PM emissions from turbines are mainly due to the carryover of noncombustible trace elements present in the fuel; this may be caused by the fuel gas predominantly originates from the natural gas input from the separation unit and bypasses the coalescing filter process, which is typical for the fuel gas used in generators to remove solids and carried-over liquid.

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Figure 4 Particulate matter midpoint

3.1.2 Global warming potential

Global Warming Potential (GWP) widely used to assess the environmental impact potential prior life cycle with Greenhouse Gas (GHG) emission as the indicator. The total GWP for natural gas production is estimated to be 3.555 kg CO$_2$-eq per 1 MMSCFD natural gas produced. Figure 5 shows that the hotspot originates from the Inlet Separation due to the operation of the compressor unit. Compared to the research by Muhyinsyah et al. (2021) for PHM-BSP, the GWP in this study is relatively higher (Muhyinsyah et al., 2021). Although both studies have similar hotspots, namely the operation of the compressor unit, the previous research was analyzed using the SimaPro application. The results of the study by Iswara et al. (2020) indicate a difference in GWP impact of up to 60% between SimaPro and OpenLCA (Iswara et al., 2020).

The combustion of fuel gas generates various emissions, including PM, CO$_2$, SO$_2$, and NO$_x$, all of which contribute to GWP emissions. Fuel gas consists of components such as N$_2$, CO$_2$, CH$_4$, and H$_2$S. During the process, O$_2$ is also burned in the compressor, resulting in the formation of NO$_x$ through the reaction between N$_2$ and O$_2$. Furthermore, at high temperatures, H$_2$S oxidizes into SO$_2$ (Khairulin et al., 2021). N$_2$O formation can occur when nitrogen-containing compounds react with NO and a radical from either HCN or NH$_3$, influenced by temperature and excess air during combustion (Colorado et al., 2017). Given that the fuel gas volume is the largest at this stage (0.03 MMSCFD), as shown in Figure 3, the emissions from Inlet-Separation are higher compared to other stages.

Figure 5 Global warming potential midpoint

3.1.3 Ozone formation

The total OF is estimated to be 3.36 kg NO$_x$-eq per 1 MMSCFD natural gas produced. Ozone (O$_3$) is well acknowledged as a major air contaminant that harms human health around the world. Precursor emissions of NO$_x$ and VOCs react in the environment to produce O$_3$ (Zhao et al., 2022). O$_3$ formation, specifically in troposphere layer, driven by NO$_x$ and VOC precursor going through photochemical reaction.

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Figure 6 shows that the hotspot originates from the Inlet-Separation, specifically operational of compressor. Most of the NO\textsubscript{x} produced by the thermal NO\textsubscript{x} mechanism, produced in the high-temperature areas when combustion air and fuel have sufficiently combined to create the peak temperature fuel/air contact. The compressor unit uses lean-premixed combustion technology to maintain a uniform air/fuel mixture and regulates the combustion process to avoid unwanted emissions (Energy Institute, 2022; Environmental Protection Agency, 2022). However, as Figure 3 indicates, the extensive use of fuel gas results in higher potential NOx emissions compared to other stages.

3.1.4 Terrestrial acidification

The term "terrestrial acidification" refers to the detrimental effects that atmospheric deposition of acidifying compounds, such as ammonia, nitrogen oxides, and sulfur oxides, has on terrestrial ecosystems by decreasing the pH of the soil (Gade et al., 2021). The total terrestrial acidification (TA) potential is estimated to be 1.72 kg SO\textsubscript{2}-eq per 1 MMSCFD natural gas produced. Its relatively lower than Pritasari (2023) research study result which have similar life cycle scope and production process prior to different impact assessment methodology used (Pritasari, 2023).

Figure 7 shows that the Inlet-Separation activity is the highest contributor to the TA impact. The gas sweetening stage functions to reduce the levels of acid gases (e.g., H\textsubscript{2}S and CO\textsubscript{2}) from the natural gas stream. The fuel gas used in the compressor unit during the Inlet-Separation stage is not pre-treated in gas sweetening; thus, there is a potential for higher levels of H\textsubscript{2}S in that fuel gas. The oxidation of H\textsubscript{2}S through the combustion of fuel gas in the compressor unit can lead to the formation of SO\textsubscript{2} (Roy et al., 2014).

Figure 6 Ozone formation midpoint and endpoint

Figure 7 Terrestrial acidification midpoint and endpoint

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3.2. Contribution analysis

The LCA approach can assess the impact of each activity stage within the system boundaries. This method is essential for understanding how emissions at each stage affect the total impact in each impact category. The contribution percentage of activities in each category is proportional to the overall environmental impact.

Figure 8 shows that the Inlet-Separation becoming a hotspot for every environmental impact. This stage contributes to PM (39%), GWP (45%), OF (54%), and TA (38%). The largest volume of fuel gas usage, along with the fact that most of the fuel gas sources come from inputs that do not pass through processing units (e.g., Gas Sweetening, Coalescing Filter), has a high composition of emission-forming components (e.g., H₂S, N₂). Therefore, it becomes the stage with the highest contribution to every environmental impact.

![Figure 8 Activity component contribution towards impact](image)

4. Conclusions

The production of 1 MMSCFD natural gas which includes inlet-separation, gas sweetening, gas dehydration, coalescing filter and other process such WHB-TOX, Flaring, PW Treatment and Generator equipment use resulted in GWP (3,555 kg CO₂-eq), FM (0.52 kg PM₁.₅-eq), OF (3.36 kg NOₓ-eq), and TA (1.72 kg SO₂-eq). Within this study, it recognizes that Inlet-Separation becoming hotspot for environmental impact due to the compressor unit's operation. To mitigate the resulting emissions, emission control devices like catalysts can be used to oxidize excess hydrocarbons and CO into H₂O and CO₂, and to convert NOₓ into N₂.

Nevertheless, it is necessary to evaluate each database from a software program to determine whether it can provide local databases better suited for evaluating the life cycle. Since the goal of impact assessment is to examine the input and output variables in each process with factors to generate the impact, the database and factors are significant variables in this study. As a result, inconsistent conversion factors will yield inconsistent outcomes.

References


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Environmental Protection Agency 2022, AP-42: *Compilation of Air Emissions Factors from Stationary Sources*.


Zhao, Y, Li, Y, Kumar, A, Ying, Q, Vandenberghhe, F & Kleeman, M J 2022, ‘Separately resolving NOx and VOC contributions to ozone formation’, Atmospheric Environment, 285, pp.119224.

doi: https://doi.org/10.7454/jmef.v3i2.1059