

Carbon Footprint in Waste Sector of Hydropower Plant: A Case Study of Nam Theun 2 Hydropower Plant

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Abstract

While hydropower is generally considered a clean energy source, it is important to recognize that their waste can still contribute to greenhouse gas emissions (GHG). The purpose of this study is to assess the carbon footprint associated with the waste sector throughout the operational phase of the Nam Theun 2 hydropower plant in Laos. Understanding the environmental impact of the waste sector is crucial for ensuring the plant's sustainability. This study utilizes the theoretical estimation method recommended in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, as well as the Requirements for Specification with guidance at the organization level for quantification and reporting of GHG emissions and removals. We emphasize the significance of implementing sustainable waste management practices to reduce GHG emissions and minimize the environmental impact of hydropower operations. By conducting a comprehensive analysis, this paper also provides insights into the environmental implications of waste management in hydropower plants and identifies strategies to mitigate the carbon footprint in the waste sector. The findings contribute to a better understanding of the environmental sustainability of hydropower plants and provide valuable guidance for policymakers, energy producers, and environmental practitioners involved in hydropower plant design and operation.

Keywords

Waste Sector, Carbon Footprint, Climate Change, Hydropower Plant

1. Introduction

Climate change is a pressing global issue that requires immediate action to protect the environment, human health, and future generations' well-being. This phenomenon, caused by anthropogenic emissions, exacerbates the atmospheric greenhouse effect, raising the Earth's surface temperature (Korre et al., 2009). Carbon dioxide, among other gases, plays an important role, with developed countries prioritizing greenhouse gas (GHG) reduction through international agreements such as the Kyoto Protocol, Paris Agreement, and regional energy policies (European Commission, 2006). Renewable energy, particularly hydropower, has attracted attention for its carbon emission implications. While hydropower generates clean electricity, its construction and operation can disrupt aquatic ecosystems, resulting in direct carbon emissions. Furthermore, GHG emissions continue throughout the hydropower system's life cycle, known as indirect emissions. This dual impact motivates scholarly research into hydropower's carbon emission dynamics (Chu et al., 2022).

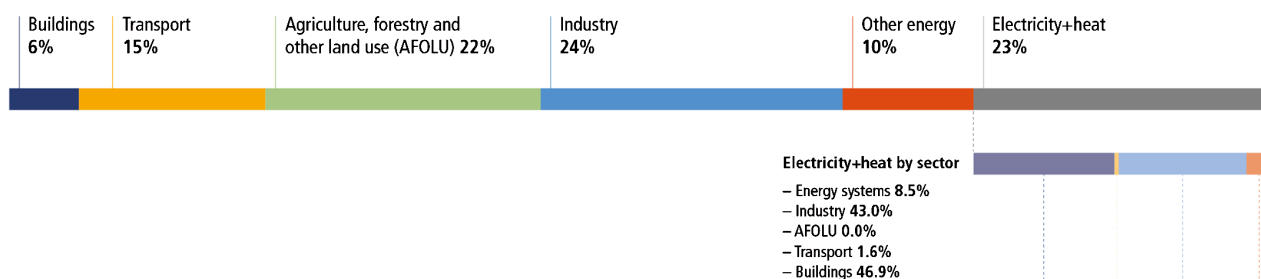
The carbon footprint and carbon credits have played a role in the establishment of a tradable permit system aimed at reducing GHG emissions through the pricing of pollution, utilizing mechanisms such as International Emission Trading, Clean Development Mechanisms, and Joint Implementation. In parallel, the Life Cycle Assessment serves to evaluate emissions and explore reduction strategies, providing a quantitative analysis of environmental aspects associated with a product or process. This assessment is crucial in assessing the environmental effectiveness of green chemicals, as it illuminates factors such as Global Warming Potential (GWP), energy consumption, eutrophication, and land use, thereby facilitating well-informed, environmentally conscious decision-making (Tufvesson et al., 2013).

Ensuring environmental sustainability in electricity production entails a comprehensive assessment of all pertinent environmental impacts, with the carbon footprint serving as a pivotal metric to gauge GHG emissions and inform decision-making processes. Notably, upstream processes, particularly transportation, wield significant influence on the carbon footprint of energy production, underscoring the importance of holistic consideration of the entire life cycle of energy sources. Environmental sustainability evaluations should encompass multiple environmental impact indices to encompass the full spectrum of global atmospheric effects, prioritizing emissions reduction (Cristóbal et al., 2010). An evaluation of the coal life cycle was conducted to quantify GHG emissions, revealing that the power generation phase notably influences environmental indicators. Comparative environmental assessments between power plants with and without CO₂ capture technology demonstrated a substantial decrease in GWP indicators post-integration, highlighting the positive impact of CO₂ capture technology in mitigating GHG emissions (Dință et al., 2013).

The IPCC's Sixth Assessment Report highlights the substantial 3.9% contribution of the waste sector to global CO₂-eq emissions. **Figure 1** illustrates that ap-

proximately 59 GtCO₂-eq emissions are attributed to various sectors: buildings (16%), transportation (15%), agriculture, forestry, and other land uses (AFOLU) (22%), industry (34%), etc. Within waste management, organic waste, encompassing food waste and sewage, stands out as a notable source of methane emissions (IPCC, 2007a; Bogner et al., 2007).

Direct emissions by sector (59 GtCO₂-eq)



Direct+indirect emissions by sector (59 GtCO₂-eq)

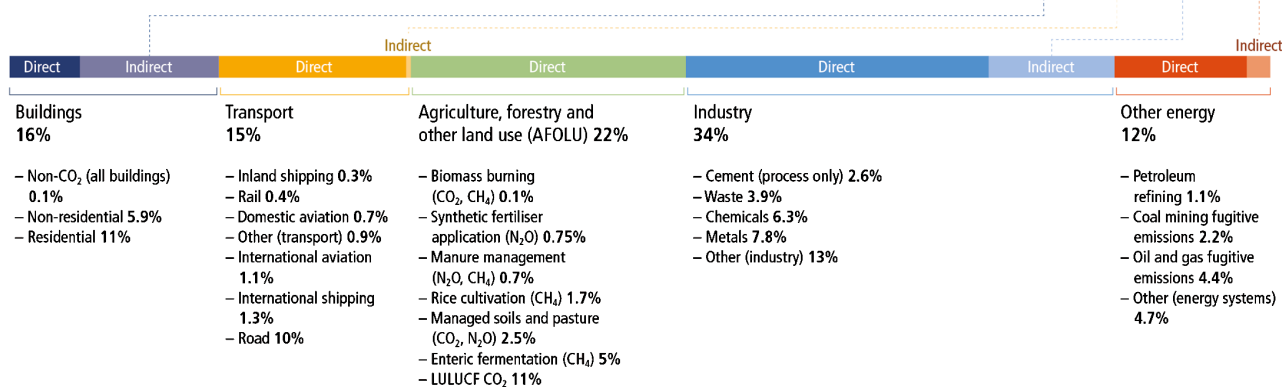


Figure 1. Total anthropogenic direct and indirect GHG emissions for the year 2019 (in GtCO₂-eq) by sector and subsector (IPCC, 2022).

In the domain of hydropower, the carbon footprint of large- and mid-scale projects in China ranges from 6.2 gCO₂-eq/kWh to 34.6 gCO₂-eq/kWh, with an average of 19.2 ± 6.8 gCO₂-eq/kWh (Li et al., 2017). For typical hydropower stations in China, focusing on four specific stations ranging from 50 to 500 MW in capacity, emission rates are measured at 13.60 tCO₂-eq/GWh for 50 years and 8.13 tCO₂-eq/GWh for 100 years (Jiang et al., 2018). The level of public awareness regarding the implementation of a Low-Carbon Economy (LCE) in China is significant. A majority of respondents in Zhengzhou have demonstrated a high awareness of the LCE and exhibit positive attitudes towards its adoption. Their proactive actions include rejecting plastic bags, recycling waste, conserving water and electricity, and purchasing environmentally friendly products, signaling a readiness to engage in pro-environmental behaviors (Chen & Taylor, 2011). Effective waste management strategies play a critical role in curbing GHG emissions and fostering resource recovery. Overreliance on landfills is environmentally unsustainable and contributes to elevated GHG emissions. Thus, it is cru-

cial to enhance public awareness and participation to ensure the success of improved waste management strategies in Jordan and similar nations (Aljaradin & Persson, 2012).

Waste management in hydropower plants includes a wide range of activities, from the disposal of construction debris and operational waste to the treatment of organic matter and effluent. Each of these components contributes to the plant's overall carbon footprint, although to varying extents. The carbon footprint of the waste sector in hydropower remains relatively under-researched, with few empirical data and systematic evaluations to inform policy and decision-making (IPCC, 2022; Wang et al., 2019). The less apparent impacts of waste management decisions remain crucial, as they are inherently linked to our choices regarding waste and materials. Recycling and waste reduction efforts notably lead to reduced energy consumption and process emissions in industry (Jha et al., 2008).

A major fraction (72% - 79%) of solid waste generated in Indian households is organic (Ramachandra et al., 2012). The authors considered methane and carbon dioxide emissions from waste samples to calculate annual solid waste emissions. With 2044 tonnes of organic waste generated daily citywide, methane and carbon dioxide emissions are 19.13 and 242.83 kilograms per day, respectively. Multiplying methane emissions by 21 yields a carbon footprint of 644.61 kilograms per day of CO₂ equivalent. Assuming untreated waste reaches disposal sites, less populated city wards emit less, contrasting densely populated wards. Core city wards, denser in population, exhibit higher carbon footprint potential (Ramachandra et al., 2014). Waste management decisions have a notable effect on GHG, and it is estimated that recycling alone could potentially save 1% to 6% of national GHG. However, it's important to acknowledge that these figures are rough estimates and may not be suitable for precise planning purposes. The passage identifies several critical areas for future research, including landfill methane capture rates, the impact of paper reduction and recycling on forest carbon sequestration, and the possibility of carbon sequestration in landfills (Ackerman, 2000). In the characterization of selected municipal solid waste including organic matter content, biochemical constituents, and leaching behavior, the research identifies lignin-like compounds as a key factor negatively impacting biodegradability. These fractions were then analyzed for organic matter content, leaching behavior, biochemical constituents, Biochemical Oxygen Demand (BOD), and Bio-Methane Potential (BMP) (Bayard et al., 2018).

Although the Lao People's Democratic Republic (Lao PDR) makes a relatively modest contribution to global GHG emissions, the country is facing the impacts of climate change as other parts of the world. This includes increased occurrences of storms, flooding, prolonged droughts, and intensified urban heat. These hazards pose a threat to socio-economic progress and hinder the nation's efforts to achieve Sustainable Development Goals. The breakdown of the national GHG emissions profile, based on data from the year 2000, reveals emissions

from multiple sectors: energy, industrial processes, agriculture, land use change and forestry (LUCF), and waste. Notably, LUCF stands out as the largest contributor, comprising 83% of the total emissions, followed by Agriculture at 15%, and Energy at 2%. The primary climate risks identified for Laos encompass floods, epidemics, storms, and droughts, detailed in **Table 1** (MoNRE, 2019).

Table 1. National GHG emissions profile.

National Greenhouse Gas Emission Profile (base year 2000)	According to the Lao PDR Second National Communication on Climate Change, the national GHG emissions by sector measured in gigagram of carbon dioxide equivalent (Gg CO ₂ .eq) are outlined as follows:				
	Sector	Emission (Gg CO ₂ .eq)	Sink (Gg CO ₂ .eq)	Net Total (Gg CO ₂ .eq)	Percentage (%)
	Energy	1039.76	0	1039.76	2
	Industries process	48.41	0	48.41	0.1
	Agriculture	7606.34	0	7606.34	15
	LUCF	43,963.25	2046.73	41,916.62	83
	Waste	131.88	0	131.88	0.3
	Total	52,789.64	2046.73	50,742.91	100
Key emitting sectors	LUCF (83%), Agriculture (15%), Energy (2%)				
Key climate risks	Floods, Epidemics, Storms, Drought				

The Nam Theun 2 hydropower plant (NT2), located in Lao PDR as depicted in **Figure 2**, stands as a significant infrastructure asset, leveraging water power to generate electricity. Oversight of environmental and social initiatives at NT2 falls under the purview of external entities, including technical advisors from lending agencies, the Laotian Government via the Panel of Experts and Independent Monitoring Agencies, independent consultants, and multilateral development institutions (Nam Theun 2, 2023; NTPC, 2004). The plant adheres to stringent waste management protocols, ensuring compliance with ISO 14001 standards, particularly in e-waste management, alongside adopting best practices to address challenges and solutions specific to Lao PDR (Keovongsa et al., 2023). As a pivotal player in regional energy provision, NT2 fulfills a vital role in meeting energy demands. Nonetheless, the operation of such a facility may draw environmental scrutiny, particularly regarding the calculation and verification of its carbon footprint for regulatory adherence and organizational transparency (Villar et al., 2014).

In NT2, an assessment was conducted to evaluate the organic carbon stock within the 450 km² reservoir area, encompassing various cover types such as forests, agricultural soils, swamps, and others. The total organic carbon stock was estimated to be 5.1 ± 0.7 MtC, with 2.2 MtC attributed to aboveground biomass,

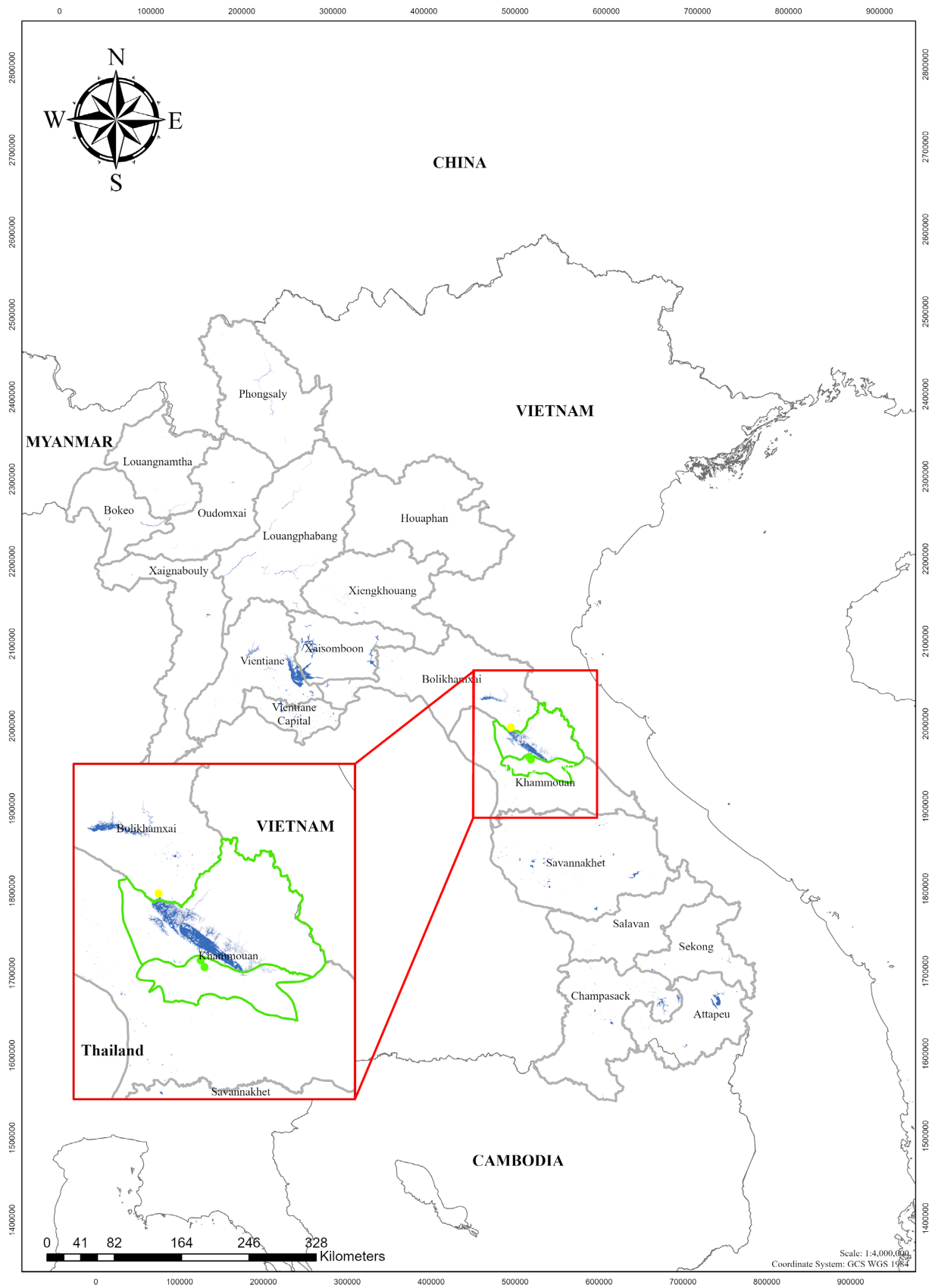


Figure 2. Location of NT2.

litter, and deadwood, and 2.9 MtC to belowground biomass and soil organic carbon. It's noteworthy that the organic carbon stock within the NT2 reservoir area was found to be lower compared to other tropical reservoirs in South America or Africa (Descloux et al., 2011).

This research study aims to analyze the carbon footprint in the sector of the hydropower plant during its operational phase. Specifically, the focus will be on evaluating carbon emissions associated with management practices, including the disposal of construction waste, organic waste, and other by-products generated during the plant's operation.

This research study conducts a comprehensive case study to gain insights into the environmental impact of waste management in hydropower plants. It also aims to identify potential strategies for reducing the carbon footprint in the waste sector, drawing from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 5 Waste (Buendia et al., 2019b), Volume 2 Energy (Buendia et al., 2019a) and Requirements for Specification with guidance at the organization level for quantification and reporting of GHG emissions and removals (ISO, 2018). The main contributions of this paper are summarized as follows:

- Providing valuable insights into the carbon footprint of the waste sector in a large-scale hydropower plant, identifying areas for reduction and sustainable waste practices. Additionally, it will contribute to the development of strategies to minimize the environmental impact of hydropower plants and enhance their overall sustainability.
- Supporting the transition towards cleaner and more sustainable energy systems by emphasizing the importance of addressing the carbon footprint in the waste sector of hydropower plants. Through the case study of the NT2, this paper seeks to highlight the carbon footprint associated with waste management in hydropower plants and offer recommendations for improving environmental performance in the waste sector of such plants.

This paper is organized as follows. Section 2 discusses the methodology used in this study. In Section 3, the study results are presented. Finally, conclusions and remarks are given in Section 4.

2. Methodology

In order to analyze the carbon footprint generated in the waste sector of the NT2 during its operational phase, the study referenced the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which includes Volume 5 Waste (Buendia et al., 2019b) and IPCC Volume 2 Energy (Buendia et al., 2019a). The methodological guidance for the estimation of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions is illustrated in **Figure 3**.

This study addresses methodological concerns, including uncertainty assessment in the choice of method, emission factors, activity data, completeness, and

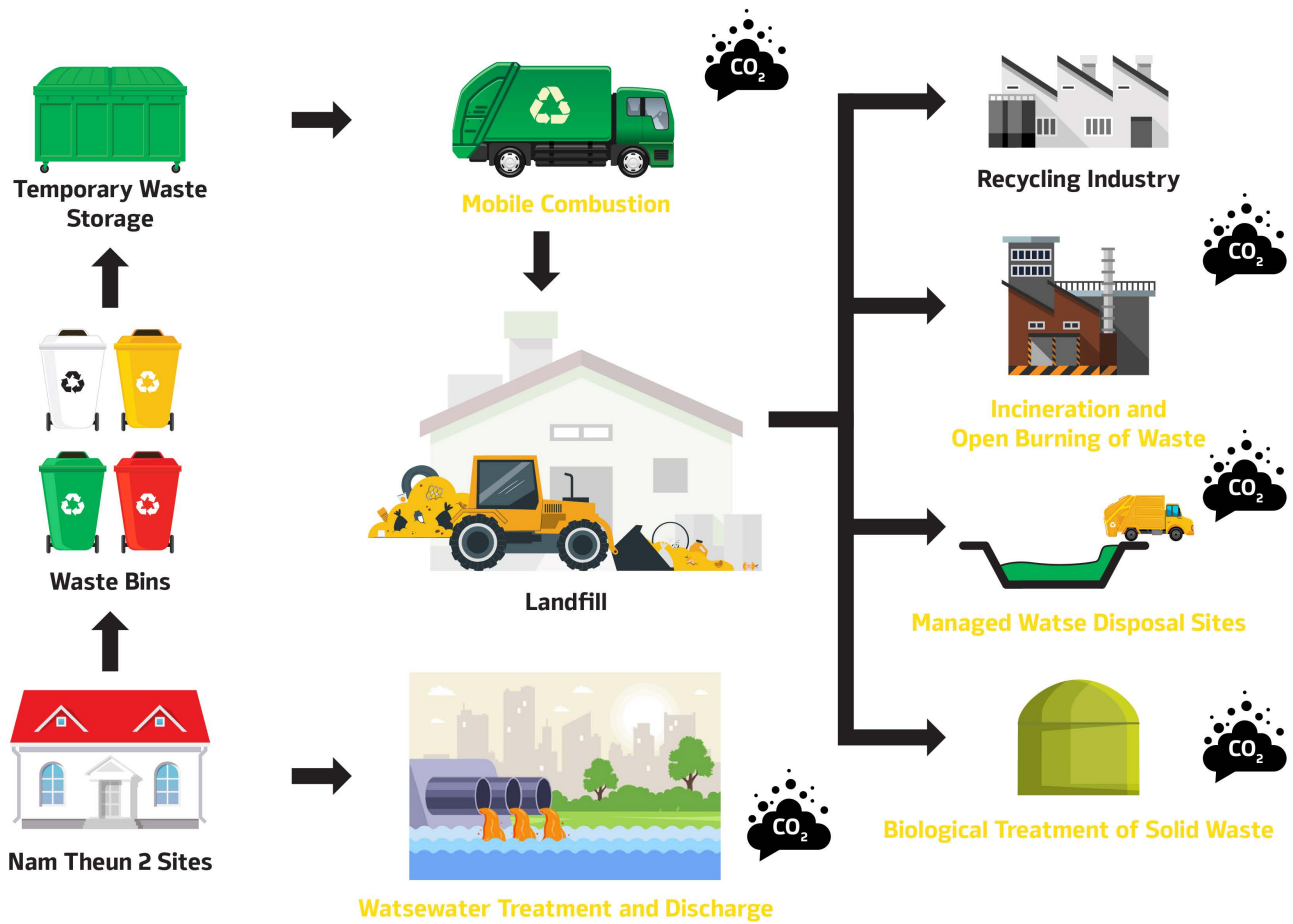


Figure 3. Approach of the carbon footprint generated in the waste sector of NT2.

developing a consistent time. These issues are associated with the classification within Volume 5 Waste (Buendia et al., 2019b) and Volume 2 Energy (Buendia et al., 2019a). The carbon footprint equation and calculation in the waste sector of the NT2 are based on the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019c).

The equation of CO₂ emission from the road transportation is (Waldron et al., 2006; IPCC, 2019a):

$$\text{CO}_2 \text{ emission} = \sum_a [\text{Fuel}_a * \text{EF}_a] \quad (1)$$

where

- CO₂ emission: Emissions of CO₂ (kg);
- Fuel_a: Fuel sold (TJ);
- EF_a: Emission factor (kg/TJ). This is equal to the carbon content of the fuel multiplied by 44/12;
- a: Fuel type (e.g. petrol, diesel, natural gas, LPG, etc).

The equation of Tier 1 emission of CH₄ and N₂O is:

$$\text{CH}_4 \text{ and N}_2\text{O emissions} = \sum_a [\text{Fuel}_a * \text{EF}_a] \quad (2)$$

where

- CH₄ and N₂O emissions: Emissions of CH₄ and N₂O (kg);
- EF_a: Emission factor (kg/TJ);
- Fuel: Fuel consumed (TJ);
- a: Fuel type (e.g. diesel, gasoline, nature gas, LPG).

The equation of CH₄ emission from solid waste disposal is (Towprayoon et al., 2019a; IPCC, 2007b):

$$\text{CH}_4 \text{ emission} = \left[\sum_x \text{CH}_4 \text{ generated}_{x,T} - R_T \right] * (1 - \text{OX}_T) \quad (3)$$

where

- CH₄ emission: CH₄ emitted in year T (Gg);
- T: Inventory year;
- x: Waste category or type/material;
- R_T: Recovered CH₄ in year T (Gg);
- OX_T: Oxidation factor in year T.

The equation of CH₄ emission from the biological treatment is (Pipatti et al., 2006):

$$\text{CH}_4 \text{ emission} = \sum_i (M_i * \text{EF}_i) * 10^{-3} - R \quad (4)$$

where

- CH₄ emission: Total CH₄ emission in inventory year (Gg CH₄);
- M_i: Mass of organic waste treated by biological treatment types i (Gg);
- EF: Emission factor for treatment i, g CH₄/Kg waste treated;
- i: Composting or anaerobic digestion;
- R: Total amount of CH₄ recovered in inventory year (Gg CH₄).

The equation of N₂O emission from the biological treatment is:

$$\text{N}_2\text{O emission} = \sum_i (M_i * \text{EF}_i) * 10^{-3} \quad (5)$$

where

- N₂O emission: Total N₂O emission in inventory year (Gg N₂O);
- M_i: Mass of organic waste treated by biological treatment types i (Gg);
- EF: Emission factor for treatment i, g N₂O /Kg waste treated;
- i: Composting or anaerobic digestion.

The equation of CO₂ emission based on the total amount of waste combusted is (Towprayoon et al., 2019b):

$$\text{CO}_2 \text{ emission} = \sum_i (\text{SW}_i * \text{dm}_i * \text{CF}_i * \text{FCF}_i * \text{OF}_i) * 44/12 \quad (6)$$

where

- CO₂ emissions: CO₂ emissions in inventory year (Gg/year);
- SW_i: Total amount of solid waste of types i (wet weight) incinerated or open-burned (Gg/yr);
- dm_i: Dry matter content in the waste (wet weight) incinerated or open-burned;
- CF_i: Fraction of carbon in the dry matter;
- FCF_i: Fraction of fossil carbon in the total carbon;
- OF_i: Oxidation factor;
- 44/12: Conversion factor from C to CO₂;

- i : Type of waste incinerated/open-burned which is specified as municipal solid waste (MSW), industrial solid waste (ISW), sewage sludge (SS), hazardous waste (HW), clinical waste (CW), others (that waste be specified).

The equation of CH_4 emission based on the total amount of waste combusted is:

$$\text{CH}_4 \text{ emission} = \sum_i (\text{IW}_i * \text{EF}_i) * 10^{-6} \quad (7)$$

where

- CH_4 emission: CH_4 emissions in inventory year (Gg/year);
- IW_i : Amount of solid waste of types i incinerated or open-burned (Gg/yr);
- EF_i : Aggregate CH_4 emission factor (kg CH_4 /Gg);
- i : Category or type of waste incinerated/open-burned, which is specified as municipal solid waste (MSW), industrial solid waste (ISW), sewage sludge (SS), hazardous waste (HW), clinical waste (CW), others (that waste be specified).

The equation of N_2O emission based on the waste input to the incinerators is:

$$\text{N}_2\text{O emission} = \sum_i (\text{IW}_i \times \text{EF}_i) * 10^{-6} \quad (8)$$

where

- N_2O emission: N_2O emissions in inventory year (Gg/year);
- IW_i : Amount of incinerated/open-burned waste of types i (Gg/yr);
- EF_i : N_2O emission factor (kg N_2O /Gg of waste) for waste of types i ;
- i : Category or type of waste incinerated/open-burned, which is specified as municipal solid waste (MSW), industrial solid waste (ISW), sewage sludge (SS), hazardous waste (HW), clinical waste (CW), others (that waste be specified).

The equation of CH_4 emission from the domestic wastewater is (Bartram et al., 2006; IPCC, 2019b):

$$\text{CH}_4 \text{ emission} = (\text{TOW}_j - \text{S}_j) * \text{EF}_j - \text{R}_j \quad (9)$$

where

- CH_4 emission _{j} : CH_4 emissions from the treatment/discharge pathway or system, j , in inventory year (kg CH_4 /yr);
- TOW_j : Organics in wastewater of the treatment/discharge pathway or system, j , in inventory year (kg BOD/yr);
- S_j : Organic component removed from the wastewater (in the form of sludge) from the treatment/discharge pathway or system, j , in inventory year (kg BOD/yr). For wastewater discharged to aquatic environments, there is no sludge removal ($\text{S}_j = 0$) and no CH_4 recovery ($\text{R}_j = 0$);
- j : Each treatment/discharge path or system;
- EF_j : Emission factor for the treatment/discharge pathway or system, j , (kg CH_4 /kg BOD);
- R_j : Amount of CH_4 recovered or flared from treatment/discharge pathway or system, j , in inventory year (kg CH_4 /yr). The default value is zero.

The equation of N₂O emission from the wastewater effluent is:

$$N_2O \text{ emission} = N_{\text{Effluent}} * EF_{\text{Effluent}} * 44/28 \quad (10)$$

where

- N₂O emission: N₂O emissions in inventory year (kg N₂O /yr);
- N_{Effluent}: Nitrogen in the effluent discharged to aquatic environments (kg N/yr);
- EF_{Effluent}: Emission factor for N₂O emissions from discharged to wastewater (kg N₂O-N/kg N);
- The factor 44/28 is the conversion of kg N₂O-N into kg N₂O.

Once the emission sources have been identified, activity data collected, and emission factors determined, GHG emissions can be calculated using the identified quantification approach (IPCC, 2019c):

$$CO_2,eq = \text{Annual Activity Intensity of Emission Source} * EF * GWP \quad (11)$$

where

- EF is an emission factor, which is a coefficient that measures the emissions or removals of a gas per unit of activity. These factors are typically derived from sampled measurement data and averaged to establish a representative rate for a specific activity level and set of conditions (IPCC, 2019c).
- GWP is a global warming potential, which is determined by a ratio of the radiative forcing of one kilogram of a GHG emitted into the atmosphere to that of one kilogram of CO₂ over a specified time (e.g., 100 years) (IPCC, 2021).

3. Study Results

3.1. Emission Intensity of Activity Sources in the Waste Sector

Based on waste generation data from 2018 to 2022, the average annual waste generation in NT2 is divided into four main types: General Waste at 88.11%, Recycled Waste at 8.48%, Hazardous Waste at 2.72%, and Composting Waste at 1.15%. The waste generation is 302.24 Kg/Person/Year, with an average daily waste generation of 0.8028 Kg/Person/Day, as shown in **Table 2**.

In 2022, the quantity of waste in NT2 amounted to 229,350 kg, with waste disposal methodology divided into two main types: 21,500 kg for hazardous waste disposal and 203,800 kg for non-hazardous waste disposal. Specifically, hazardous waste disposal included 7370 kg via landfill and 14,130 kg via incineration, while non-hazardous waste disposal included 183,980 kg via landfill and 19,820 kg via recycling, as illustrated in **Figure 4**.

Moreover, waste transportation plays a significant role in fuel consumption and emissions. The carbon footprint provides a method to estimate fuel consumption based on gas usage. Specifically, in 2022, fuel consumption (and gas emissions) amounted to 10,035 liters of diesel, encompassing 8649 liters for waste transportation from sites to the landfill, 1395 liters for waste transportation from the landfill to disposal in a local factory in Laos, and 1440 liters of gasoline for waste transportation from sites to the landfill and waste management

activities such as grass cutting and management vehicle usage, as illustrated in **Figure 5**. The fuel intensity stands at 50.03 liters per ton of waste, as shown in **Table 3**.

Table 2. Waste generation from 2018 to 2022.

Waste type	Waste Generation (Kg)					Total	Average
	2018	2019	2020	2021	2022		
Population	654	703	715	751	786	3609	721.8
General waste	199,518	189,187	189,319	197,182	183,981	959,187	191,837
Recycle waste	14,252.50	9472	20,173	18,823	30,986	93,706	18,741
Hazardous waste	3515	3174	4837	5853.33	12,763	30,142	6028
Composting waste	4967	-	-	1144.20	1619	7730	2576
Total	222,253	201,833	214,329	223,003	229,350	1,090,767	218,153
Person per Year	339.84	287.10	299.76	296.94	291.79	1515	302.24
Person per Day	0.93	0.79	0.82	0.81	0.80	4.15	0.83

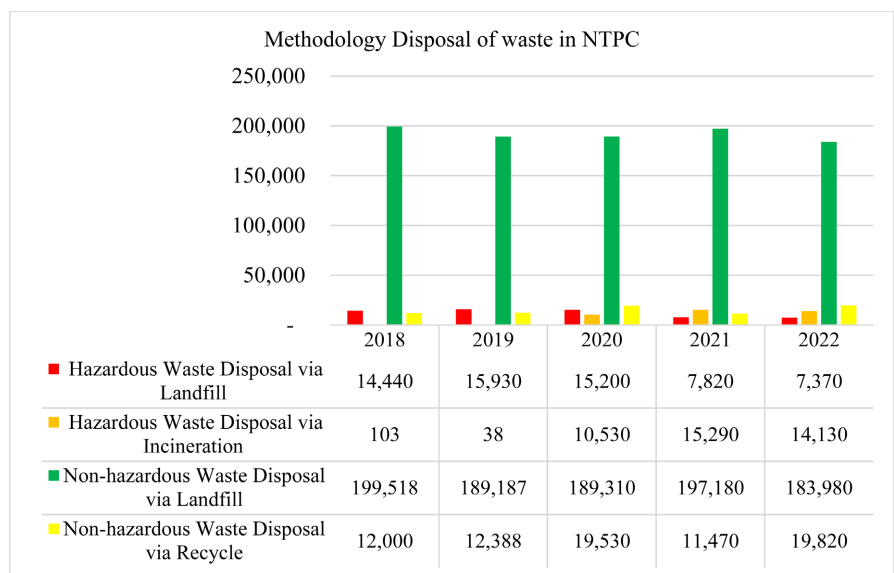


Figure 4. Quantity of waste disposal methodology in NT2.

3.2. Carbon Footprint in the Waste Sector of Hydropower Plant

The evaluation of the carbon footprint in the waste sector of a hydropower plant unveiled several key insights. The analysis encompassed various waste management activities and the quantification of carbon footprint or GHG emissions. The study revealed that the waste sector of the hydropower plant is a significant source of GHG emissions, primarily attributed to the transportation of waste, solid waste disposal, biological treatment, incineration processes, and wastewater treatment. The quantification of carbon footprints for these emissions, encompassing Carbon Dioxide (CO₂), Methane (CH₄), and Nitrous Oxide (N₂O), has provided

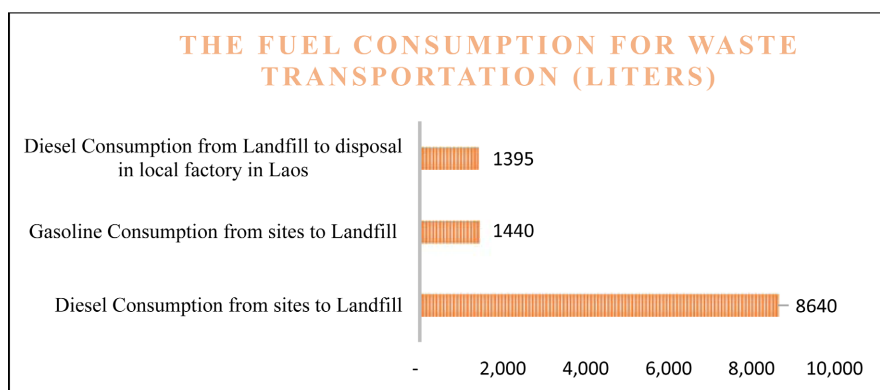


Figure 5. Fuel consumption in waste management.

valuable insights into the environmental impact of waste management activities. This includes emissions totaling 3858.25 tCO₂, 8.77 tCH₄, and 2.00E-02 tN₂O, with a Carbon Intensity of 17.83 tCO₂-eq/tWaste and Fuel Intensity of 50.03 Liters/tWaste. Total anthropogenic direct and indirect GHG emissions are attributed to Solid Waste Generation (5.42%), Hazardous Waste Incineration (0.0003%), Wastewater Treatment and Discharge (0.50%), and Fuel Consumption (0.75%), as illustrated in **Table 3**.

Table 3. Carbon footprint in the waste sector of NT2.

Emission Source Items		GHG Emission (ton)				
		CO ₂	CH ₄	N ₂ O	tCO ₂ equivalent Percentage	
Solid Waste Generation	Solid Waste Disposal		8.19		222.77	5.42%
	Garden Waste Disposal		2.78E-04	1.67E-05	1.21E-02	0.0003%
Hazardous Waste Incineration	Waste Incineration	3828	1.66E-07		3828.00	93.16%
Wastewater Treatment and Discharge	Domestic Wastewater		5.77E-01	1.85E-02	20.73	0.50%
The Fuel Consumption	Waste Transportation	30.25	3.00E-03	1.50E-03	30.74	0.75%
	Total GHG Emission	3858.25	8.77	2.00E-02	4109.11	
	Total GHG Emission without Wastewater Sector	3858.25	8.19	1.52E-03	4088.38	
	Carbon Intensity (tGHG/tWaste)	16.82	3.57E-02	6.61E-06	17.83	
	Fuel Intensity (Liters/tWaste)				50.03	

We can also observe that the overall carbon footprint or GHG emissions, totaling 4109.11 tCO₂ equivalent, with a Carbon Footprint Intensity of 17.83 tCO₂ equivalent per ton of waste. The assessment of primary emission sources highlighted specific waste management practices that significantly impacted the hydropower plant's carbon footprint. Notably, incineration processes emerged as a significant emission source, contributing 3828 tCO₂-eq. Furthermore, waste disposal in landfills amounted to 222.77 tCO₂-eq, fuel consumption in waste transportation added 30.74 tCO₂-eq, wastewater treatment contributed 24.65

tCO₂-eq, and garden waste accounted for 1.21E-02 tCO₂-eq.

The highest CO₂ equivalent emission comes from waste incineration, totaling 3,828 tCO₂-eq. Following closely is solid waste disposal, with 222.77 tCO₂-eq emitted from dumps in waste cells. Additionally, there are emissions of 30.74 tCO₂-eq from fuel consumption during waste transportation from on-site to the landfill and from the landfill to disposal services, as depicted in **Figure 6**.

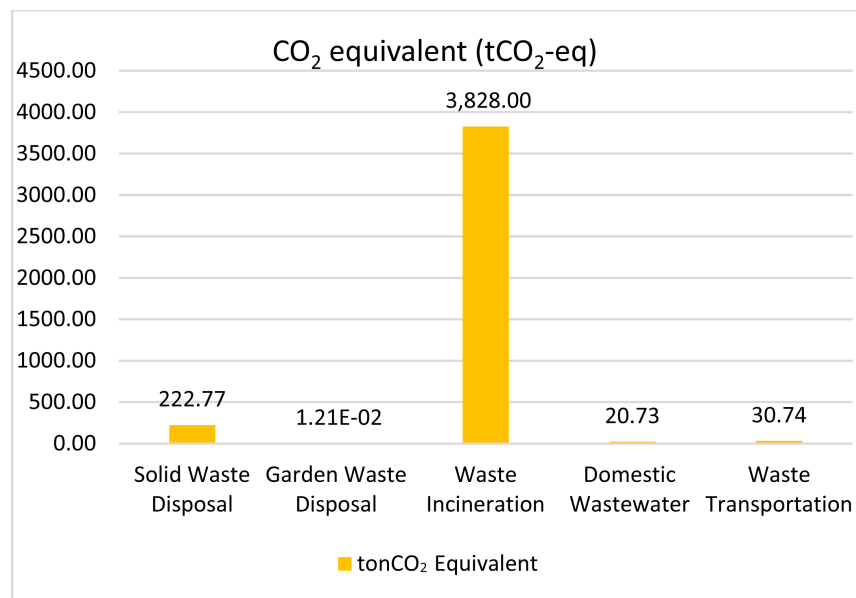


Figure 6. CO₂ equivalent (CO₂-eq) emission in the waste sector.

The highest CO₂ emissions, totaling 3828 tCO₂, stem from waste incineration, which includes 12.6 tons of hazardous waste and 1.5 tons of clinical waste disposed of via stoker semi-continuous incineration and batch-type incineration. Additionally, there are emissions of 30.25 tCO₂ resulting from fuel consumption during waste transportation from onsite to the landfill and from the landfill to disposal services, as elaborated in **Figure 7**.

The highest CH₄ emission, totaling 8.19 tCH₄, originates from solid waste disposal through dumping in waste cells. Following closely is emission from domestic wastewater treatment, amounting to 5.77E-01 tCH₄, attributed to three activated sludge systems (Centralized, Aerobic Treatment Plant) and one wetland (Anaerobic Shallow Lagoon). Additionally, significant emissions result from fuel consumption in waste transportation, as outlined in **Figure 8**.

The highest N₂O emissions total 185E-02 tN₂O, stemming from indirect emissions from two activated sludge systems (Centralized, Aerobic Treatment Plant) and one wetland (Anaerobic Shallow Lagoon) utilized for wastewater treatment, as outlined in **Figure 9**.

The study revealed that the carbon footprint in the waste sector of the hydro-power plant resulted in emissions with a carbon intensity of 17.83 tCO₂ equivalent per ton of waste. This includes 16.82 kgCO₂/kg, 3.57E-02 kgCH₄/kg, and

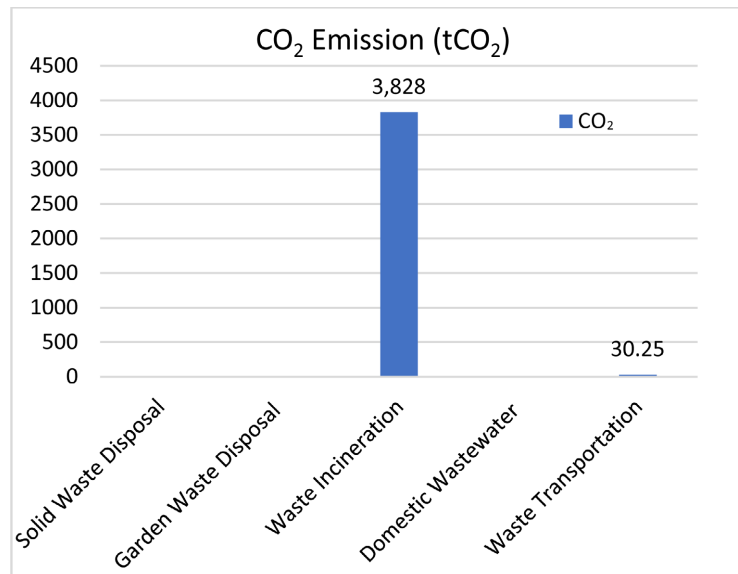


Figure 7. CO₂ Emission in the waste sector.

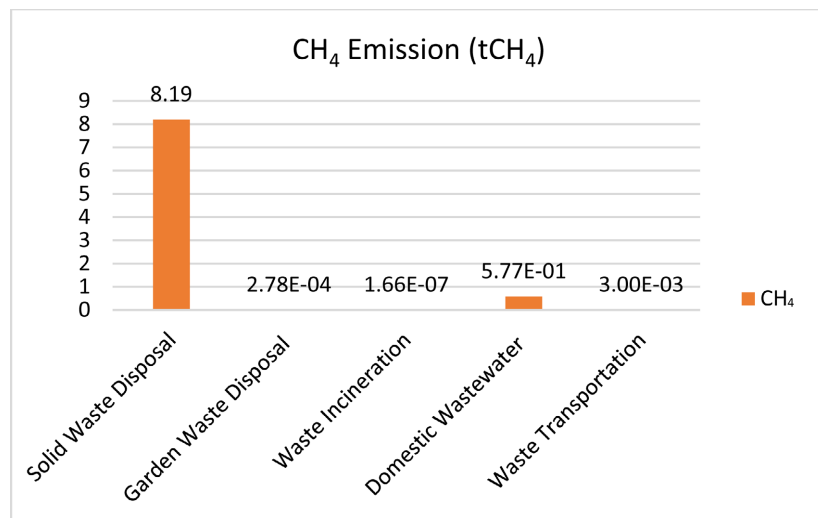


Figure 8. CH₄ Emission in the waste sector.

6.61E-06 kgN₂O/kg. This figure is significantly higher when compared to the carbon intensity of the solid waste sector in Greater Bangalore, India, which stands at 0.355 kg CH₄/kg and 0.991 kg CO₂/kg of waste (Ramachandra et al., 2014).

The study's assessment identified specific waste management activities that had the most significant on the carbon footprint of the NT2. Waste incineration was identified as a major source of emissions, along with solid waste disposal, waste transportation, and domestic wastewater. Despite hydropower being a clean and renewable energy source, the study emphasized the need to address emissions associated with waste management to achieve a more sustainable energy production process.

The results prompted a discussion on potential mitigation strategies to reduce

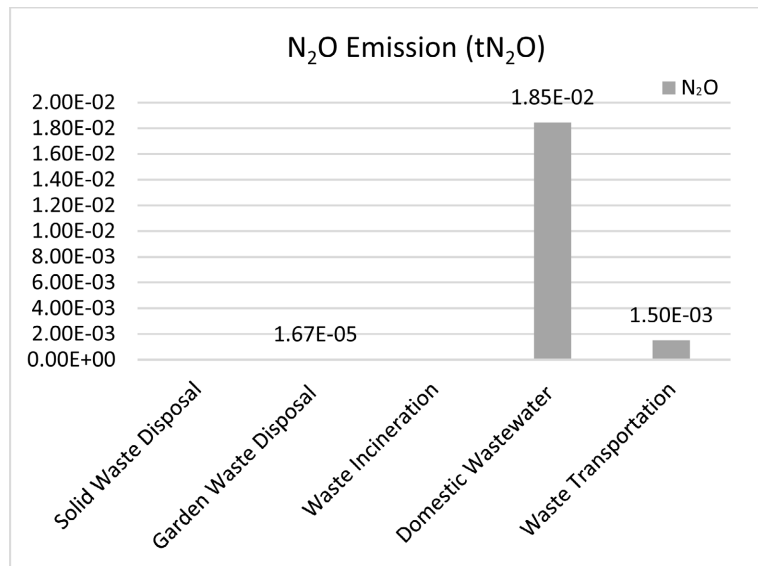


Figure 9. N₂O emission in the waste sector.

the carbon footprint in the waste sector of the hydropower plant. This included exploring alternative transportation methods, such as electric or hybrid vehicles, as well as implementing waste reduction and recycling initiatives to minimize the amount of waste requiring disposal. The discussion also emphasized the importance of conducting a comprehensive lifecycle analysis of waste management practices to fully understand the carbon footprint of the hydropower plant. This would involve assessing the emissions associated with the production, use, and disposal of materials throughout their lifecycle, providing a more holistic view of the environmental impact.

Overall, the results and discussion underscore the imperative for targeted initiatives aimed at studying and implementing pathways to minimize the carbon footprint within the waste sector of hydropower plants. This aligns with broader sustainability objectives and the imperative transition towards a low-carbon energy future. Such a transition is crucial in the global fight against climate change and its adverse effects on sustainable development. It demands a shift away from fossil fuels towards clean energy production, along with the development and promotion of low carbon technologies for energy generation, the advancement of renewable energy sources, and the enhancement of energy efficiency measures. Achieving a low-carbon economy represents a global challenge requiring the collective commitment of nations and individuals alike. Urgent action is required to meet the targets set under the 2°C threshold (Carrasco, 2014).

3.3. Discussion on Potential Mitigation Strategies

The assessment of the carbon footprint in the NT2's waste sector reveals that activities such as incineration and solid waste disposal are significant contributors to emissions. To address this topic, it is important to adopt alternative transportation methods, such as electric vehicles, and prioritize waste reduction and re-

cycling initiatives. Additionally, conducting comprehensive lifecycle analyses of waste management practices and integrating sustainable strategies operations are crucial for long-term environmental sustainability.

3.3.1. Alternative Transportation Methods

One promising approach involves the adoption of alternative transportation methods [33], particularly the integration of electric or hybrid for waste transportation. By transitioning from conventional fossil fuel-powered vehicles to electric or hybrid counterparts, the plant can significantly reduce emissions associated with waste transportation activities. Such a shift not only aligns with broader sustainability objectives but also underscores the plant's commitment to mitigating its carbon footprint.

3.3.2. Waste Reduction and Recycling Initiatives

Furthermore, there is a strong emphasis on implementing waste reduction and recycling initiatives as fundamental strategies for reducing the volume of waste that ends up in landfills and incineration, both of which are significant contributors to emissions. By promoting recycling efforts and fostering waste reduction practices, the plant can substantially diminish its environmental impact (Eneh & Oluigbo, 2012). These initiatives not only curtail GHG emissions but also contribute to resource conservation and environmental preservation.

3.3.3. Comprehensive Lifecycle Analyses

An essential aspect of the discussion involves conducting comprehensive lifecycle analyses of waste management practices. By scrutinizing the environmental impact of waste management activities across their entire lifecycle, from production to disposal in hydropower plants, key areas for emissions reduction can be identified (Leonzio, 2023). Through lifecycle analyses, the plant gains valuable insights into emission hotspots and can effectively implement targeted mitigation measures, thereby minimizing its overall carbon footprint.

3.3.4. Integration of Sustainable Practices

Furthermore, the integration of sustainable waste management practices into the operations of the hydropower plant is essential for achieving long-term environmental sustainability (Sen et al., 2022). This involves not only addressing emissions from waste management activities but also considering broader environmental and social implications. Stakeholder engagement and collaboration with local communities play a crucial role in ensuring the implementation of effective waste management strategies that are socially acceptable and environmentally responsible.

In summary, by exploring and implementing these potential mitigation strategies, NT2 can take proactive steps towards reducing its carbon footprint in the waste sector, contributing to global efforts to combat climate change while advancing environmental sustainability.

4. Conclusion

The waste sector of NT2 was assessed for its carbon footprint, revealing emissions totaling 4109.11 tCO₂ equivalent. The Carbon Footprint Intensity was calculated at 17.83 tCO₂ equivalent per ton of waste, with contributions from various sources including waste incineration, solid waste disposal, waste transportation, and domestic wastewater. These findings emphasize the necessity of mitigating emissions from waste management to maximize the environmental benefits of renewable energy production at the hydropower plant. Key mitigation measures include transitioning to alternative transportation methods, reducing waste generation, implementing waste reduction at the source, and promoting recycling initiatives.

Conducting a comprehensive lifecycle analysis of waste management practices is essential for gaining a holistic understanding of the carbon footprint and developing effective strategies to minimize environmental impact. However, this presents challenges such as resource allocation and the need for expertise. Addressing these challenges is crucial for devising strategies that effectively reduce environmental impact.

Integrating sustainable waste management practices into hydropower plant operations poses additional challenges, including stakeholder engagement and ensuring social acceptability. Despite these challenges, it is imperative to incorporate sustainable waste management practices into hydropower plant operations to align with global efforts to mitigate climate change and transition towards a more sustainable energy production paradigm.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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