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Implementation of Life Cycle Assessment (LCA) and Analytical Hierarchy Process (AHP) for Greenhouse Gas Impact Analysis and Its Emission Control in Crude Oil Production Processes

Clairine Sola Gratia Hagins[1], Joni Hermana[2]

[1]Magister of Environmental Management Program, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, 60111

[2]Environmental Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, 60111

ABSTRACT: Company X is one of the entities operating in the oil and gas industry that is required to contribute to Indonesia's Nationally Determined Contribution (NDC) targets for reducing greenhouse gas emissions. This obligation aligns with the achievement of the Zero Routine Flaring (ZRF) 2030 target, as stipulated in the Ministry of Energy and Mineral Resources Regulation No. 17 of 2021 concerning the Implementation of Flare Gas Management in Oil and Gas Business Activities, which mandates the elimination of routine flaring by 2030. Currently, Company X has undertaken efforts to reduce emissions in its crude oil production processes. However, it faces significant challenges, particularly in meeting the 2030 target of a 29% reduction in CO_2 which are critical to the sustainability of its business operations.

To ensure effective emission reduction, it is essential to control greenhouse gas emissions at the sources that contribute most significantly to air pollution within the crude oil production process. In this regard, Company X needs to adopt a Life Cycle Assessment (LCA) approach using SimaPro 9.5 software, which can identify the magnitude of environmental impacts and pinpoint the most impactful activities (hotspots). The LCA will employ the EDIP (Environmental Design of Industrial Products) 2003 method to quantify air pollution impacts in the categories of global warming, ozone depletion, ozone formation (human), and human toxicity (air), within the cradle-to-gate scope of Company X's crude oil production process. The next step involves determining the most effective improvement alternatives using the Analytical Hierarchy Process (AHP) with Expert Choice software. Inputs for the criteria and improvement alternatives for each selected hotspot will be obtained from five respondents through pairwise comparisons to identify the optimal emission control strategy.

KEYWORDS: life cycle assessment, analytical hierarchy process, EDIP 2003, SimaPro, Expert Choice, emission control in crude oil production processes

INTRODUCTION

Global warming caused by greenhouse gas (GHG) emissions has intensified in recent years. Since the baseline year, direct warming effects from human-induced GHGs have increased by 49%, with the AGGI index reaching 1.49 W/m² by the end of 2021 (Taryono, 2022). The oil and gas industry in Indonesia plays a significant role in contributing to GHG emissions. According to the Ministry of Energy and Mineral Resources (2013), greenhouse gases emitted by the energy sector include nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). CO_2 emissions dominate those from fossil fuel combustion processes, including flaring, venting, and the use of chemicals. This study emphasizes the importance of measuring and analysing the environmental impact of GHG emissions from crude oil production. To evaluate this, the Life Cycle Assessment (LCA) method is used to identify emission hotspots during drilling and fluid processing stages. This helps determine effective GHG emission control strategies based on priority (Supriyono, et al., 2007). The study also integrates the Analytical Hierarchy Process (AHP) to support decision-making by ranking alternatives based on predefined criteria. Company X, a major oil and gas company, struggles to meet its CO_2 reduction target which is 29% to not affecting business continuity. The study proposes the combined use of LCA (supported by SimaPro software) and AHP (supported by Expert Choice software) to design effective emission control improvements. These findings aim not only to optimize production systems at Company X but also to provide applicable insights for other upstream oil and gas industries pursuing cleaner production initiatives.

METHOD

This study establishes a structured framework to systematically guide research on reducing greenhouse gas (GHG) emissions in crude oil production. The primary objectives are to identify emission-related activities, quantify emission burdens, and propose process improvement alternatives. The study proceeds through sequential stages: formulation of research objectives, literature review, and the collection of both primary and secondary data. GHG emissions are assessed using the Life Cycle Assessment (LCA) method, implemented via SimaPro 9.5 software. Initial implementation involves secondary data collection and LCA modelling in SimaPro, followed by primary data acquisition through questionnaires to support the AHP-based prioritization of mitigation strategies.

Questionnaires are designed to assess various GHG mitigation alternatives and assign weights to criteria relevant to emission control in crude oil production. Primary data are obtained from five respondents with expertise in production operations, emission control system design, and environmental regulation. Secondary data including raw material input, emission test results, production volumes, and equipment specifications are entered into the Life Cycle Inventory (LCI) for analysis using SimaPro in scope of cradle-to-gate. Data interpretation focuses on upstream production processes, from drilling and steam injection (cradle) to facilities such as gathering stations, steam generators, gas turbine power plant, and sand management facility (gate). The Life Cycle Impact Assessment (LCIA) using EDIP (Environmental Design of Industrial Products) 2003 method includes classification, characterization, normalization, and weighting stages to quantify and compare the environmental impact of each unit process, particularly in terms of GHG emissions to air (e.g., CO_2, CH_4, N_2O, SO_2, NO_2, and PM). Monte Carlo simulation is employed to conduct sensitivity analysis, further strengthening the robustness of LCA findings.

The resulting emission profiles from LCA inform the development of potential improvement strategies. These alternatives are then evaluated using the Analytical Hierarchy Process (AHP), supported by Expert Choice software, considering both technical and financial aspects. Financial performance is assessed using the Life Cycle Cost (LCC) approach to support objective decision-making.

RESULT AND DISCUSSION

Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique used to evaluate the environmental aspects and potential impacts associated with a product. This is achieved by compiling an inventory of relevant inputs and outputs of the product system, assessing the potential environmental impacts associated with those inputs and outputs, and interpreting the results from the inventory analysis and impact assessment phases in relation to the objectives of the study (ISO 14040, 2006). There are four key components involved in conducting a Life Cycle Assessment (LCA), namely:

1. Determination of goal and scope
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation and conclusion

Determination of goal and scope

The goal of this LCA is to analyze the magnitude of environmental impacts in the form of greenhouse gas emissions throughout the life cycle of crude oil production processes at Company X. The LCA analysis was conducted using the SimaPro software version 9.5, encompassing impact categories related to air pollution caused by greenhouse gas emissions. It also aims to identify the activities that contribute most significantly to these impacts, thereby providing the basis for recommending alternative emission control strategies to reduce greenhouse gas emissions within Company X's operations. The scope of this LCA covers a cradle-to-gate system boundary for Company X's crude oil production processes that is divided into three main groups:

1. Raw material acquisition processes, which include drilling activities, Wellhead 5, Wellhead 10, and steam injection
2. Core processing units, comprising Gathering Station 10 and Gathering Station 5
3. Supporting facilities, which consist of the Casing Vapor Collection (CVC) system, Power Generation and Distribution units, Central Steam Generating Station, and Oily Sand Treatment Facility.

Steam is utilized in the oil field of Company X to lower the viscosity of crude oil, enhancing its mobility and efficiency during the extraction process.

Life Cycle Inventory

The inventory data used in this Life Cycle Inventory (LCI) was sourced from Company X's 2023 dataset.

Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is an environmental impact evaluation stage that applies methods tailored to the geographical context and materials under study. All impacts arising from resource use and emissions are categorized and quantified into specific impact categories, which are then weighted based on their relative contribution. In this study, the LCIA phase was conducted using the SimaPro software, applying the EDIP (Environmental Design of Industrial Products) 2003 impact assessment method. This process yielded outputs including impact categories, characterization values, normalization results, and weighting factors. The EDIP 2003 methodology complies with all ISO 14042 requirements and recommendations, offering a comprehensive framework for evaluating multiple environmental impact categories, including global warming, ozone depletion, ozone formation (human health), and human air toxicity.

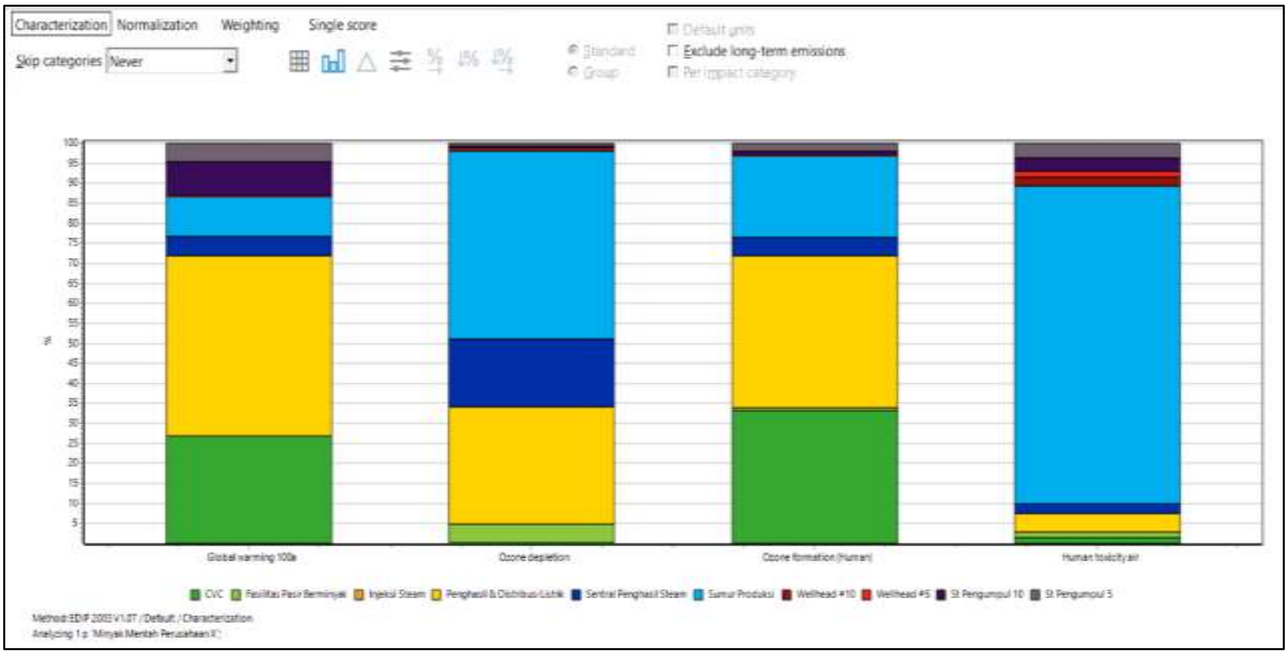

Figure 1. Result of Process Unit Characterization

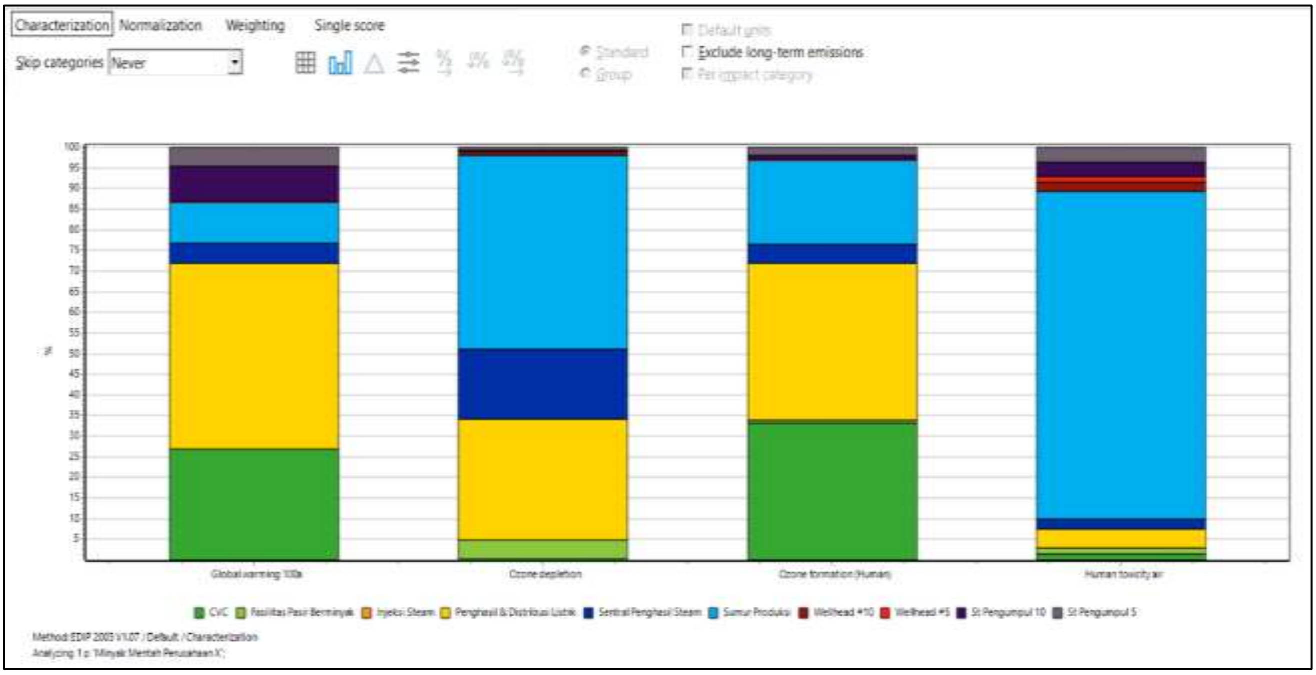

Figure 2. Result of Process Unit Normalization

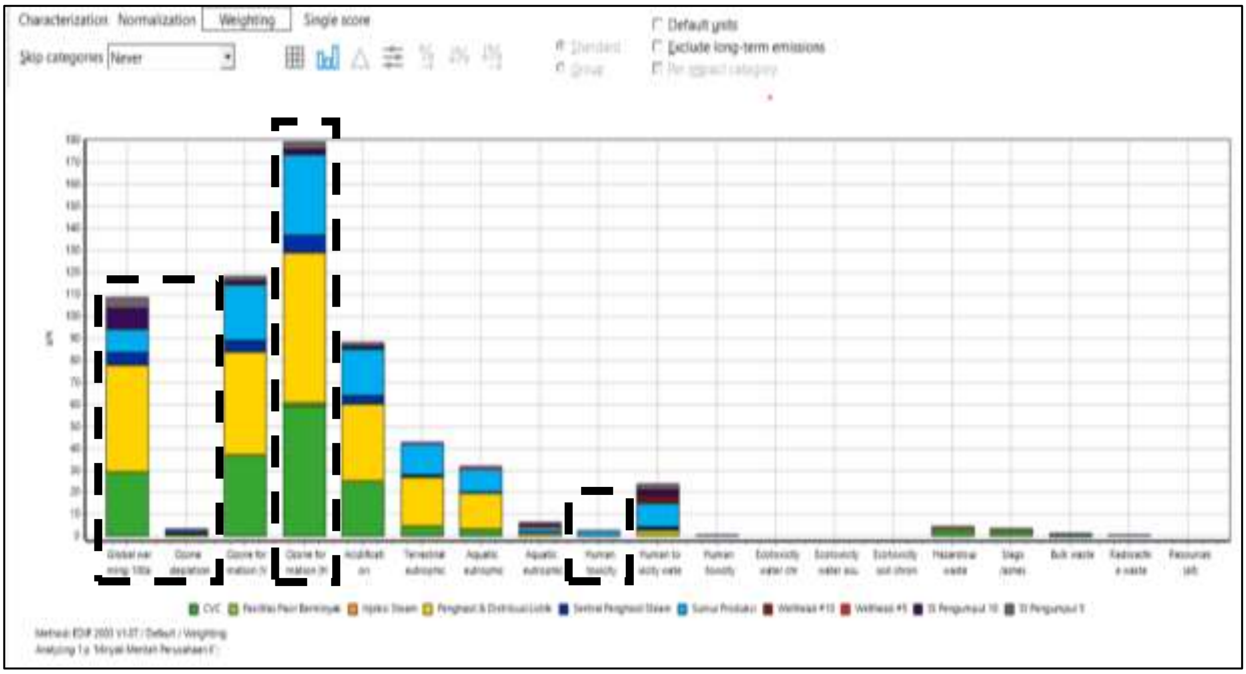

Figure 3. Result of Process Unit Weighting

In the weighting stage of the analysis, all impact values were converted into the same unit, kPt, which enables a clearer and more coherent comparison across impact categories. Based on the results, ozone formation (human health) and global warming emerged as the dominant environmental impact categories in the crude oil production process at Company X. The Power Generation and Distribution unit, classified under supporting processes, was identified as the primary contributor to both ozone formation (human health) and global warming impacts. Within the core processes, Gathering Station 10 contributed most significantly to global warming, while Gathering Station 5 had the highest contribution to ozone formation (human health). For the raw materials acquisition phase, the Production Wells were found to be the largest contributors to both impact categories.

Interpretation and Hotspot Analysis

Based on the impact categories assessed using the EDIP 2003 method, Global Warming 100a and Ozone Formation (Human) represent the highest potential environmental impacts. The total impact associated with Global Warming is 109 kPt, while Ozone Formation (Human) reaches 179 kPt. Assuming alignment with Company X's targeted CO_2 emissions reduction of approximately 29%, this goal would significantly reduce the Global Warming impact to 77.39 kPt.

Table 1. Environmental Impact Weighting Results According to EDIP 2003 Methodology

Impact Category	Unit	Total
Global warming 100a	kPt	109
Ozon *depletion*	kPt	3.58
Ozone formation (*Human*)	kPt	179
Human toxicity air	kPt	2.73

Each process unit was analysed to identify the major contributors to the most significant impact categories, serving as environmental hotspots. Two main considerations were used in determining these critical points:

1. The linkage between the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), the full range of impacts resulting from the inventory data developed in this study. Figures 4 and 5 present the distribution of impacts based on the input data processed in SimaPro 9.5. In general, these figures indicate that, when comparing the cradle system boundary to the gate system boundary, emissions exhibit greater variability in the gate system boundary.

2. The results of the LCIA using the EDIP 2003 method based on Figure 3, when each process unit is examined, the Power Generation and Distribution, Casing Vapour Collection (CVC), Gathering Station 10, and Production Wells are identified as the major emission contributors.

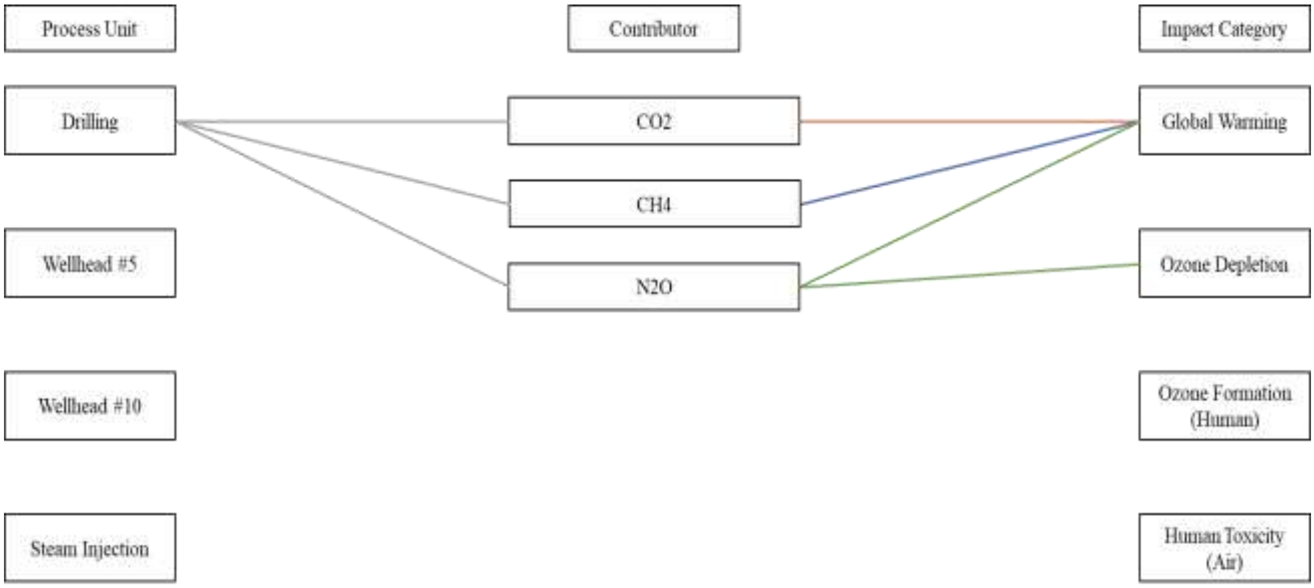

Figure 4. Linkage Between Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) in the Cradle System Boundary

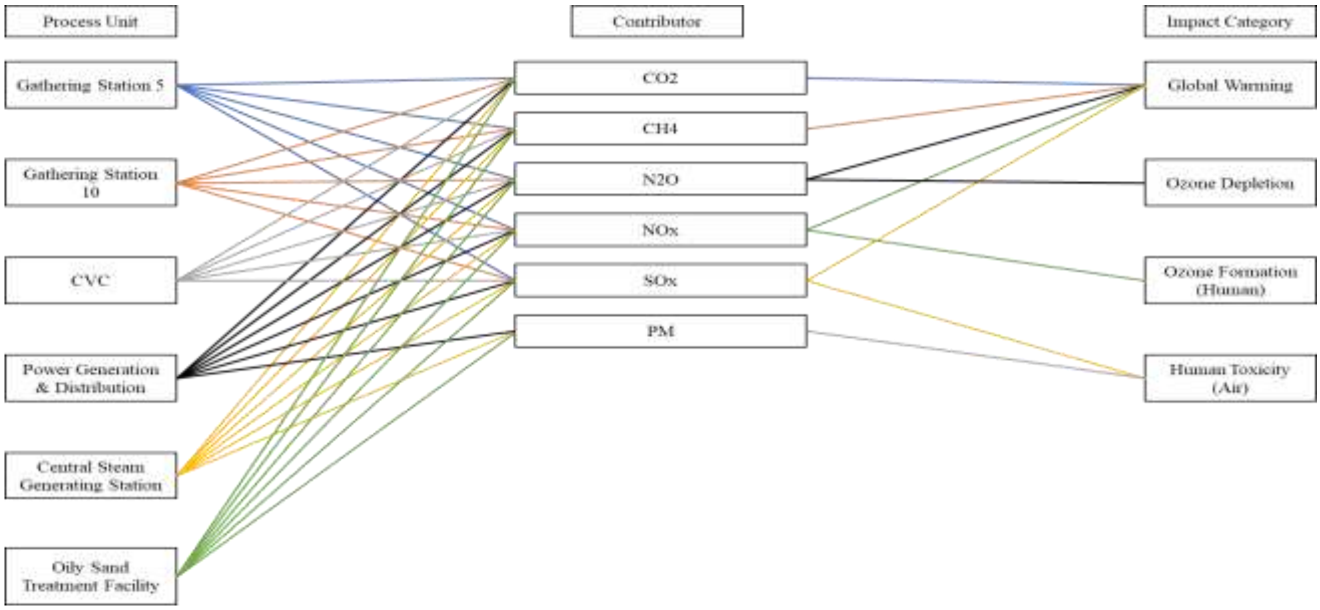

Figure 5. Linkage Between Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) in the Gate System Boundary

These two considerations ultimately converge on identifying the critical hotspot within the gate system boundary, selection is made based on the classification of process units into core processing unit and supporting facilities:

1. In the core processing unit of crude oil production, Gathering Station 10 is identified as a key hotspot due to its significant and variable contributions to the Global Warming impact category. This can be attributed to the larger volume of oil fluids processed at this facility compared to other gathering stations, as well as the continued use of an open flare stack to combust associated gas, an activity with notable potential for air pollution.
2. In the supporting facilities, the Power Generation and Distribution unit is recognized as a major hotspot, again due to its high and variable contribution to the Global Warming impact category. This is primarily due to Company X operating its own gas turbine-based power plant to support crude oil production.

Sensitivity Analysis

Sensitivity analysis aims to identify the most influential input variables. A local one-at-a-time approach is employed due to its computational simplicity and the ease with which the results can be interpreted and communicated. Consequently, this technique has become one of the most widely used methods in the scientific community over the past decades (Saltelli et al., 2006). Sensitivity analysis in this study was performed using Monte Carlo simulation, which is employed to assess the influence of uncertainty and variability within the LCA framework. The sensitivity analysis targeted both cradle and gate system boundary data, evaluating each emission-related impact category and LCIA stage based on the EDIP 2003 method, as simulated in the SimaPro 9.5 software. The resulting environmental impact ranges, derived from uncertainty analysis, span from the 2.5th percentile (lower bound) to the 97.5th percentile (upper bound), corresponding to a 95% confidence level.

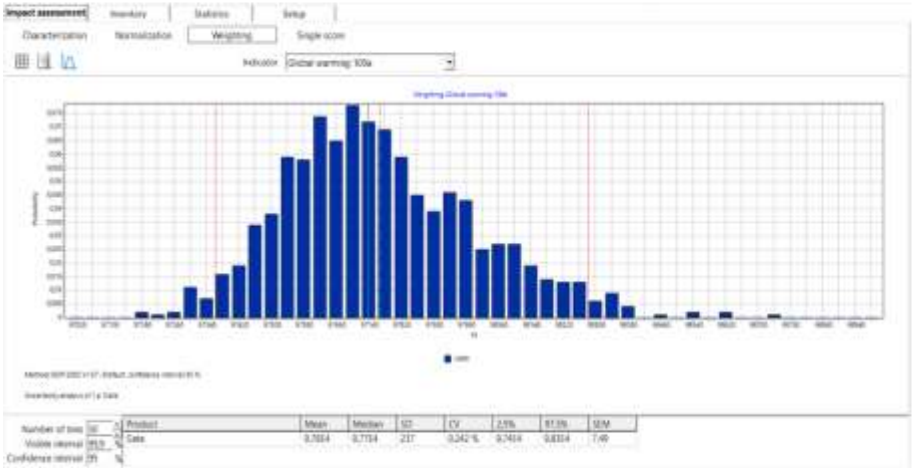

Figure 6. Results of Monte Carlo-Based Sensitivity Analysis for Weighted Global Warming Impact in the Cradle System Boundary

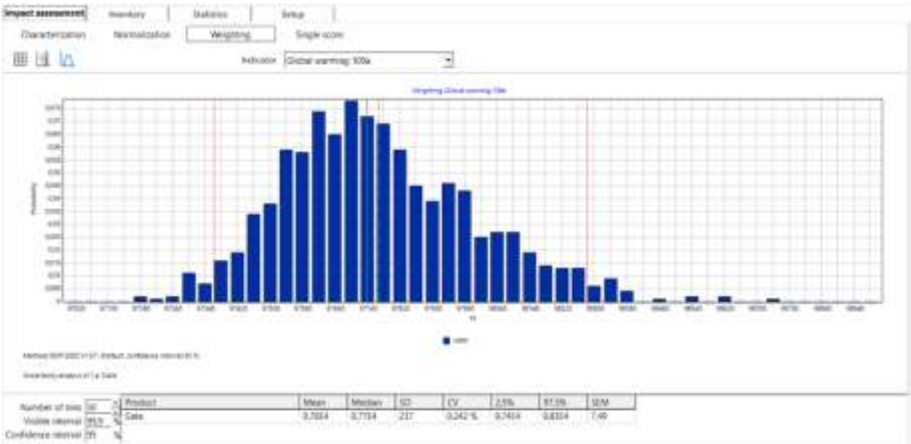

Figure 7. Results of Monte Carlo-Based Sensitivity Analysis for Weighted Global Warming Impact in the Gate System Boundary

Based on the results of the sensitivity analysis, within the cradle system boundary, the Global Warming impact category exhibits a narrow and symmetrical distribution, indicating that the results are stable and reliable. Ozone Depletion shows a wider distribution, suggesting a moderate level of uncertainty. Ozone Formation (Human) displays a very broad distribution, reflecting high uncertainty, while Human Toxicity Air appears to yield invalid results, as indicated by a confidence interval that is both equal and negative. In the gate system boundary, both Global Warming and Ozone Formation (Human) exhibit very narrow and symmetrical distributions, indicating highly stable and reliable results. Ozone Depletion has a wider distribution, suggesting greater uncertainty. Human Toxicity Air, despite its relatively small magnitude, shows a fairly narrow distribution and yields reasonably stable results.

In addition to the Monte Carlo simulation, the sensitivity analysis also involved testing the effects of varying key assumptions and data inputs within a defined range of ±29%, which corresponds to Company X's targeted CO_2 emissions reduction by 2030. A variation is considered significant if the resulting change exceeds 10%, as stipulated in ISO 14044:2016. Based on the LCA results, the key driver of environmental impact at the Gathering Station 10 hotspot is hydrocarbon fluid throughput, while at the Power Generation and Distribution hotspot, it is electricity consumption. Sensitivity analysis was performed by adjusting the inventory data for oil fluid and electricity usage by +29% and –29%. The resulting changes in impact values exceeded 10%, confirming that a 29% reduction represents the minimum threshold for effective emissions reduction in determining alternative mitigation strategies for each respective hotspot.

Table 2. Adjustment of Hotspot Inventory

Hotspot	Inventory	+ 29%	Normal	-29%	Units
Gathering Station	Hydrocarbon fluid	18,855,465.69	14,616,640.07	10,377,814.45	TOE
Power Generation and Distribution	Electricity consumption	2,364,684.04	1,833,088.40	1,301,492.76	kWh

Table 3. Adjustment of Hotspot Weighting Result

Hotspot	Weighting (kPt) + 29%	Normal Weighting (kPt)	Weighting (kPt) - 29%	% Impact Change
Gathering Station	12	9.18	6.52	>10
Power Generation and Distribution	57.8	49	40.2	>10

The resulting changes in impact values exceeded 10%, confirming that a 29% reduction represents the minimum threshold for effective emissions reduction in determining alternative mitigation strategies for each respective hotspot.

Analytical Hierarchy Process

The steps employed in the Analytical Hierarchy Process (AHP) are as follows (Saaty, 2008):

1. Define the goal, criteria, and alternatives, and structure them into a hierarchy.
2. Establish priorities or weights for each criterion by conducting pairwise comparisons, forming a judgment matrix. The weights are derived in accordance with Table 2.1, followed by a consistency check using Table 2.2.
3. Develop limited preferences or local priorities for each alternative, based on each criterion. Normalize and verify consistency of judgments as needed.
4. Aggregate the overall priorities of each alternative by calculating the weighted sum of local priorities. The alternative with the highest overall priority is considered the optimal choice.
5. Conduct sensitivity analysis to examine the impact of changes in criterion weights and understand the robustness of the results.
6. Make a final decision based on model synthesis and the outcomes of the sensitivity analysis to select the most appropriate alternative.

Element Identification

The LCA results identified two primary hotspots contributing to air pollution through greenhouse gas (GHG) emissions in the crude oil production process: the Gathering Station 10 unit and the Power Generation and Distribution unit. Gathering Station 10 functions as the receiving unit for fluids from production wells, where oil is separated from water, gas, and solids/mud before being transferred to the shipping line. Currently, emission control at this facility relies on a flare stack, which emits CO_2, CH_4, N_2O, NO_x, and SO_x during gas combustion. The Power Generation and Distribution unit is a gas-fired power plant that supplies electricity through turbines with a capacity of 20 MW. The electricity is transmitted via 115 kV and 230 kV lines to substations distributed across Company X's operational areas. Currently, the steam required to enhance crude oil production in the Company's field is also generated by this unit. Moreover, several machines within this facility are not yet equipped with catalytic converters for emission reduction. As a result, the Power Generation and Distribution unit contributes significantly to emissions of CO_2, CH_4, N_2O, NO_x, SO_x, and particulate matter (PM).

Development of the Hierarchical Structure

The objectives considered within the AHP process are as follows:

1. Determination of emission control improvement alternatives for the Gathering Station 10 process unit
2. Determination of emission control improvement alternatives for the Power Generation and Distribution process unit

The criteria incorporated within the AHP to achieve these objectives include:

1. Environmental Impact: This refers to the environmental burdens generated by the processes at Gathering Station 10 and the Power Generation and Distribution unit, as identified through LCA results, as well as the extent to which each alternative measure can technically mitigate these impacts to achieve Company X's targeted 29% emission reduction.
2. Financial Aspect: This includes the total cost and Net Present Value (NPV) derived from the Life Cycle Cost assessment of each emission control alternative.
3. Ease of Implementation: This criterion encompasses the availability of resources, technical complexity, implementation timeline, and coordination feasibility associated with executing each emission control alternative.

Several alternative GHG emission control strategies are proposed for implementation at Gathering Station 10:

1. Replacement of the existing flare stack with an Enclosed Ground Flare (EGF)
2. Utilization of flare gas through Carbon Capture and Storage (CCS) technologies
3. Conversion of flare gas via Gas-to-Liquid (GTL) or Gas-to-Chemical (GTC) processes
4. Use of flare gas for electricity generation, commonly referred to as Gas-to-Wire (GTW)

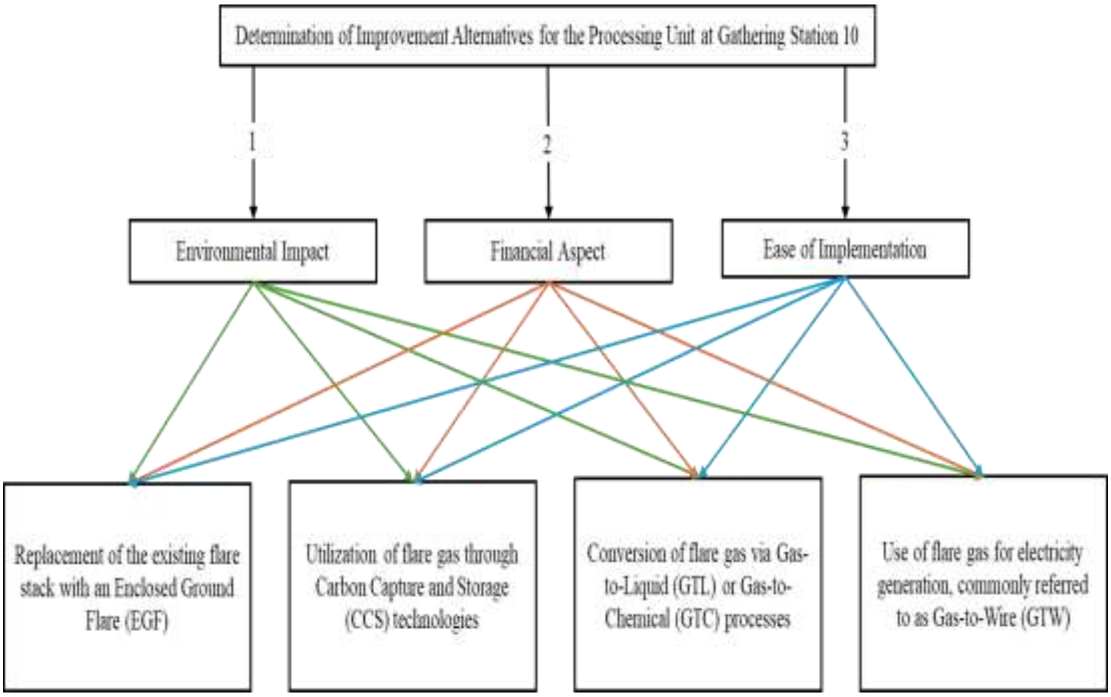

Figure 8. Hierarchy of Emission Control Improvement Alternatives at Gathering Station 10

Proposed mitigation strategies for reducing GHG emissions from Power Generation and Distribution unit include:

1. Replacing the electricity and fuel gas supply with solar energy or solar-generated steam, particularly for enhanced oil recovery (EOR) operations
2. Utilizing emitted gases through Carbon Capture and Storage (CCS) technology
3. Installing catalytic converters on gas turbine exhaust systems used at the power plant

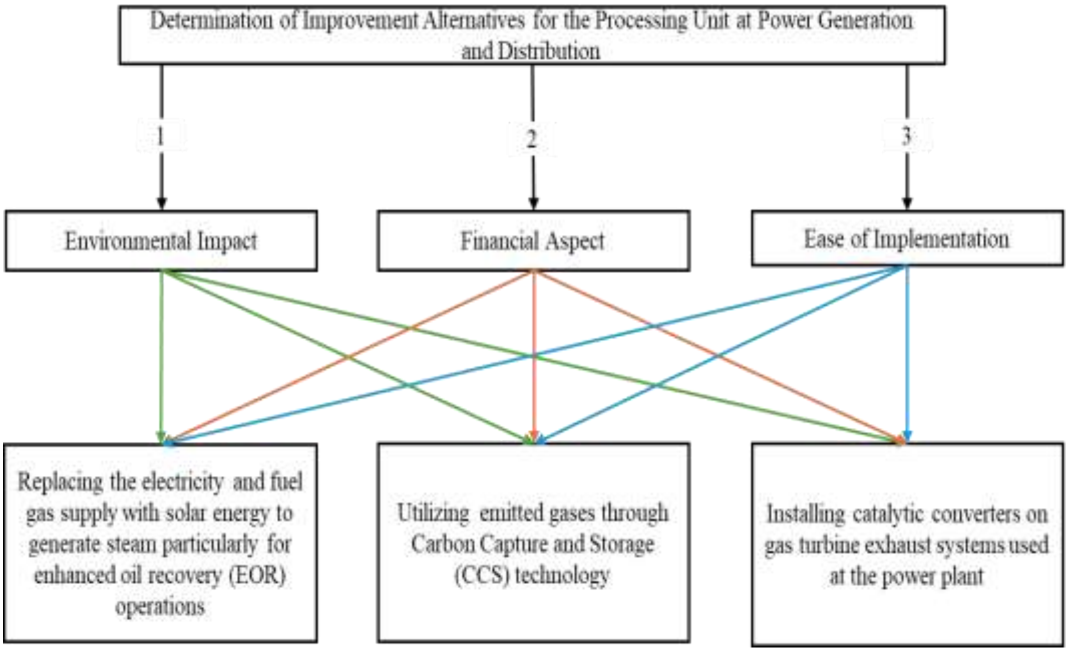

Figure 9. Hierarchy of Emission Control Improvement Alternatives at Power Generation and Distribution

Evaluation of Criteria and Alternative Measures for Emission Control Improvement

The assessment of these elements is conducted using a pairwise comparison scale. Each criteria and alternative measure for greenhouse gas emission control across all process units is compared against one another to determine their relative importance.

Table 4. Definition of Pairwise Comparison Scale According to Saaty (1980)

Level of Importance	Definition
1	Same importance
2	Preference between same and moderate
3	Moderate preference
4	Preference between moderate and strong
5	Strong preference
6	Preference between strong and very strong
7	Very strong preference
8	Preference between very strong and absolute
9	Absolute preference

Weight Calculation

Once all 5 respondents consists of Manager Environment, Senior Environmental Engineer, Senior Facility Engineer, HSE Field Officer, and Air Pollution Expert from Company X have completed the rating scale in the questionnaire, the assigned scales are then weighted using the Expert Choice software.

Determination of Priority Scale

The prioritization of alternatives was conducted following the weighting of each criterion and emission control alternative using the Expert Choice software. At Gathering Station 10, the highest-priority emission control alternative is flare gas utilization for Gas-to-Wire (GTW), with a priority score of 0.557 (56%). This is followed by the replacement of the flare stack with an enclosed ground flare (0.189 or 19%), flare gas-to-liquid conversion (0.131 or 13%), and flare gas capture using carbon capture technologies (0.123 or 12%). In the Power Generation and Distribution unit, the top-ranked emission control alternative is the installation of catalytic converters on gas turbines, with a priority score of 0.411 (41%). This is followed by the replacement of electricity and fuel gas sources with solar energy to generate steam (0.302 or 30%), and the utilization of emitted gas through Carbon Capture and Storage (CCS) (0.287 or 29%).

Determination of Alternative Greenhouse Gas Emission Control

Environmental impact emerged as the most critical criterion in selecting emission control improvement alternatives at the identified hotspot, with a weight of 0.474 (47%). The top-priority emission control alternative at this hotspot is flare gas utilization through Gas-to-Wire (GTW), with a priority score of 0.557 (56%). This alternative is considered the most favorable because it can significantly reduce emissions at the hotspot, is more cost-effective compared to other alternatives, and is relatively easy to implement within Company X's operational context. In the Power Generation and Distribution process unit, inputs from the five respondents were aggregated and analyzed using Expert Choice software to derive weightings. The Environmental Impact criterion emerged as the most critical factor in determining emission control alternatives at this hotspot, with a weight of 0.514 (51%). The top-priority emission control alternative is the installation of catalytic converters on gas turbines, with a priority score of 0.411 (41%). This alternative is regarded as the most suitable due to its effectiveness in reducing emissions at the hotspot, cost-efficiency compared to other options, and ease of implementation.

CONCLUSIONS

This study assesses the environmental impacts of crude oil production at Company X using Life Cycle Assessment (LCA) with the EDIP (Environmental Design of Industrial Products) 2003 method implemented in SimaPro 9.5, focusing on emissions from cradle-to-gate. The analysis identifies that the greatest environmental burdens are associated with global warming (109 kPt) and ozone formation (human) (179 kPt). The main emission "hotspots" are Gathering Station 10 Unit and the Power Generation and Distribution Unit, which significantly contribute to CO_2, CH_4, NO_x, and PM emissions. To identify optimal mitigation strategies, the study employs the Analytical Hierarchy Process (AHP) via Expert Choice software, considering environmental impact, financial feasibility (Life Cycle Cost or LCC), and implementation ease. Alternatives such as Gas-to-Wire (GTW) technology at Gathering Station 10 Unit and Selective Catalytic Reduction (SCR) technology at the Power Generation and Distribution Unit were prioritized based on expert input. GTW yielded the highest priority (56%) due to its emission reduction potential and positive NPV, while SCR was ranked highest (41%) for the power unit despite a negative NPV. The study also uses sensitivity analysis and Monte Carlo simulation to validate the robustness of the LCA outcomes and inform emission reduction targets aligned with Company X's 2030 goals. Findings support the integration of LCA and AHP in environmental management decision-making and provide a replicable framework for emissions mitigation in upstream oil and gas operations.

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