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Projection of Transportation CO_2 Emissions and Local Biogas Potential in Jember Regency

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Keywords

Co_2 emissions; daily transportation; local biogas; renewable energy; fuel substitution

Abstract

The daily transportation sector is a major source of air pollution and CO_2 emissions in Jember Regency, driven by the growth of motorized vehicles and fossil fuel consumption. This study aims to project CO_2 emissions from daily transportation and to assess the potential of local biogas as a renewable energy alternative for fossil fuel substitution. A quantitative approach based on secondary data was applied using multi-horizon projections for 2030, 2045, and 2060. Transportation-related CO_2 emissions were estimated using the IPCC methodology for mobile combustion, while biogas potential was calculated from organic municipal waste, livestock manure, agricultural and plantation residues, and landfill methane using volatile solids–biochemical methane potential and first-order decay approaches. The results indicate that transportation emissions are projected to increase, while Jember Regency has significant local biogas potential, equivalent to 2.98–3.20 PJ of energy per year, indicating opportunities for partial fossil fuel substitution through a scenario-based approach.

INTRODUCTION

The transportation sector is one of the major contributors to air pollution and carbon dioxide (CO_2) emissions in urban areas and developing regions. The rapid increase in motorized vehicles, which are predominantly powered by fossil fuels, has led to higher greenhouse gas emissions and a decline in ambient air quality, directly affecting public health and the environment (Intergovernmental Panel on Climate Change, 2006, 2019). In developing countries such as Indonesia, the growth of motorized vehicles has occurred more rapidly than improvements in energy efficiency and the adoption of low-emission technologies, making the transportation sector a priority in pollution control efforts and climate change mitigation strategies.

The Government of Indonesia has established greenhouse gas emission reduction commitments through the Nationally Determined Contribution (NDC), targeting a 29% reduction through domestic efforts and up to 41% with international support by 2030, as well as a long-term commitment to achieving Net Zero Emissions (NZE) by 2060 '(Kementerian Lingkungan Hidup dan Kehutanan, 2021). However, scenario-based analyses of road transport systems indicate that achieving deep decarbonization targets remains highly challenging even under ambitious policy interventions (Henke et al., 2024). Within this framework, the transportation sector plays a strategic role due to its substantial contribution to energy-related emissions and urban air pollution. Therefore, data-driven approaches are required to understand the medium and long term dynamics of transportation emissions, as well as the potential of alternative energy sources that can be realistically

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implemented at the local level.

Jember Regency is one of the regions in East Java characterized by high levels of daily transportation activity, with motorcycles dominating the modal structure. Previous studies indicate that CO_2 emissions from the daily transportation sector in Jember Regency could reach approximately 3.8 million tons by 2030 in the absence of adequate policy interventions and energy substitution measures (Angin et al., 2022). These findings highlight the role of the transportation sector as a major source of local air pollution; however, the analysis remains focused on baseline emission calculations and does not explicitly link emissions with the availability of alternative energy sources based on local resources.

Conversely, Jember Regency possesses considerable biogas potential derived from organic municipal waste, livestock manure, agricultural and plantation residues, and methane gas from final disposal sites (Reja et al., 2023). Several previous studies have identified the potential of biogas from organic and livestock waste in Jember and other regions in Indonesia, both for electricity generation and local-scale energy utilization (Agustin et al., 2023; Cahyono et al., 2025; Fitri & Hamdi, 2024; Lesmana et al., 2022; Novita et al., 2023; Purnomo & Yusriadi, 2023; Rahmat et al., 2023).

Nevertheless, the utilization of biogas as an alternative fuel for the transportation sector, particularly in the form of Bio-CNG, remains limited and has not yet been integrated with daily transportation energy demand or long-term emission projections (Ferrari et al., 2024). However, at the application level, empirical studies indicate that biomethane utilization can improve energy efficiency and reduce greenhouse gas emissions, supporting its role as a low-carbon transport fuel (Kwon et al., 2026). In addition to technical performance, the deployment of biomethane as a transport fuel is also influenced by technological compatibility, regulatory frameworks, and infrastructure readiness, particularly with respect to gas quality standards and system integration (Štimac et al., 2025).

At the international level, the use of biomethane as a transportation fuel has expanded significantly and has been shown to reduce greenhouse gas emissions and air pollutants compared to conventional fossil fuels (Angelidaki et al., 2009; Dahlgren, 2020; Hidalgo et al., 2025; International Energy Agency, 2020; Korberg et al., 2020; Prussi et al., 2019; Scarlat et al., 2018). This approach demonstrates that integrating transportation emission projections with the potential supply of renewable energy is a key element in formulating effective mitigation strategies tailored to local conditions (Korberg et al., 2020).

Based on these considerations, this study aims to project CO_2 emissions from the daily transportation sector in Jember Regency for the 2030, 2045, and 2060 horizons, and to assess local biogas potential as an alternative energy source for fossil fuel substitution. The findings are expected to provide an initial quantitative basis for air pollution control and the development of transportation emission mitigation strategies based on local resources, while supporting the achievement of national emission reduction targets.

RESEARCH METHODS

This study employed a quantitative approach based on secondary data, using a multi-horizon projection framework to analyze CO_2 emissions from the daily transportation sector and local biogas potential in Jember Regency. The time horizons considered include 2030, 2045, and 2060, representing short-, medium-, and long-term emission reduction policy targets. The data utilized comprise motor vehicle statistics, fuel consumption, population figures, organic waste generation, livestock populations, agricultural and plantation production, and operational data of final disposal sites (landfills). These data were obtained from official government publications and regional planning documents.

Projections of motor vehicle numbers were developed using a geometric growth approach based on historical vehicle trends. The vehicle projection equation was expressed as follows:

$$P_t = P_0(1+r)^2 \quad (1)$$

where P_t was the number of vehicles in year *t*, P_0 was the number of vehicles in the base year, *r* was the annual vehicle growth rate, and *t* represented the projection period (years).

CO_2 emissions from the transportation sector were calculated using the Intergovernmental Panel on Climate Change (IPCC) methodology for mobile combustion. Emissions were estimated based on motor vehicle fuel consumption by considering the net calorific value, carbon emission factor, and oxidation factor, as expressed by the following equation:

$$E_{CO_2} = \sum (A_i \times NCV_i \times EF_i \times OF_i) \times \frac{44}{12} \quad (2)$$

where E_{CO_2} was carbon dioxide emissions (tons Co_2), A_i was the consumption of fuel type *I*, NCV_i was the net calorific value of the fuel, EF_i was the carbon emission factor, and OF_i was the oxidation factor.

Local biogas potential was estimated from several major biomass sources, including organic municipal waste, livestock manure, and agricultural and plantation residues. The estimation of technical biogas potential was conducted in line with established analytical frameworks that integrate feedstock classification and biomass availability assessment at regional scales (Steindl et al., 2025). Methane production from these biomass sources was calculated using the volatile solids–biochemical methane potential (VS–BMP) approach, expressed as follows:

$$CH_4 = VS \times BMP \times R \quad (3)$$

where Ch_4 was the volume of methane produced (m^3/year), VS was the mass of volatile solids (kg/year), BMP was the specific methane potential (m^3 CH_4/kg VS), and R was the effective conversion ratio representing process efficiency. Methane potential from final disposal sites (landfills) was estimated using the first-order decay (FOD) method in accordance with IPCC guidelines, which describes the exponential degradation of organic matter over time. Landfill methane generation was expressed as:

$$CH_4(t) = \sum_{i=0}^{t} M_i \times L_0 \times k \times e^{-k(t-1)} \quad (4)$$

where CH_4 (t) was methane production in year *t*, M_i was the mass of waste disposed in year *i*, L_0 was was the methane generation potential per ton of waste, and *k* was the decay rate constant.

All estimated methane potentials were subsequently converted into energy units using the lower heating value of methane to obtain the annual biogas energy potential, as expressed by:

$$E_{biogas} = V_{CH_4} \times LHV_{CH_4} \quad (5)$$

where E_{biogas} was the biogas energy potential (MJ/year), V_{CH_4} was the methane volume (m^3/year), LHV_{CH_4} and was the lower heating value of methane (MJ/m^3).

The potential for fossil fuel substitution was analyzed by comparing the projected biogas energy supply with the projected energy demand of the transportation sector for each time horizon. The evaluation was conducted using a scenario-based approach to illustrate different levels of biogas adoption in priority transportation segments, without performing a detailed operational implementation analysis.

RESULTS AND DISCUSSION

The projection results indicated that CO_2 emissions from the daily transportation sector in Jember Regency increased across all analyzed time horizons, namely 2030, 2045, and 2060 (Table 1). The upward trend was primarily driven by the growth in the number of motorized vehicles, with motorcycles remaining the dominant mode over the long term. This characteristic reflects a strong reliance on individual transportation patterns at the regency level, which leads to high fossil fuel consumption and rising carbon dioxide emissions. These findings are consistent with previous studies showing

Table 1
Projected CO_2 Emissions from the Daily Transportation Sector in Jember Regency

Year	Projected CO Emissions (million tons/year)	Description
2030	4.06	Increase driven by motorcycle dominance
2045	9.08	Growth of light commercial vehicles
2060	22.03	Long -term emission pressure without substitution

Source: Processed Primary Data, 2025

that the transportation sector is a major contributor to CO_2 emissions in urban and peri-urban areas in Indonesia (Angin et al., 2022; Intergovernmental Panel on Climate Change, 2019).

The projection results indicated a substantial increase in CO_2 emissions from the daily transportation sector in Jember Regency across all analyzed time horizons (Table 1). Emissions are projected to reach 4.06 million tons/year in 2030, more than double to 9.08 million tons/year in 2045, and further surge to 22.03 million tons/year by 2060. This represents an approximately 5.4 fold increase between 2030 and 2060.

The sharp escalation between 2045 and 2060 suggests accelerating emission pressure in the absence of structural interventions, particularly considering the continued dominance of motorcycles and the projected growth of light commercial vehicles. The magnitude of emissions in 2060 indicates that, without effective energy substitution strategies, the transportation sector could significantly undermine regional emission reduction targets.

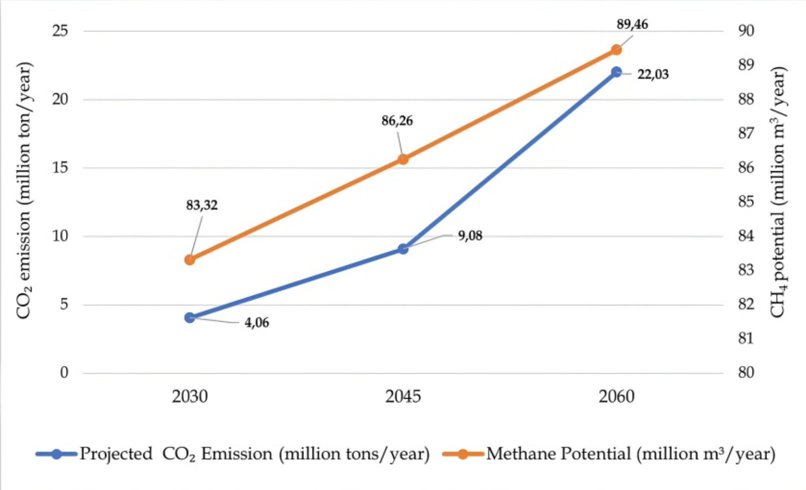
From environmental perspective, such emission growth implies increased atmospheric CO_2 accumulation and associated co-pollutants from fossil fuel combustion, potentially exacerbating air quality deterioration and public health risks. These findings underline the urgency of implementing both demand-side management measures and cleaner energy transitions within the transportation sector.

When compared with the energy demand of the transportation sector, the estimated biogas potential is not sufficient to fully replace fossil fuel consumption. Nevertheless, through a scenario-based approach, biogas can be selectively utilized in priority transportation segments, such as public service vehicles, local government operational vehicles, and waste management fleets. This phased approach is consistent with international practices in the use of biomethane as a transportation fuel, which typically begins with controlled vehicle fleets before being expanded to a broader scale (International Energy Agency, 2020; Scarlat et al., 2018).

Table 2
Recapitulation of Local Biogas Potential in Jember Regency

Biogas Source	Methane Potential (million m^3/year)			Energy Potential (PJ/year)			Contribution (%)
	2030	2045	2060	2030	2045	2060	
Organic waste	8.73	9.51	10.35	0.31	0.34	0.37	10.48
Livestock manure	22.64	24.66	26.85	0.81	0.88	0.96	27.17
Agricultural and plantation residues	50.35	50.35	50.35	1.80	1.80	1.80	60.43
Landfill methane gas	1.60	1.74	1.90	0.06	0.06	0.07	1.92
Total	**83.32**	**86.26**	**89.46**	**2.98**	**3.09**	**3.20**	**100.00**

Source: Processed Primary Data, 2025



Source: Processed Secondary Data, (2026)

Figure 1

Comparison of projected transportation emission trends and local biogas potential in Jember Regency (2030–2060)

The relationship between the increasing trend of transportation emissions and the potential supply of local renewable energy is illustrated in **Figure 1**. The figure shows that the growth rate of CO_2 emissions from the transportation sector is substantially faster than the increase in local biogas potential. This condition highlights the gap between emission growth and the capacity of regional renewable energy supply, indicating that biogas utilization is more realistically directed toward partial substitution strategies based on scenario development. The integration of biomethane into broader renewable energy systems has also been recognized as a critical component of long-term decarbonization pathways, particularly in energy system transition modeling studies(Korberg et al., 2020).

From the perspective of source composition, the largest contribution to biogas potential originates from agricultural and plantation residues, accounting for approximately 60% of the total methane potential. Similar findings have been reported in national-scale assessments, where crop residues dominate biogas feedstock availability ""(Vaskina et al., 2025). This dominance reflects the agrarian characteristics of Jember Regency, where biomass residue production remains relatively stable over the long term.

Livestock manure represents the second-largest contributor, with a share of approximately 27%, corresponding to the increasing livestock population across the analyzed time horizons. This is consistent with state-level analyses demonstrating substantial biomethane generation and greenhouse gas mitigation potential from livestock manure(Ahmed & Vijay, 2026).

Organic municipal waste contributes a smaller share, while landfill methane provides the lowest contribution; nevertheless, it remains environmentally significant due to its role in reducing methane emissions, which have a higher global warming potential than carbon dioxide. Global assessments of landfill-based waste-to-energy systems similarly indicate substantial energy recovery and greenhouse gas mitigation potential when methane capture systems are effectively implemented(Alrbai et al., 2025).

Overall, the composition of biogas potential indicates that biogas utilization strategies in Jember Regency should prioritize agricultural and plantation residues as well as livestock manure as the backbone of energy supply, with organic waste and landfill methane serving as complementary sources. These findings agree with empirical assessments showing that biomethane utilization can enhance energy efficiency and reduce greenhouse gas emissions in practical applications (Kwon et al., 2026). The integration of multi-horizon transportation emission projections and local biogas potential estimates within a single analytical framework provides a scientific basis for formulating contextual, resource-based strategies for air pollution control and energy transition in the transportation sector (Ferrari et al., 2024). In this context, beyond resource availability, the practical utilization of biomethane for transportation is shaped by technological requirements and regulatory constraints associated with gas upgrading and system integration, as highlighted in international assessments (Štimac et al., 2025).

CONCLUSION

This study demonstrates that CO_2 emissions from the daily transportation sector in Jember Regency are projected to continue increasing through 2060, driven by the growth in motorized vehicles and the continued dominance of fossil fuel use. At the same time, Jember Regency possesses significant local biogas potential derived from agricultural and plantation residues, livestock manure, organic waste, and landfill methane, with an energy capacity relevant to supporting partial fossil fuel substitution. Although the estimated biogas potential is not sufficient to fully replace transportation energy demand, its utilization through a scenario-based approach targeting priority transportation segments has the potential to contribute meaningfully to air pollution control and emission mitigation. The integration of multi-horizon transportation emission projections and local renewable energy potential assessment in this study provides a scientific foundation for developing a contextual, phased, and resource-based energy transition strategy for the transportation sector.

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