Life cycle assessment of natural gas and crude oil: case study in PT Pertamina Hulu Mahakam – BSP Site

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Abstract. Life cycle assessment (LCA) is a methodology for assessing the environmental impacts of a product. PT Pertamina Hulu Mahakam - BSP Site has conducted an LCA study to quantify the environmental impact of natural gas and crude oil producing and then identify the activities that give significant impact on the environment which is referred to as a hotspot. The methodology used in this LCA study refers to ISO 14040:2016 and 14044:2017. The impact categories considered are Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Photochemical Oxidant Creation Potential (POCP), Abiotic Depletion Potential - fossil (ADP-fossil), Human Toxicity Potential (HTP), Eco-Toxicity Potential (ETP), Land Used (LU) and Water Footprint (WFP). The result of this study identifies several activities in PT Pertamina Hulu Mahakam – BSP Site that can be categorized as hot spot: (1) The oil and gas extraction process, (2) Emission from transportation activities (3) Emission from electricity generator unit and compressor unit (4) Gas venting from surface facilities (5) Steel production that used in offshore platform infrastructure and (6) Fugitive emission from produced water. Several recommendations have been proposed to reduce the impact of those activities: reduce water content in the oil and gas extraction process, optimized transportation routes, use more environmentally friendly fuel for transportation activities, optimize the performance of compressor and electricity generator, and install the new offshore platform with a slimmer design. This study shows that LCA can help oil and gas producers to improve operational efficiency and reduce the impact on the environment to achieve sustainable development.

1. Introduction
Sustainability is conserving the natural environment for resources that directly or indirectly impact our survival and the environmental, economic, and social well-being of a community [1]. The ultimate goal of sustainable development is to achieve a balance between environmental, economic, and social sustainability [2]. Sustainability also becomes an important issue in the oil and gas industry to guarantee access to affordable and reliable energy which is essential for economic growth, sustain improvements in the quality of life, and the eradication of poverty [3]. Life Cycle Assessment (LCA) is the most widely used environmental sustainability assessment tools. LCA evaluates the environmental impact of a product, process, or activity throughout its life cycle or lifetime [4].
Environmental impacts include those from emissions into the environment and through the consumption resources, as well as other interventions (e.g. land use) associated with providing products that occur when extracting resources, producing materials, manufacturing the products during consumptions/use, and at the end of the product of life [5]. LCA in the oil and gas sector gives us the idea to enumerate the various emission, energy use, fuel usage, raw material requirement, resource consumption, material requirement related to each life cycle stages [6].

PT Pertamina Hulu Mahakam – Bekapai Senipah Peciko & South Mahakam Site (PHM – BSP) is an oil and gas producer located in the southern part of Mahakam Block in Kutai Kartanegara, East Kalimantan Province. PHM - BSP plays an important role in Mahakam Block operation following its Senipah Terminal which collecting crude oil and condensate production from other PHM production sites (including additional condensate production from other operators). Figure 1 shows the operation area of PHM - BSP.

![Figure 1. Operation area PT Pertamina Hulu Mahakam – BSP Site](image)

This study attempts to provide an assessment of environmental impacts for oil and gas production in PHM – BSP according to life cycle assessment perspective. This study refers to ISO 14040:2006 "Environmental management – Life cycle assessment – Principles and Framework" and ISO 14044:2006 "Environmental Management – Life Cycle Assessment – Requirements and Guidelines" and then identify the activities that gives a significant impact on the environment which referred as hotspot.

2. Method

ISO 14040:2006 mentioned that the framework of LCA consists of four steps: (1) goal and scope, (2) inventory analysis, (3) life cycle impact assessment, and (4) interpretation as shown in Figure 2 [7]. This study was conducted on all products produced by PT Pertamina Hulu Mahakam Lapangan BSP that is: Export Gas, Bekapai Crude Oil (BCO), Handil Mixed Crud (HMC), and Senipah Condensate (SCD).

2.1 Goal and scope

The goal of this study is to assess the environmental impact assessment from PHM BSP-Site activities and identified which activities that give a significant impact on the environment which is referred to as hotspot. The scope of this study is from cradle to gate system started from the acquisition of raw material (including raw material of supporting material), oil and gas extraction, process area until custody meter before being distributed to the consumer. Figure 3 shows the system boundary in this study. Treatment of hazardous waste and non-hazardous waste did not include in this study. The functional unit used in this study is 1 barrel (bbl.) for BCO, HMC, SCD, and 1 million standard cubic feet per day (MMSCF) for export gas.
2.2 Life cycle inventory

Inventory analysis conducted on natural resources, supporting material, energy, water, infrastructure, land use, wastewater, and emission. Due to PHM – BSP produces more than one product, so the allocation factor needs to be defined. The allocation factor in this study calculates by the amount of energy contained in each product. Allocation factors for natural gas, BCO, HMC, and SCD are 78.15%, 2.63%, 8.58%, and 6.77%, respectively. Table 1 shows the life cycle inventory of this study.
Natural resources accounted for this study are natural gas, condensate, and crude oil that directly transferred from the well. Gas and oil transferred from other PT Pertamina Hulu Mahakam's sites are not considered as natural resources in this study, for example, HMC product. Supporting material accounted for all additional material used in the drilling operation, well intervention processes area, and supporting the process. Supporting material is divided into the solid material (91.05%) and liquid material (8.95%). Material or substance used for cement and mud contributes more than 99% of solid material, meanwhile, chemical injection in the process area contributes to most of the liquid material.

**Table 1.** Life cycle inventory for producing 1 MMSCF export gas, 1 bbl SCD, 1 bbl HMC and 1 bbl BCO.

| Item                           | Export Gas | SCD   | HMC   | BCO   |
|--------------------------------|------------|-------|-------|-------|
| Natural Resource [MMSCF]       | 9.40E-01   | 5.24E-01 | -     | 1.00E+01 |
| Supporting Material            |            |       |       |       |
| Solid Material [kg]            | 1.64E+01   | 7.00E-02 | 7.00E-02 | 8.00E-02 |
| Liquid [L]                     | 1.62E+00   | 2.00E-01 | 4.00E-02 | 4.00E-02 |
| Energy                         |            |       |       |       |
| Electricity [kWh]              | 4.67E+01   | 2.00E-01 | 2.00E-01 | 2.00E-01 |
| Diesel [L]                     | 5.39E+01   | 2.30E-01 | 2.30E-01 | 2.40E-01 |
| Fuel Gas [MMSCF]               | 4.82E-03   | 2.03E-05 | 2.09E-05 | 2.11E-05 |
| Water                          |            |       |       |       |
| Water Use [m3]                 |            | 1.48E-03 | 1.52E-03 | 1.53E-03 |
| Total Wastewater [m3]          |            | 1.12E-01 | 1.15E-01 | 1.16E-01 |
| Infrastructure [kg]            | 1.12E-05   | 9.68E-07 | 1.23E-06 | 3.76E-07 |
| Land Use [m2]                  | 1.38E-07   | 1.20E-08 | 1.52E-08 | 4.65E-09 |
| Waste                          |            |       |       |       |
| Hazardous waste [kg]           | 9.10E+00   | 4.00E-02 | 4.00E-02 | 4.00E-02 |
| Non-hazardous waste [kg]       | 3.67E+01   | 1.60E-01 | 1.59E-01 | 1.60E-01 |
| Air Emission                   |            |       |       |       |
| CO₂                            | 1.55E+03   | 6.89E+00 | 7.09E+00 | 7.15E+00 |
| CH₄                            | 1.72E+00   | 1.00E-02 | 1.00E-02 | 1.00E-02 |
| N₂O                            | 1.20E-01   | 5.21E-04 | 5.36E-04 | 5.41E-04 |
| SO₂                            | 1.70E-01   | 7.43E-04 | 7.64E-04 | 7.71E-04 |
| NOₓ                            | 8.57E+00   | 3.82E-02 | 4.00E-02 | 4.00E+02 |

Energy consumption is an essential part of LCA. Electricity, diesel consumption, and fuel gas will be the energy consumption accounted for in this study. The highest energy consumption for electricity is LP (Low Pressure) booster compressor unit. Vessel transportation gives a significant contribution to diesel consumption following operation coverage of PHM – BSP operation in the offshore area. Electricity generator unit (Turbo Engine Generator – TEG) is the highest fuel gas consumption.

PHM – BSP uses water for drilling activities and supporting activities like office and camp. Water consumption only evaluates for activities or processes that take water directly from the environment. Water that transferred from other process or other PT. Pertamina Hulu Mahakam's site didn't account for this study. The impact assessment of water use is allocated only for oil and condensate product. The highest water usage is for supporting activities that cover 92.20% of total water use.

Steel is the most material used for construction in PHM-BSP. The infrastructure accounted for is the platform, pipeline, and processing area. Pipeline accounted as the highest infrastructure composition which is 68.81% of the total infrastructure. Land use accounted for in this study only land used for the processing area.
Waste produced by PHM – BSP categorized as hazardous waste and non-hazardous waste. Drilling activities dominance all waste produced in PHM –BSP for both hazardous (Synthetic based mud cutting) and non-hazardous waste (water based mud and water based mud cutting).

The emission of each operation unit is calculated by emission factors, which is a coefficient that allows converting activity data into GHG emissions. Several emission sources that don't have primary emission data, the emission data is calculated based on the database in EcoInvent.

2.3 Methodology for impact assessment
The methodology used to calculate the impact assessment are IPCC 100a, CML Baseline, Recipe 2016 Midpoint (H), and AWARE. IPCC 100a uses to evaluates the impact assessment for the GWP category. Recipe 2016 Midpoint (H) uses to evaluates impact assessment for AP, HTP, ETP, and LU. CML Baseline uses to evaluates impact assessment of EP, ODP, POCP, ADP, and ADP-Fossil. AWARE use to evaluates the impact assessment of WFP. Hotspot activities were determined by weighting the impact assessment result. Weighting was conducted by multiplying the normalized result of each impact category with the EF (Environmental Footprint) method [8].

3. Results and discussions
3.1 Life cycle impact assessment
Table 2 shows the result of eleven environmental impact categories for each PHM – BSP product in this study. Detailed information about each impact in this study is explained in the following subsections.

Table 2. The impact potential contributions in production of 1 MMSCF export gas, 1 bbl SCD, 1 bbl HMC, and 1 bbl BCO.

| Impact Category                  | Unit     | Gas Export | SCD    | HMC  | BCO  |
|---------------------------------|----------|------------|--------|------|------|
| Global warming potential (GWP)  | kg CO₂-eq| 2.41E+03   | 6.23E+00 | 5.89E+00 | 6.19E+00 |
| Acidification potential (AP)    | kg SO₂-eq| 3.66E+00   | 1.28E-02 | 1.00E-02 | 1.00E-02 |
| Eutrophication potential (EP)   | kg PO₄-eq| 1.27E+00   | 5.46E-03 | 6.15E-03 | 1.00E-02 |
| Ozone depletion potential (ODP) | kg CFC-11-eq | 2.00E-05 | 9.17E-08 | 7.29E-08 | 9.86E-08 |
| Photochemical Oxidant Creation Potential (POCP) | kg C₂H₄-eq | 7.80E-01 | 9.64E-04 | 5.62E-04 | 1.24E-03 |
| Abiotic Resource Depletion Potential (ADP) | kg Sb-eq | 2.78E-04 | 8.93E-07 | 1.35E-07 | 9.34E-07 |
| Abiotic Resource Depletion Potential - fossil (ADP) | MJ | 1.00E+06 | 2.59E+03 | 1.69E+02 | 6.13E+03 |
| Human toxicity potential (HTP)  | kg 1,4-DB-eq | 7.15E+01 | 2.10E+01 | 5.00E-02 | 2.80E-01 |
| Eco-toxicity potential (ETP)    | kg 1,4-DB-eq | 1.71E+02 | 6.10E-01 | 1.20E-01 | 6.10E-01 |
| Land used (LU)                  | m² a     | 1.17E+00   | 4.48E-03 | 1.87E-03 | 3.97E-03 |
| Water footprint (WFP)           | m²-eq    | 1.47E+01   | 2.57E+00 | 3.00E-02 | 2.82E+00 |

3.1.1 Global warming potential (GWP)
Greenhouse Gas (GHG) emission is an indicator of the impact of GWP. The GWP of Gas export is 2.41E+03 kg CO₂-eq, it means that to produced 1 MMSCF export gas will give 2,406 kg CO₂-equivalent to the environment. The same interpretation is also applicable for GWP of SCD, HMC, and BCO, to produce those products that will contribute 6.23 kg-CO₂-eq, 5.89 kg-CO₂-eq, and 6.19 kg CO₂-eq to the environment, respectively. Emission from MP (Medium Pressure) Compressor gives a major contribution to GWP for export gas production. In SCD production, emission from electricity generators gives a significant contribution to GWP. Meanwhile, in production HMC and BCO fugitive emission from produced water treatment is the main contributor to GWP. Figure 4 shows the GHG emissions from crude production [9]. The GHG emission for PHM-BSP products is relatively low,
below the global average upstream carbon intensity estimate for crude oil production which is 10.3 g CO2eq./MJ [10].

### 3.1.2 Acidification potential (AP)

The AP is contributed by SO2, NOx, SO3, NO2, and NH3 emission. AP for gas export, SCD, HMC and BCO production is 3.66 kg SO2-eq, 1.28E-02 kg SO2-eq, 1.00E-02 kg SO2-eq, and 1.00E-02 kg SO2-eq respectively. The major contributor for this AP in all products is diesel combustion from vessel transportation in the PHM-BSP area.

### 3.1.3 Eutrophication potential (EP)

Pollutant contributors to EP are NOx, NO2, NH3, and COD. EP value for gas export, SCD, HMC and BCO production is 1.27 kg PO4-eq, 5.46E-03 kg PO4-eq, 6.15E-03 kg PO4-eq, and 1.00E-02 kg PO4-eq respectively. The major contribution to this impact is the same as per the AP category which is diesel combustion from vessel transport in the PHM-BSP area.

![Figure 4. The GHG emissions from crude oil production](image)

### 3.1.4 Ozone depletion potential (ODP)

Ozone depletion potential accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone-depleting substances (CFCs, HFCs, and halons). ODP value for gas export, SCD, HMC and BCO production is 2.00E-05 kg CFC 11-eq, 9.17E-08 kg CFC 11-eq, 7.29E-08 kg CFC 11-eq, and 9.86E-08 kg CFC 11-eq respectively. The major impact of ODP comes from the indirect impact which is the diesel production process used in PHM activities.

### 3.1.5 Photochemical oxidant creation potential (POCP)

POCP quantifies the relative abilities of volatile organic compounds (VOCs) to produce ground-level ozone. Therefore, the highest contribution to these impact categories in PHM-BSP activities comes from venting gas and fugitive emission.

### 3.1.6 Abiotic depletion potential (ADP)

ADP defines the natural resources which are generally non-renewable such as iron ore, sand, air, etc. ADP value for export gas, SCD, HMC and BCO is 2.78E-04 kg Sb-eq, 8.93E-07 kg Sb-eq, 1.35E-07 kg Sb-eq, 9.34E-07 kg Sb-eq respectively. The major contribution to this impact category is the indirect impact that is the production of steel that use for platform, production of steel used for pipeline, and production of potassium chloride used in drilling mud.
3.1.7 Abiotic depletion potential-fossil (ADP - Fossil)
This impact category is specific to the depletion of fossil fuel. The ADP-Fossil value for export gas, SCD, HMC, and BCO is 1.00E+06 MJ, 2.59E+03 MJ, 1.69E+02 MJ, and 6.13E+03 MJ, respectively. This impact category determines by the amount of fossil extracted in terms of energy with the Mega Joule unit. Therefore, the impact contribution of gas export production is higher than crude oil due to the energy contained in natural gas is higher.

3.1.8 Human toxicity potential (HTP)
HTP defines the effect on individual human health that can lead to disease or death. HTP value for production of gas export, SCD, HMC and BCO is 7.15E+01 kg 1,4-DB-eq, 2.10E+01 kg 1,4-DB-eq, 5.00E-02 kg 1,4-DB-eq, and 2.80E-01 kg 1,4-DB-eq, respectively. Indirect impact gives significant impact on this category that is the production of steel that use for platform, production of steel used for pipeline steel production, and drilling mud's substance production.

3.1.9 Eco-toxicity potential (ETP)
ETP define impacts on the whole ecosystem that can decrease biodiversity that usually affected by emission of metal and organic chemical. ETP value for gas export, SCD, HMC and BCO is 1.71E+02 kg 1,4-DB-eq, 6.10E-01 kg 1,4-DB-eq, 1.20E-01 kg 1,4-DB-eq and 6.10E-01 kg 1,4-DB-eq respectively.

3.1.10 Land use (LU)
LU indicates the environmental impact of occupying, reshaping, and managing land for the human process [10]. LU value for producing gas export, SCD, HMC and BCO is 1.17E+00 m2 a, 4.48E-03 m2 a, 1.87E-03 m2 a, and 3.97E-03 m2 a, respectively. The major contributor to these impact categories is the indirect impact that is the production of substances used in drilling mud. Process area in PHM – BSP also gives a significant contribution to HMC and BCO production.

3.1.11 Water footprint (WF)
WF indicates the impacts of oil and gas production on the water resource. WF value for producing gas export, SCD, HMC and BCO is 1.47E+01 m3-eq, 2.57E+00 m3-eq, 3.00E-02 m3-eq, and 2.82E+00 m3-eq respectively. Diesel production, indirect impact, that use in transportation give a significant impact on Export Gas production and HMC. Meanwhile, oil extraction gives a significant impact on WF value for SCD and BCO.

3.2 Hotspot analysis
Hotspot analysis identified areas that need to be prioritized for action because it gives significant impact based on life cycle impact assessment. Table 3 shows five activities that are categorized as hotspot for each PHM – BSP product.

3.3 Improvement Opportunities.
Life cycle assessment has identified the PHM – BSP activities with a significant impact on the environment. The list of hotspot activities gives opportunities for PHM to improve operational efficiency and reduce the impact of those activities on the environment. Several improvement opportunities that will reduce the impact of hotspot activities are:

3.3.1 Reduce water content in oil and gas extraction process
Water is produced during the extraction process of oil and gas. This produced water will burden emission to the water and fugitive emission to the air. PHM – BSP develop MIFI (Mahakam Integrated Fluid Interpretation) that can interpret the fluid status of the wells so it can improve gas production and reduce the volume of produced water.
Table 3. Hotspot activities in oil and gas production at PHM - BSP

| No | Product | Hotspot Activities                                                                 |
|----|---------|-----------------------------------------------------------------------------------|
| 1  | Gas Export | a. Natural gas extraction process  
b. Gas venting at PHM-BSP site  
c. Emission from transportation and logistics activities  
d. Activities to produce steel that has been used in PHM – BSP Platform  
e. Emission from MP Compressor |
| 2  | SCD     | a. Emission from transportation and logistics activities  
b. Condensate extraction process  
c. Emission from electricity generator  
d. Emission to water from produced water  
e. Land use in PHM - BSP |
| 3  | HMC     | a. Condensate extraction process  
b. Emission from transportation and logistics activities  
c. Fugitive emission from oily water treatment unit  
d. Emission to water from produced water  
e. Emission from TEG |
| 4  | BCO     | a. Crude oil extraction process  
b. Emission from transportation and logistics activities  
c. Activities to produce steel that has been used in PHM – BSP Platform  
d. Fugitive emission from oily water treatment unit  
e. Emission from TEG |

3.3.2 Fuel monitoring and control system (FMCS)
PHM develop FMCS to monitor vessel movement and diesel consumption of each vessel. This FMCS system is digital based monitoring that consist of AVTS (Automatic Vessel Tracking) to control speed and vessel position, FMS (Fuel Measurement System) to track diesel consumption of each vessel, FIA (FMCS Integrated Algorithm), and module speed amnesty. All data produced by this system is evaluated periodically to optimize the fuel consumption of each vessel.

3.3.3 Dual diesel fuel
A dual diesel fuel engine is a diesel engine that can run on both gaseous and liquid fuels. Junli Shi et al. [11] reported that the application of Liquefied Natural Gas (LNG) in vehicles could reduce 42.62% of primary energy demand and reduce 46.42% global warming potential. So this system can give economic and environmental advantages.

3.3.4 Optimize energy performance of compressor and electricity generator
PHM – BSP conducts energy audits and implements ISO 50001: 2018 "Energy Management System" to achieve continual improvement for energy performance including energy efficiency. This standard will guide PHM – BSP to reduce energy use and therefore will reduce energy cost and greenhouse gas emission.

3.3.6 New offshore platform with slimmer design
To reduce the indirect impact of steel production, PHM will install a new minimalist platform with a 66% weight decrease in the PHM-BSP area. The 66% weight decrease will reduce the amount of steel that will be used in platform installation.

4. Conclusions
The life cycle assessment method can be used to assess the environmental impact of Export Gas, SCD, HMC, and BCO product in PHM - BSP. Life cycle assessment study also can identify several activities that are categorized as a hotspot in which has a significant impact on the environment. The
list of hotspots gives opportunities for the company to improve operational efficiency and reduce the impact on the environment from those activities so the oil and gas producer can contribute to achieving sustainable development.

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