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Carbon Footprint Assessment of a Combined Cycle Gas Turbine (CCGT) Power Plant from a Life Cycle Perspective: A Case Study of Energy Transition in Indonesia

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ABSTRACT

Climate change, driven by greenhouse gas (GHG) emissions, necessitates transformative shifts in the global energy sector. This is particularly critical for Indonesia, which continues to rely heavily on fossil fuels. In this context, Combined Cycle Gas Turbine (CCGT) power plants have emerged as a potential transitional technology, offering higher efficiency and lower operational emissions than coal-fired power plants. This study employs a Life Cycle Assessment (LCA) framework to analyze the carbon footprint of a CCGT power plant in Indonesia, providing a comprehensive evaluation of its environmental impacts across all stages—from fuel extraction to plant operation and electricity distribution. The findings reveal that the natural gas combustion process and upstream gas production are the primary contributors to the total emissions, accounting for approximately 0.473 kg CO_2-eq/kWh and 0.26 kg CO_2-eq/kWh, respectively. Despite these emissions, the CCGT plant demonstrates a significantly lower carbon footprint compared to coal-fired power generation. The study also identifies key strategies for mitigating emissions, including enhancing methane leak detection technologies, optimizing natural gas transportation, and integrating Carbon Capture and Storage (CCS). Based on these findings, we provide technical and policy recommendations to support a sustainable energy transition in Indonesia.

1. INTRODUCTION

Climate change is a multidimensional and urgent global challenge, primarily driven by greenhouse gas (GHG) emissions that cause global warming. The rise in GHG emissions—predominantly carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O)—is strongly correlated with anthropogenic activities, with the energy sector being the largest contributor globally. This is also the case in Indonesia, which continues to rely heavily on fossil fuels to meet its energy demands (Tyas & Prakoso, 2022). Consequently, the transformation of the energy sector has become a crucial element of climate change mitigation strategies. In response to this challenge, the international community has established several policy frameworks, most notably the Paris Agreement of 2015. Under this agreement, nations committed to limiting the global average temperature increase to well below 2°C above pre-industrial levels and to pursue efforts to limit the rise to 1.5°C (Ekardt et al., 2018; Bokde, 2020). Aligning with this global effort, Indonesia has adopted Nationally Determined Contributions (NDCs), pledging to reduce emissions by 29% through domestic efforts or by up to 41% with international support by 2030 (Tyas & Prakoso, 2022).

To address emissions from the energy sector, a global transition towards renewable energy sources and the adoption of high-efficiency technologies are imperative. Numerous studies have demonstrated that renewable energy integration and the deployment of low-carbon technologies can significantly contribute to achieving emission reduction targets (Soza & Ayres, 2018; Bréchet et al., 2016). For Indonesia, the energy transition is an increasingly urgent strategic priority, driven by the escalating impacts of climate change and the nation's high GHG emissions. The national energy supply structure remains heavily dominated by fossil fuels, with coal accounting for approximately 60% of the primary energy mix (Bokde, 2020). This dependence not only positions the energy sector as a major source of emissions but also highlights the critical need to accelerate the shift towards a cleaner and more sustainable energy system, as mandated by Indonesia’s NDC targets and its commitments under the Paris Agreement.

Combined Cycle Gas Turbine (CCGT) power plants have emerged as a strategic solution for Indonesia's energy transition, offering a unique combination of high efficiency and lower emissions. This power generation system integrates gas and steam turbines into a single cycle. Natural gas is used as the primary fuel to drive the gas turbines, while the waste heat from the exhaust is recovered to generate steam that drives a secondary turbine (Bokde, 2020). This configuration achieves a thermal efficiency of up to 60% under optimal conditions—nearly double that of conventional coal-fired power plants, which typically operate at 30–40% efficiency (Soza & Ayres, 2018). From an environmental perspective, CCGT plants emit approximately 50% less CO_2 than coal-fired power plants of equivalent capacity (Bréchet et al., 2016; Rahayu & Windarta, 2022), positioning them as a more sustainable medium-term option. The advantages of CCGTs extend beyond efficiency and environmental performance to include high operational flexibility. Their ability to ramp up and down quickly makes them ideal for balancing power systems that integrate intermittent renewable energy sources (Fauzi, 2023). CCGT plants act as grid stabilizers by providing backup power during fluctuations in solar or wind generation, thereby serving as a crucial transitional technology that bridges the shift from fossil-based systems to renewable energy. This flexibility is particularly vital for Indonesia, which is still developing large-scale energy storage infrastructure. The strategic position of CCGTs is further strengthened by various external factors. Indonesia possesses substantial natural gas reserves, providing a reliable fuel supply for CCGT deployment. From a policy perspective, the government has demonstrated its commitment through various gas infrastructure development programs (Poerwantika et al., 2022; Patrianti et al., 2023). Within the framework of its Nationally Determined Contributions (NDC), CCGT technology can play a crucial role in national emission reduction strategies while ensuring energy supply reliability during the transition period.

In the context of the transition towards a cleaner and more sustainable energy system, research employing a life cycle perspective to assess the carbon footprint of gas-fired power plants has become highly relevant. Many current emission assessments focus solely on the operational phase, particularly direct emissions from fuel combustion, which provides an incomplete picture of the actual environmental impact. This limited approach often overlooks significant contributions from other stages of the CCGT life cycle, including raw material extraction and electricity distribution. By adopting a Life Cycle Assessment (LCA) framework, this study aims to comprehensively evaluate the carbon footprint of a CCGT plant in Indonesia, accounting for emissions generated at each stage to provide a more accurate and holistic understanding of its overall environmental impact. An LCA perspective enables stakeholders to identify emission hotspots and prioritize areas for improvement, facilitating more informed and environmentally sound decisions within the energy transition process. This is critical for supporting Indonesia's commitment to reducing greenhouse gas emissions and addressing the urgent challenge of climate change. The application of LCA not only provides holistic insights but also contributes to the development of robust energy policies aligned with sustainability principles. Therefore, this study aims to assess the carbon footprint of a CCGT power plant in Indonesia from a cradle-to-grave perspective. The findings are intended to serve as a critical step in ensuring that the nation's energy transition yields net positive and sustainable environmental outcomes.

2. METODE

The carbon footprint was calculated by identifying GHG emission sources from various activities within the power generation industry that contribute to climate change (Imaniar et al., 2022). LCA framework was employed to analyze the environmental impacts of the power plant's operations throughout its entire life cycle, from raw material extraction to end-of-life disposal. This approach allows for the calculation of GHG emissions in a more structured and validated manner (Chang-chun et al., 2013; Santosa et al., 2024). The study was conducted in accordance with the ISO 14040 and 14044 standards, encompassing the four fundamental phases of LCA: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation of the results (Yoshida et al., 2013; Corona et al., 2017). The technical research framework for this carbon footprint assessment, which is grounded in these LCA principles, is illustrated in Figure 1.

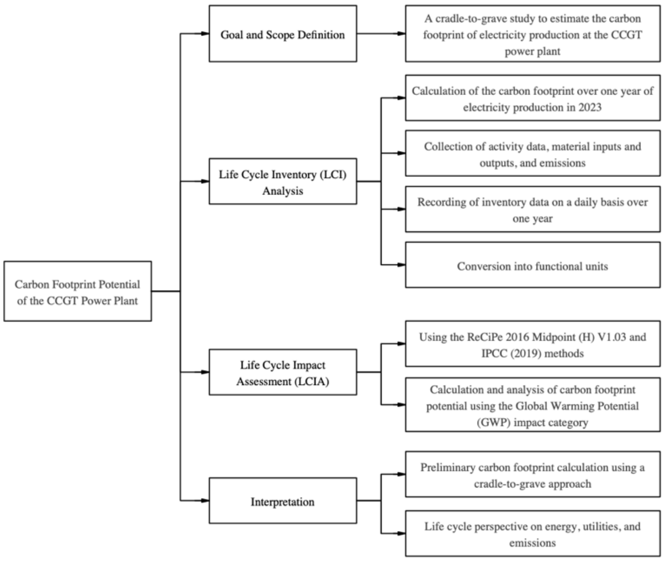

Figure 1. Technical research framework for carbon footprint analysis

The carbon footprint assessment for electricity generated from CCGT power plants was conducted in accordance with the ISO 14040 standard. LCA process, as defined by the standard, consists of four iterative stages: (1) goal and scope definition, (2) LCI analysis, (3) LCIA, and (4) interpretation of the results (International Organization for Standardization, 2006). A detailed explanation of each stage is provided in the subsequent subsections.

a. Goal and Scope Definition

This study aims to assess the carbon footprint associated with a CCGT power plant throughout its entire life cycle, employing a cradle-to-grave approach based on operational data from the year 2023. The goal and scope of this assessment are defined by the following key elements:

1) The carbon footprint is defined as the cumulative GHG emissions generated from electricity production, expressed in kilograms of carbon dioxide equivalent (kg CO_2-eq), and characterized using the ReCiPe impact assessment methodology.
2) Primary data for production activities within the operational boundary (gate) were obtained through direct monitoring over a one-year period.
3) Input data encompasses quantities of raw materials, energy, and fuel consumed.
4) Output data includes the amount of electricity generated (the product), air emissions, and waste streams.

b. System Boundaries

The life cycle of electricity generation is delineated into three primary stages:

1) Upstream Processes (Cradle): This stage encompasses natural gas production (including extraction and processing) and its transportation to the power plant.
2) Core Processes (Gate): This stage includes electricity generation at the CCGT power plant and the on-site management of resulting non-hazardous and hazardous waste.
3) Downstream Processes (Grave): This stage involves the transmission and distribution of the generated electricity over an average distance of 500 km to end-users.

Accordingly, the system boundary for this assessment is defined from the acquisition of raw materials (cradle) to the delivery of the final electricity product to the consumer (grave), as illustrated in Figure 2.

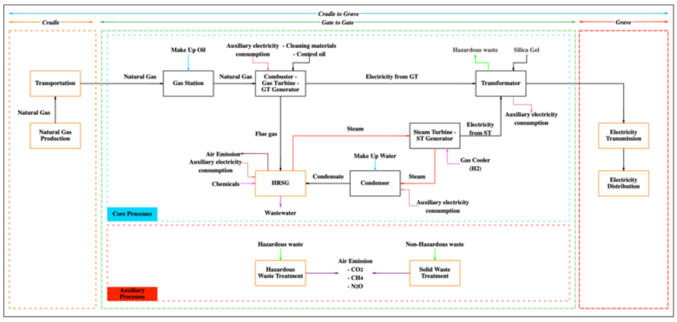

Figure 2. System boundaries of the CCGT power plant

c. Functional Unit

The functional unit provides a quantified reference to which all inputs and outputs of the system are normalized, enabling a consistent basis for comparing the environmental impacts of product systems. In this LCA study, the functional unit is defined as 1 kilowatt-hour (1 kWh) of electricity delivered to the transmission grid (i.e., measured at the plant boundary before distribution to end-users).

d. Assumptions and Limitations

The following assumptions and simplifications were necessary to model the life cycle inventory:

1) GHG emissions from combustion are calculated based on the stoichiometry of complete combustion and the specified chemical composition of the natural gas feedstock.
2) Auxiliary electricity consumption within the power plant (e.g., for pumps, control systems) is estimated based on equipment design specifications rather than direct, sub-metered monitoring.
3) Annualized operational data was extrapolated from representative daily data provided by the plant operator.
4) Distances for fuel transportation and electricity transmission were estimated using route mapping software (e.g., Google Maps) and represent typical or average pathways.
5) Equipment operating hours were derived from plant logbooks and operational reports rather than continuous direct measurement.

e. LCIA Method

LCIA is a key component of LCA that translates inventory data into quantifiable environmental impact indicators. The standard LCIA methodology comprises four stages: classification, characterization, normalization, and weighting (ISO, 2006). However, this study focuses specifically on the characterization stage to quantify the carbon footprint. This focused approach allows for the efficient identification of primary emission sources without the additional complexity introduced by normalization and weighting (Ren & Su, 2013). The carbon footprint is defined as the total GHG emissions, expressed in kg CO_2-eq. This conversion uses the Global Warming Potential (GWP) over a 100-year timeframe (GWP_{100}), which is an index measuring a gas's relative radiative forcing potential compared to carbon dioxide (Nurzamilov et al., 2024; Santosa et al., 2024). For instance, methane has a GWP_{100} of 27–30, meaning it has a significantly higher climate impact than CO_2 even when emitted in smaller quantities (Ismail, 2020; IPCC, 2021). This study employed the ReCiPe 2016 midpoint method for LCIA to quantify the global warming potential (Jolliet et al., 2018; Mikosch et al., 2022). The midpoint approach was selected as it establishes a clear cause-and-effect relationship between emissions and impact category, making the results more interpretable for stakeholders (Alvarenga et al., 2013). The analysis was performed using SimaPro 9.5 software, with the Ecoinvent v3. and USLCI databases serving as the primary sources of background data.

3. RESULTS AND DISCUSSION

The life cycle assessment of the CCGT power plant in Indonesia reveals the carbon footprint dynamics across its entire value chain. This comprehensive analysis encompasses three critical phases: (1) upstream, involving natural gas production and transportation (cradle); (2) core, covering power plant operations (gate); and (3) downstream, consisting of electricity transmission and distribution (grave).

3.1 Life Cycle Inventory for the CCGT Power Plant

Developing a LCI for a CCGT plant requires a detailed accounting of all energy and material flows throughout its life cycle. In the context of the energy transition towards cleaner sources, it is imperative to quantify the GHG emissions generated at each stage. The LCI provides the foundational data for this quantification, enabling a robust assessment via LCA methodology, which is critical for comparing the environmental performance of different power generation technologies (Hafizan et al., 2013; Motahari et al., 2023). The inventory data for this study, compiled in Table 1, detail the emission characteristics of the CCGT plant and identify the primary sources of GHG emissions across its life cycle.

Tabel 1. Life Cycle Inventory Data of The CCGT Power Plant

Process Unit	**Emissions Inventory**		
	Substance	**Quantity (kg/kWh)**	**Percentage**
Cradle			
Natural Gas Production	*Methane, fossil*	-	74
	Carbon Dioxide, Fossil	-	24.8
	Dinitrogen Monoxide	-	0.12
	Remaining Substances	-	0.18
Natural Gas Transportation	*Carbon dioxide, fossil*	-	89.72
	Methane, fossil	-	8.47
	Carbon dioxide, land transformation	-	0.72
	Remaining substances	-	1.09
Gate			
Heat Recovery Steam Generator (HRSG)	*Carbon dioxide*	4.73E-04	99.87
	Methane	9.33E-09	0.07
	Dinitrogen monoxide	9.33E-10	0.06
Hazardous Waste Treatment	*Carbon dioxide*	7.46E-09	0.0004
	Methane	1.71E-03	8.28
	Dinitrogen monoxide	1.54E-04	91.72
Solid Waste Treatment	*Carbon dioxide*	2.71E-07	3.23
	Methane	7.56E-06	90.2
	Dinitrogen monoxide	5.49E-07	6.55
Grave			
Electricity transmission	*Carbon dioxide, fossil*	-	88
	Dinitrogen monoxide	-	2
	Remaining substances	-	10
Electricity distribution	*Carbon dioxide, fossil*	-	88
	Dinitrogen monoxide	-	2
	Remaining substances	-	10

For processes within the upstream (cradle) and downstream (grave) system boundaries, which are external to the core power plant operations, a secondary data approach was employed using the Ecoinvent 3.0 and USLCI databases. The secondary data for the upstream stage encompassed the extraction and production of natural gas, transportation logistics to the power plant, and background processes for other material and energy inputs. For the downstream stage, secondary data included the transmission and distribution infrastructure for electricity delivery over 500 km, incorporating data on construction materials, operational energy requirements, and waste generated throughout the infrastructure lifecycle. A comprehensive summary of the specific secondary datasets utilized, including their sources and key characteristics, is systematically presented in Table 2.

Table 2. Secondary Data Used in the Study

Scope	**Inventory Data**	**Secondary Data**
Cradle	Natural gas production	Natural gas, high pressure {RoW}| natural gas production | Cut-off, U
	Natural gas transportation	Pipeline, Natural gas, high-pressure distribution network {GLO}| market for | Cut-off, U
Grave	Electricity transmission	Transmission network, electricity, high voltage {RoW}| construction | Cut-off, U
	Electricity distribution 500 km	Distribution network, electricity, low voltage {RoW}| construction | Cut-off, U

Based on the life cycle inventory data presented in Table 1, the GHG emissions from the CCGT power plant are comparatively low, which is attributed to the use of natural gas as its primary fuel. CCGT's CO_2 emission intensity outperforms the 2022 benchmark of 0.0496 Ton CO_2/GJ (0.01787 kg/kWh), which defines the top performace quartile for CCGT in Indonesia (Ministry of Environment and Forestry, 2022). This characteristic also aligns with the findings of Zaky and Sari (2024), who state that natural gas combustion in CCGT units generates lower CO_2 emissions than coal-fired power plants. Furthermore, CCGT operations produce smaller volumes of both hazardous and non-hazardous waste due to more efficient and cleaner combustion processes (Zaky & Sari, 2024). Unlike coal-fired power plants, natural gas combustion systems do not generate fly ash or bottom ash, significantly simplifying waste management requirements (Alber & Kiono, 2022). In this regard, CCGT plants hold a substantial advantage, as they do not require complex hazardous waste treatment facilities. According to Ramdhani et al. (2021), waste from CCGT plants can often be repurposed or managed without causing significant environmental impacts, in contrast to coal-based power generation, which necessitates specialized handling for hazardous by-products.

For the cradle-to-grave analysis, this study utilized secondary data from the Ecoinvent 3.0 and USLCI databases, processed using SimaPro software. These databases provide over 10,000 integrated data points, encompassing life cycle inventories for a wide range of processes (Carvalho et al., 2019). The integration of data from both sources enabled a comprehensive assessment of the CCGT plant's carbon footprint, energy consumption, and waste emissions (Orozco et al., 2023). Secondary data were primarily employed to analyze stages beyond the plant's direct operational control, such as upstream fuel extraction and downstream end-of-life processes, for which primary data were unavailable from the power company. This approach ensures a robust analysis across the entire cradle-to-grave scope, including phases outside the direct purview of the power plant operator.

3.2 Carbon Footprint of the CCGT Power Plant

Carbon footprint analysis, conducted within a LCA framework using the GWP impact category, provides a comprehensive method for evaluating the environmental impact of a product or service. This holistic approach encompasses all life cycle stages, from raw material extraction to end-of-life disposal. GWP is quantified in units of CO_2-eq, representing the integrated radiative forcing over a specified time horizon, with 100 years (GWP_{100}) being the most commonly used benchmark. Within the LCA methodology, GWP measures the potential of GHGs to contribute to global warming, where the relative impact of each gas is calculated in comparison to carbon dioxide, which is defined as having a reference value of 1 (Bodoga et al., 2024). The carbon footprint results for the CCGT power plant, expressed as GWP values, are presented in Table 3.

Table 3. Carbon Footprint of the CCGT Power Plant

Process Unit	**Global Warming Potential**
	(kg CO_2 eq/kWh)
Cradle	
Natural Gas Production	2.602E-01
Natural Gas Transportation	6.47E-03
Gate	
HRSG	4.73E-01
Solid Waste Treatment	8.38E-06
Hazardous Waste Treatment	1.86E-03
Grave	
Electricity Transmission	7.34E-04
Electricity Distribution	2.03E-03

The natural gas production stage was identified as the largest contributor to the life cycle emissions, accounting for 0.260 kg CO_2-eq/kWh. This significant share is attributed to the energy-intensive processes of extraction and processing, coupled with the potential for methane leaks. Various studies indicate that fugitive methane emissions can contribute over 20% of the total GHG emissions from gas processing facilities, highlighting the critical need for enhanced monitoring technologies and improved maintenance of upstream infrastructure. Natural gas transportation constituted the second-largest component of the carbon footprint. The emissions from this stage are highly dependent on the efficiency of the transportation infrastructure, including the technical condition of transmission pipelines and the energy consumption of storage facilities. Therefore, optimizing the transportation system through routine maintenance and advanced leak detection technologies represents a strategic opportunity for emission reduction.

Within the power plant's operational boundary (gate), the electricity generation process in the HRSG was the primary emission source, producing 0.473 kg CO_2-eq/kWh. This value underscores the direct correlation between combustion efficiency and the resulting carbon footprint. Consequently, enhancing thermal efficiency through advanced combustion technologies and maximizing heat recovery is paramount to mitigating emissions at this stage. In contrast, emissions from waste management during operations were relatively minimal (solid waste: 0.00000838 kg CO_2-eq/kWh; hazardous waste: 0.00186 kg CO_2-eq/kWh). Nevertheless, the cumulative impact of waste-related emissions warrants attention. The implementation of integrated waste treatment systems and recycling technologies is recommended to further minimize the environmental footprint of these ancillary activities.

The final stage of the life cycle analysis encompasses electricity transmission and distribution, with calculated emission values of 0.000734 kg CO_2-eq/kWh for transmission and 0.00203 kg CO_2-eq/kWh for distribution. Although these stages contribute a relatively small proportion to the total carbon footprint, optimizing the efficiency of electricity grid infrastructure remains crucial for further reducing the system's overall environmental impact. Enhancements in grid management, reduction of transmission losses, and integration of smart grid technologies represent potential strategies for minimizing emissions at this stage.

3.3 Assessing the Feasibility of Combined Cycle Power Plants in the Energy Transition

The transition to gas-fired power plants offers a cleaner and more efficient solution for meeting growing energy demands. CCGT plants utilize natural gas as their primary fuel, emitting up to 50% less carbon dioxide than conventional coal-fired power plants (Moore & Kulay, 2019). Furthermore, the combined cycle technology employed in CCGTs achieves exceptional energy conversion efficiencies of 55–60%, significantly surpassing the 30–40% efficiency typical of conventional thermal power plants (Adewuyi et al., 2019). This heightened efficiency not only reduces greenhouse gas emissions but also optimizes the utilization of finite natural gas resources.

To further enhance sustainability, CCGT operations can be integrated with carbon capture and storage (CCS) technology, which has the potential to capture up to 90% of the CO_2 emissions generated during combustion (Moore & Kulay, 2019). However, this transition faces significant challenges, particularly concerning the availability and development of natural gas infrastructure—such as pipelines and storage facilities—which require substantial capital investment. Government policy support, including fiscal incentives and regulations mandating emission reductions, is crucial for accelerating CCGT adoption (Graczyk et al., 2023).

Additionally, social and environmental considerations must be thoroughly evaluated through rigorous Environmental Impact Assessments (EIA) to mitigate potential adverse effects on local ecosystems and communities (Jolliet et al., 2015). Thus, while CCGT plants represent a promising transitional solution in the energy landscape, their successful implementation necessitates a holistic strategy that integrates technical innovation, economic viability, and supportive policy frameworks.

4. CONCLUSION

Based on a comprehensive life cycle assessment of the carbon footprint of the CCGT power plant, several strategic recommendations can be formulated to minimize its environmental impact across all stages of its life cycle. In the upstream stage, encompassing natural gas production and transportation, the implementation of advanced monitoring technologies—such as infrared-based methane leak detection and aerial sensors—is crucial for the rapid identification and mitigation of fugitive emissions (Robertson et al., 2020), and should be coupled with infrastructure upgrades to more efficient equipment. Concurrently, for transportation, route optimization and the modernization of pipeline networks using leak-resistant materials are essential (Balcombe et al., 2016), alongside exploring multi-modal transportation options to enhance logistical flexibility and reduce risks. Within the core operational stage, the adoption of advanced combustion technologies and enhanced heat recovery systems is paramount to significantly improve generation efficiency (Burns & Grubert, 2021), while an integrated waste management strategy founded on recycling and reuse principles must be implemented (Ravikumar & Brandt, 2017). For the downstream electricity transmission and distribution, deploying smart grid technology is necessary to minimize energy losses (Ravikumar et al., 2020). Furthermore, supportive policy frameworks play a critical role through regulations that promote sustainable energy and fiscal incentives for low-carbon technologies (Lyon et al., 2021), complemented by increased allocations for research and development into clean energy technologies and innovative natural gas management techniques. These comprehensive recommendations target all critical stages of the CCGT life cycle to achieve optimal efficiency with minimal environmental impact, thereby supporting a sustainable energy transition.

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