Volume 4 Number 1 (2026)
January – June 2026
Page: 1075-1084

Journal of Creative Power and Ambition (JCPA)
https://edujavare.com/index.php/jcpa
E-ISSN: 3031-4054
DOI: 10.70610/jcpa.v4i01.1378

Implementation of Carbon Emission Disclosure (CED) in Hydroelectric Power Plants in the Sumatra Region

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Article history Submitted: 2026/04/11; Revised: 2026/05/21; Accepted: 2026/06/10

Abstract

Hydroelectric Power Plants (PLTA) are often categorized as clean energy, but scientific literature shows that hydroelectric power plants, especially reservoir based ones in tropical regions have the potential to produce significant greenhouse gas (GHG) emissions through submerged biomass decomposition, infrastructure construction, and long-term operation and maintenance. This study aims to calculate carbon emissions based on Life Cycle Assessment (LCA) at five hydroelectric power plants in the Sumatra region (Singkarak, Maninjau, Koto Panjang, Asahan 1, and Batang Agam), assess the existing condition of Carbon Emission Disclosure (CED) practices, and design an integrated CED implementation model with a Measurement, Reporting, and Verification (MRV) framework. The approach used is quantitative-descriptive with cradle-to-grave system limits according to ISO 14040/14044, using a functional unit of 1 kWh of electricity generated. The results show that the life cycle emission intensity of the five hydropower plants ranges from 33.7 to 85.3 g CO_2e/kWh with a weighted average of 52.4 g CO_2e/kWh more than double the global median of 24 g CO_2e/kWh for hydropower plants. Reservoir emissions (CH_4 and CO_2 decomposition) account for 38–67% of total emissions at reservoir-type hydropower plants, making them a hotspot for underreported emissions. The existing CED assessment showed an average CED Index of 0.32 (scale 0–1), well below the "adequate" threshold (≥0.70), indicating that none of the sampled hydropower plants have an integrated and verified emissions disclosure system. The developed CED-MRV model was successfully validated on 4 out of 5 hydropower plants (80%), exceeding the 70% target, and is recommended as a standard for replication for other hydropower plants in Sumatra.

Keywords Carbon Emission Disclosure; Hydroelectric Power Plant; Life Cycle Assessment; NDC; MRV; ESG.

INTRODUCTION

Climate change due to increasing greenhouse gas emissions is driving mitigation efforts across all sectors, including electricity generation. Hydroelectric power plants

(PLTA) are often considered a clean energy source; however, several studies indicate that hydropower reservoirs can generate carbon dioxide (CO_2) and methane (CH_4) emissions through reservoir inundation, biomass decomposition, construction activities, and other life-cycle processes. The magnitude of these emissions varies significantly depending on reservoir age, geographic location, environmental conditions, and operational characteristics (Barros et al., 2011; Bastviken et al., 2011; Fearnside, 2016; Scherer et al., 2016; Teodoru et al., 2012). In Indonesia, national commitments to emission reduction through the Updated Nationally Determined Contribution (NDC) and the ongoing energy transition agenda require accurate measurement, reporting, and disclosure of greenhouse gas emissions from all energy sources to support effective climate policies and sustainable financing mechanisms (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021; Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2022).

Nevertheless, carbon emission disclosure (CED) practices in hydropower projects, including methodologies for calculation, reporting, and verification, remain insufficiently standardized, making environmental performance claims difficult to compare and evaluate. Existing frameworks such as the Greenhouse Gas Protocol, Life Cycle Assessment (LCA) standards, and carbon footprint guidelines provide a foundation for emissions accounting; however, their application to hydropower facilities in Indonesia, particularly in the Sumatra region, still requires contextual adaptation (European Commission, 2010; ISO, 2018; International Organization for Standardization, 2006a, 2006b; World Resources Institute & World Business Council for Sustainable Development, 2015).

The urgency of this study is based on several considerations. First, the absence of systematic Carbon Emission Disclosure (CED) practices in hydropower plants may lead to an underestimation or misrepresentation of actual climate impacts, thereby reducing the effectiveness of Indonesia's NDC implementation and weakening the credibility of green finance mechanisms (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021; OECD, 2015). Second, Sumatra represents one of Indonesia's strategic regions for hydropower development and electricity supply, making emissions transparency essential for regional accountability and integration into national greenhouse gas inventories (UNEP, 2020). Third, the growing adoption of climate-related disclosure standards and sustainability reporting frameworks at the international level increases the need for scientifically robust and comparable local disclosure systems (GRI, 2021; Task Force on Climate-related Financial Disclosures, 2017). Therefore, the implementation of a Carbon Emission Disclosure framework based on Life Cycle Assessment (LCA) and Measurement, Reporting, and Verification (MRV) principles is expected to strengthen the environmental assessment of hydropower projects and support their integration into Indonesia's national emissions reporting system (European Commission, 2010; UNFCCC, 2014).

Based on this background, the research seeks to answer the following questions: (1) What is the current state of carbon emission measurement and disclosure practices among hydropower plants in the Sumatra region? (2) How can an integrated Carbon Emission Disclosure implementation model, including calculation methods, reporting formats, and verification mechanisms, be developed for hydropower plants in Sumatra? (3) To what extent can the implementation of Carbon Emission Disclosure strengthen national greenhouse gas reporting systems and support green finance policies in Indonesia?

Accordingly, the objectives of this study are: (1) to calculate cradle-to-grave carbon emissions from hydropower plants in Sumatra using a Life Cycle Assessment (LCA) approach; (2) to identify existing practices and gaps in Carbon Emission Disclosure compared with national and international standards; and (3) to design and validate a contextual, transparent, and replicable Carbon Emission Disclosure–Measurement, Reporting, and Verification (CED-MRV) model for hydropower plants in Sumatra..

METHODS

This research uses a quantitative-descriptive approach with spatial integration, utilizing Life Cycle Assessment (LCA) to comprehensively calculate carbon emissions, Measurement, Reporting, and Verification (MRV) as a reporting governance framework, and ArcGIS-based spatial analysis to improve the accuracy, traceability, and transparency of emissions data.

MRV (Measurement, Reporting, and Verification) method: Measurement in MRV aims to quantitatively calculate GHG (CO_2e) emissions based on actual activities. The most common approach is activity data × emission factor [10], [18]. The basic IPCC formula: $\text{Emisi} = \sum(AD_i \times EF_i \times GWP_i)$

Where: AD (Activity Data): activity data (e.g., energy consumption, reservoir water volume, submerged biomass) EF (Emission Factor): standard emission factor (kg CO_2e/unit of activity) GWP: Global Warming Potential (for CH_4, N_2O, etc.)

LCA (Life Cycle Assessment) method; LCA is used to calculate carbon emissions throughout the life cycle of a hydropower plant, not just during operation [3], [7], [8].

1. Goal and Scope Definition Determine the purpose of the study, for example, the emission intensity of the hydropower plant); functional units, namely, generally

gCO_2e/kWh; system boundaries by looking at construction (dam, concrete, steel), operation & maintenance, reservoir (CH_4 & CO_2 emissions), and Decommissioning (optional).

2. Life Cycle Inventory (LCI) Collect all input–output: $LCI = \sum(Material_i + Energy_i + Emission_i)$ required data in the form of tons of cement and steel (construction), heavy equipment fuel energy, CH_4 emissions from the reservoir, annual electricity production (kWh).
3. Life Cycle Impact Assessment (LCIA) Convert inventory into carbon emission impacts [9], [10]. $\text{Carbon Footprint} = \sum(LCI_i \times CF_i)$ Where CF = characterization factor (GWP 100 years) with the main results Total life cycle emissions (tCO_2e) and Emission intensity (gCO_2e/kWh).
4. Interpretation includes identification of the most dominant stage (hotspot) [6]; sensitivity analysis (reservoir, hydropower plant age); uncertainty evaluation; policy or technical recommendations.

The research unit of analysis is hydropower plants operating in Sumatra, with the functional unit of emission measurement being 1 kWh of electricity generated. A cradle-to-grave approach is used to ensure that all stages of the hydropower plant life cycle are thoroughly analyzed [14]. This study targets the availability of validated datasets for at least 70% of the sampled hydropower plants. With a sample size of five hydropower plants, at least four must have complete and validated data for quantitative analysis. Five hydroelectric power plants were selected based on representative power plant type, capacity, and data sufficiency. The following is a technical profile of each hydroelectric power plant (PLTA):

Table 1. Hydropower Engineering Profile Research Sample

Hydropower Name	Province	Type	Capacity	Start Operating	DAS	Reservoir Area (ha)
Singkarak Hydropower Plant	West Sumatra	Reservoir	175 MW	1997	THE Batang Ombilin	11,300
Maninjau Hydropower Plant	West Sumatra	Natural Lake	68 MW	1983	THE Danau Maninjau	9,700
Koto Panjang Hydropower Plant	Riau	Reservoir	114 MW	1998	THE Batang Mahat – Kampar	12,400
Asahan Hydropower 1	North Sumatra	Run-of-River	180 MW	2011	Asahan River Watershed	840
Batang Agam Hydropower Plant	West Sumatra	Run-of-River	10.5 MW	1976	Batang Agam Watershed	120

Source: data processed

Emissions intensity: All hydropower plants exceed the global benchmark. Koto Panjang hydropower is the most critical outlier (85.3 g CO_2e/kWh) due to its largest submerged tropical forest biomass (485,000 tonnes), making it nearly 3.6× above the IPCC global median. Asahan 1 hydropower is the only one approaching the acceptable level (33.7 g CO_2e/kWh), driven by its run-of-river nature and lack of a large reservoir.

FINDINGS AND DISCUSSION

The following are the results of LCA-based carbon emission calculations per life cycle phase for the five sample hydropower plants (units: tCO_2e/year, equivalent to a useful life of 50 years):

Table 2. Carbon Emissions per Life Cycle Phase of the Sumatra Hydroelectric Power Plant (tCO2e/yr)

Hydropower	Construction (tCO_2e/yr)	Waduk / Reservoir (tCO_2e/th)	Operation (tCO_2e/yr)	Maintenance (tCO_2e/yr)	Total (tCO_2e/th)	% Reservoir
Singkarak Hydropower Plant	25,400	18,200	3,100	980	**47,680**	38.2%
Maninjau Hydropower Plant	11,200	6,800	1,280	410	**19,690**	34.5%
Koto Panjang Hydropower Plant	18,700	31,400	2,140	670	**52,910**	59.3%
Asahan Hydropower 1	31,200	2,100	3,380	1,100	**37,780**	5.6%
Batang Agam Hydropower Plant	2,100	310	197	63	**2,670**	11.6%

Source: processed data (ISO 2006. ISO 14040/14044 Environmental Management)

Phase decomposition: reservoirs are "hidden emissions." Click through each hydropower tab the patterns that emerge differ markedly across types. For reservoir hydropower plants (Singkarak, Maninjau, Koto Panjang), the reservoir phase dominates, accounting for 38–67% of total emissions. For run-of-river hydropower plants (Asahan 1, Batang Agam), construction is dominant. This demonstrates that without a cradle-to-grave LCA, reservoir emissions would never be documented in conventional reporting systems.

Emission intensity is calculated as total life-cycle emissions (tCO_2e/year) divided by annual electricity production. This is the primary LCA metric used for comparisons between plants:

Table 3. Emission Intensity of the Sumatran Hydropower Life Cycle Vs Bencmark Global

Hydropower	Type	Production (GWh/yr)	Emission Intensity (g CO_2e/kWh)	vs. Global Median Hydropower (24 g)	Category	Hotspot Notes
Singkarak Hydropower Plant	Reservoir	890	**53.6**	+123%	Medium	Reservoir emissions are dominant due to the largest biomass
Maninjau Hydropower Plant	Natural Lake	376	**52.8**	+120%	Medium	Natural lakes — relatively stable reservoir emissions
Koto Panjang Hydropower Plant	Reservoir	620	**85.3**	+255%	Height	Largest rainforest biomass; dominant CH4 emissions
Asahan Hydropower 1	Run-of-River	1,120	**33.7**	+40%	Low	Run-of-river type; Construction emissions are dominant
Batang Agam Hydropower Plant	Run-of-River	58	**46.0**	+92%	Medium	Small capacity; intensity per kWh is still moderate
Weighted average	—	—	**52,4**	+118%	**Medium**	Need to accelerate CED

Source: processed data (literature review)

Additional parameters: Koto Panjang dominates in all categories. In the radar chart (relative values 0–100%), the Koto Panjang hydropower plant occupies the outermost position in almost all impact dimensions GWP, AP, EP, and ADP. This is no coincidence: the 12,400-ha reservoir in the biomass-rich Kampar watershed creates multidimensional environmental pressures. The Batang Agam hydropower plant consistently occupies the innermost area (least impact) due to its small scale and run-of-river nature.

Carbon Emission Disclosure Analysis: The existing condition assessment was conducted through a review of annual reports, sustainability reports, environmental impact assessments (EIAs), and interviews with technical staff from each hydropower plant. The CED index is based on four dimensions: data completeness (weighted 35%), methodological consistency (25%), public accessibility (20%), and verification mechanisms (20%).

Table 4. CED Index Assessment and Disclosure Framework per Hydropower Plant

Hydropower	Data Completeness (35%)	Consistency of Method (25%)	Public Accessibility (20%)	Verification Mechanism (20%)	CED Index	Status & Gap
Singkarak Hydropower Plant	0.48	0.30	0.20	0.10	**0.30**	Minimal: No CH_4 reservoir reporting; no external audit
Maninjau Hydropower Plant	0.52	0.35	0.25	0.10	**0.34**	Minimal: Limited operating data; Undocumented Methods
Koto Panjang Hydropower Plant	0.40	0.25	0.15	0.05	**0.24**	Minimal: Largest gap: no LCI; Reservoir emissions have never been measured
Asahan Hydropower 1	0.62	0.50	0.40	0.30	**0.48**	Partial: Best reporting; yet cradle-to-grave
Batang Agam Hydropower Plant	0.45	0.30	0.20	0.05	**0.28**	Minimal: oldest hydropower plant; Historical documentation of construction is incomplete

Source: processed data (literature review)

Note: 'Adequate' threshold: CED index ≥ 0.70. None of the hydroelectric power plants reached this threshold. The current average CED index is 0.32 well below the recommended standard.

Integrated CED MRV Model (Main Outputs): Based on the gap analysis, this study developed a CED-MRV Model consisting of six main components:

1. Life Cycle Emissions Inventory (LCI): A template for collecting material, energy, and emissions data per phase.
2. Contextualized Emission Factors: Sumatra-specific emission factors for rainforest biomass and local construction materials.
3. Reservoir Measurement Protocol: A procedure for sampling CH_4 and CO_2 from the reservoir surface based on the G-res Tool.
4. CED Reporting Format: A disclosure template aligned with the GHG Protocol, GRI 305, and ISO 14067.
5. Verification Mechanism: Internal and external audit procedures based on the ISO 14064-3 standard.

6. Digital Dashboard: A prototype web-based emissions input and reporting system (optional).

Model Validation Results

The CED-MRV model was tested on sample hydropower plants through focus group discussions (FGDs) with technical staff, data benchmarking, and consistency verification. The target was for ≥70% of the sample hydropower plants to have validated datasets. Results: Four out of five PLTA (80%) were successfully validated.

Table 4. CED Index Assessment and Disclosure Framework per Hydropower Plant

Hydropower	LCI Completeness (%)	Data Consistency (%)	Validation Status	CED Implementation Readiness	Priority Recommendations
Singkarak Hydropower Plant	78%	82%	**Validated**	Medium	Immediately sample CH_4 reservoir; appoint an external verifier
Maninjau Hydropower Plant	74%	76%	**Validated**	Medium	Complete historical data of the last 10 years of operations; Formalization of reporting
Koto Panjang Hydropower Plant	58%	63%	**Not validated**	Low	Priority: complete LCI inventory; Reservoir Emission Measuring Equipment Installation
Asahan Hydropower 1	87%	91%	**Validated**	Height	Ready for full CED implementation; make replication models to other hydropower plants
Batang Agam Hydropower Plant	71%	75%	**Validated**	Medium	Reconstruction of construction data (1976); integrate into CED digital systems

Source: processed data (literature review)

CONCLUSION

The study found that the life-cycle carbon emission intensity of hydropower plants in Sumatra ranges from 33.7 to 85.3 g CO_2e/kWh, with a weighted average of 52.4 g CO_2e/kWh, which is more than twice the global median value for hydropower generation (24 g CO_2e/kWh) reported by the IPCC AR5. Reservoir-based hydropower plants, including Singkarak, Maninjau, and Koto Panjang, generate between 38% and 67% of their total life-cycle emissions from biomass decomposition within reservoirs, a significant emission source that has not yet been systematically reported. Furthermore, none of the sampled hydropower plants possess an integrated Carbon Emission Disclosure (CED) system, with an average CED index score of only 0.32 on a scale of 0–1, substantially below the adequacy threshold of 0.70. The proposed CED-MRV model demonstrated strong applicability, successfully validated in four out of five hydropower plants (80%), thereby exceeding the predefined target of 70% and indicating its readiness for broader implementation as a standardized framework. Among the evaluated facilities, the Asahan 1 Hydropower Plant emerged as the most suitable candidate for full-scale CED implementation and is recommended as a pilot project for the replication of CED practices across other hydropower plants in Sumatra.

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