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Dynamic Modeling of Tourism-Related Carbon Footprints for Low-Carbon Destination Management: A System Dynamics Monitoring, Reporting, and Verification Approach

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ABSTRACT

Tourism-related activities are increasingly recognized as major sources of greenhouse gas (GHG) emissions, particularly in ecologically sensitive protected areas with limited environmental resilience. Despite the rapid expansion of ecotourism in Indonesia, dynamic and integrated assessments of its carbon footprint remain limited. This study aims to quantify carbon emissions from ecotourism activities in the Sembalun area of Mount Rinjani National Park and to evaluate alternative mitigation strategies using a system dynamics–based Monitoring, Reporting, and Verification (MRV) framework. It is hypothesized that (i) transportation and waste sectors dominate tourism-related emissions, and (ii) integrated mitigation policies significantly reduce emissions over time. A system dynamics model was developed to integrate emissions from transportation, electricity consumption, and solid and liquid waste, following IPCC guidelines and expressed in CO_2 equivalents. Primary data were collected through tourist surveys, complemented by secondary institutional statistics. Simulation results for a defined scenario of 500 tourists staying two days indicate total emissions of 17.46 tCO_2e, with waste contributing 55%, transportation 40%, and electricity 5% within this specific system boundary and short-term assessment period. Although waste contributed the largest share in this snapshot, transportation emerged as the primary driver of emissions in the dynamic system under increasing tourist flows and longer simulation horizons. Under business-as-usual (BAU) conditions, emissions increase steadily, whereas moderate and ambitious mitigation scenarios reduce cumulative emissions over the 30-day simulation period by approximately 22–25% and up to 50%, respectively, relative to the BAU baseline. These findings highlight the effectiveness of integrated low-carbon strategies and provide a robust MRV-based decision-support framework for sustainable ecotourism management.

1. INTRODUCTION

Climate change has become a critical global challenge, impacting ecosystem stability and human well-being significantly. The tourism sector emerges as a notable contributor to greenhouse gas (GHG) emissions, accounting for approximately 11% of global carbon emissions. This figure is primarily driven by activities related to transportation, accommodation, and supporting services within the industry, with projections indicating a substantial increase in emissions stemming from tourism activities over the forthcoming decades [1-3]. While tourism generates considerable economic benefits, including job creation and enhanced local infrastructure, its environmental externalities, particularly carbon emissions, present serious challenges to achieving sustainability objectives [4, 5]. Consequently, there is an escalating interest from scholars and policymakers alike in developing analytical frameworks aimed at quantifying and managing the environmental impacts of tourism in alignment with climate mitigation targets [5-7]. Ecotourism is frequently advocated as an environmentally responsible alternative to mass tourism. However, empirical evidence has revealed that it is not inherently carbon-neutral. Factors such as tourist mobility, energy-intensive accommodation, and inadequate waste management practices contribute significantly to emissions, even in destinations that market themselves as "green" [8-11]. For instance, in studies conducted in Indonesia, key sources of emissions in tourism destinations were identified to include electricity consumption, fossil fuel-based transportation, and waste decomposition [12, 13]. These findings underline the necessity for integrated assessment approaches that can effectively capture the complex interactions among the number of tourists, infrastructure development, resource consumption, and environmental degradation, particularly in ecologically sensitive areas [14-16]. Moreover, the link between tourism practices and waste generation is critical. Understanding the dynamics of solid waste management within tourist regions has become increasingly important in addressing the environmental footprint of tourism. Research indicates that solid waste generation correlates directly with tourist numbers and local economic activity, suggesting the need for robust waste management systems to promote sustainability [11, 17]. For example, studies highlight that the volume of waste generated can escalate dramatically in popular tourist destinations if not managed effectively, leading to further environmental degradation and threatening the tourism sector's sustainability [2, 18].

The growth of ecotourism in Indonesia has gained significant attention in recent years; however, a comprehensive understanding of the carbon emissions generated by tourist activities, particularly within protected areas, remains inadequate. This research highlights the critical issue of limited awareness regarding the cumulative impact of various tourism-related sectors on carbon emissions and the evolution of these emissions over time. Given the complex interplay of multiple factors influencing carbon emissions in tourism, a system dynamics–based modeling approach emerges as a viable solution, enabling the integration of disparate emission sources and the simulation of mitigation policy scenarios within a coherent and predictive framework [19, 20]. A key concern is that current studies often neglect the multifaceted nature of tourism's carbon footprint, encompassing transportation, accommodation, and recreational activities, among other factors. Static assessments fail to capture the dynamic relationships between these sectors, which can significantly affect true emissions over time. Research has shown that different tourism segments generate varying levels of carbon emissions; for instance, transportation-related emissions are often substantial, particularly when considering air travel, while accommodation and on-site activities also contribute significantly to the overall carbon footprint [21, 22]. The call for a more integrated assessment approach becomes particularly pertinent in the context of protected areas, where ecological sensitivity heightens the need for accurate emission evaluations. The application of system dynamics can facilitate a holistic view, incorporating diverse data sources and allowing for simulations that forecast potential emissions under various scenarios [23, 24]. This modeling can enable stakeholders to make informed decisions regarding tourism development, balancing economic benefits against environmental impacts.

Using system dynamics to model tourism emissions provides a framework for assessing the effects of policies aimed at reducing carbon emissions. Such models can account for feedback loops and time delays inherent in tourism systems, allowing for the exploration of how changes in one sector (e.g., implementing stricter emissions regulations for transportation) could influence outcomes across interconnected sectors. The complexity of these interactions necessitates a robust analytical framework that can accommodate various emission sources, ultimately aiding in the identification of effective mitigation strategies. Integrating findings from diverse geographical contexts can enhance the understanding of tourism-related carbon emissions, providing benchmarks for best practices in emissions management [25, 26]. Previous studies have established that system dynamics serves as an effective methodological framework for analyzing intricate environmental systems characterized by feedback loops and non-linear relationships. In the realm of tourism, researchers have employed system dynamics models to explore the interrelationships among tourist flows, energy consumption, waste generation, and environmental quality. These models leverage tools such as Causal Loop Diagrams (CLDs) and Stock Flow Diagrams (SFD) to delineate reinforcing and balancing mechanisms that influence emission trajectories and assess the long-term efficacy of various management interventions. For instance, the work of Liu and Meng [27] presents a significant correlation between tourism development and carbon emissions, highlighting how various components of the tourism economy engage in dynamic interactions influencing overall emissions.

Furthermore, carbon footprint calculators based on internationally recognized emission factors, such as those provided by the Intergovernmental Panel on Climate Change (IPCC), have gained traction in quantifying emissions associated with tourism activities. When these calculators are integrated within system dynamics frameworks, they enable the conduct of scenario-based simulations that critically assess the effectiveness of mitigation strategies. These strategies include enhancements in energy efficiency, adoption of low-carbon transportation methods, and promotion of waste reduction through principles of Reduce, Reuse, and Recycle (3R) [28]. Such integrated approaches afford decision-makers quantitative evidence that is crucial for fostering sustainable tourism planning and climate-resilient destination management.

Despite the advancements in understanding tourism-related carbon emissions, existing literature tends to focus narrowly on sector-specific analyses, often examining transportation, accommodation energy consumption, or waste management in isolation. Notably, integrative studies that encompass ecological carrying capacity, waste-generated methane and nitrous oxide emissions, and the economic valuation of carbon offsets within a consolidated modeling framework remain scarce. More importantly, several critical gaps persist. First, most existing studies adopt static or fragmented approaches, lacking a dynamic and integrated assessment that simultaneously captures emissions from transportation, electricity consumption, and solid and liquid waste at the destination level. This limitation restricts the ability to understand the complex interactions and feedback mechanisms among key emission sources in tourism systems. Second, there is a lack of auditable and standardized emission indicators that can be directly aligned with Monitoring, Reporting, and Verification (MRV) frameworks, which are essential for transparent and policy-relevant carbon accounting. Third, the application of scenario-based policy analysis within protected-area ecotourism contexts remains limited, particularly in evaluating the long-term effectiveness of mitigation strategies under different intervention levels. These deficiencies underscore a pronounced research gap in formulating holistic, dynamic, and policy-oriented carbon footprint models tailored to conservation-based tourism systems.

The objective of this study is to analyze the main sources of carbon emissions in the Sembalun ecotourism area of Mount Rinjani National Park, quantify the contribution of tourist activities to the overall carbon footprint, and simulate alternative mitigation policy scenarios using a system dynamics approach. The novelty of this research lies in the integration of transportation, energy consumption, and waste management emissions into a unified system dynamics–based carbon footprint model, complemented by an MRV-oriented calculator that links environmental impacts with ecological and economic indicators. The scope of the study is limited to the Sembalun ecotourism destination within TNGR, focusing on short-term tourist visits and policy-relevant mitigation strategies applicable to similar conservation-based ecotourism areas in Indonesia.

2. MATERIALS METHOD

2.1 Study area

This study was conducted in the Sembalun ecotourism area of Mount Rinjani National Park (MRNP), East Lombok Regency, West Nusa Tenggara Province, Indonesia. MRNP is one of Indonesia's most prominent protected areas, covering approximately 41,330 hectares and serving as a major destination for nature-based tourism, particularly trekking and mountain climbing activities. In 2024, the park recorded approximately 80,216 visitors, reflecting its significance as a high-intensity ecotourism destination. Located on the eastern flank of Mount Rinjani, Sembalun serves as a main gateway for trekking and nature-based tourism. The study area lies approximately at 8°21′–8°24′ S and 116°31′–116°34′ E, with elevations ranging from 1,100 to 1,300 m above sea level, and is characterized by mountainous terrain, agricultural land, settlements, and tourism-supporting infrastructure within the park's buffer and utilization zones. The Sembalun area functions as a primary access point for tourists, supported by tourism-related facilities such as trekking routes, accommodation services (e.g., homestays and lodges), transportation services, and basic infrastructure, including electricity supply and waste management systems. Despite its ecological importance, the increasing number of visitors has led to growing environmental pressures, particularly in terms of waste generation, energy consumption, and transportation-related emissions. From a management perspective, MRNP is administered under Indonesia's national park system, which integrates conservation objectives with controlled tourism utilization. This dual role makes it a representative case for analyzing the environmental impacts of ecotourism in protected areas, particularly in developing countries where tourism growth and conservation goals must be carefully balanced.

2.2 Data sources and collection techniques

The study employed both primary and secondary data. Primary data were collected through field surveys and structured interviews using questionnaires administered to tourists. The survey captured information on transportation modes, length of stay, energy consumption behavior, and waste management practices during tourist activities. Secondary data were obtained from relevant institutions, including the Central Bureau of Statistics (BPS) and the Mount Rinjani National Park Authority, as well as from official reports and peer-reviewed scientific literature related to tourist arrivals, energy consumption, and waste generation. The study population comprised all tourists visiting MRNP in 2024, totaling 80,216 visitors. The minimum sample size was determined using the Slovin formula with a margin of error of 10% ($\alpha = 0.10$), resulting in at least 100 respondents. Respondents were selected using accidental sampling, whereby tourists encountered at the study site during the survey period were invited to participate.

2.3 Data analysis

This study applies a system dynamics–based MRV framework to quantify the carbon footprint of ecotourism activities. GHG emissions are estimated in accordance with the IPCC inventory principles, whereby emissions are calculated as the product of activity data and corresponding emission factors, and subsequently converted into carbon dioxide equivalents (CO_2e) using 100-year Global Warming Potential (GWP) values. The overall research workflow is presented in Figure 1.

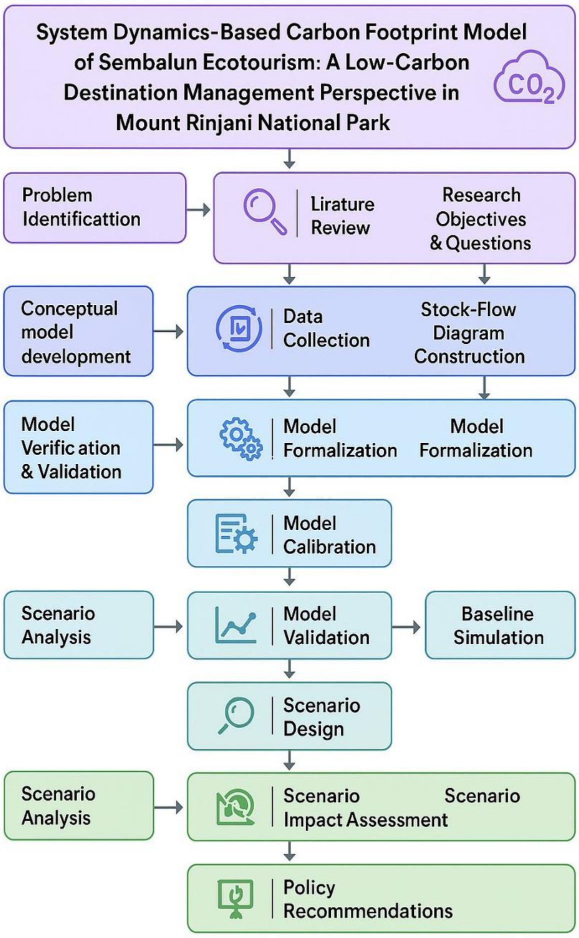


Figure 1. Research workflow

2.4 General emission accounting framework

Questionnaire data collected from tourists were systematically converted into quantitative model variables to support the system dynamics simulation (Table 1). For the transportation sector, daily travel distance per tourist was estimated based on reported travel routes and transportation modes, and subsequently converted into fuel consumption using average vehicle fuel economy values. Emissions were then calculated using standard emission factors per unit of fuel consumption. Electricity consumption was expressed as energy use per tourist per day (kWh/tourist/day), derived from accommodation-based electricity usage (e.g., kWh/tourist/day) and adjusted based on average room occupancy rates. Solid waste and wastewater generation were quantified on a per tourist per day basis (kg/tourist/day), estimated from survey responses related to consumption patterns and waste disposal behavior, and supplemented with literature-based coefficients where necessary. These standardized units enable consistent integration across sectors within the system dynamics framework and allow aggregation over time based on tourist flow.

The parameter values were derived from survey responses (n = 100) and supplemented with literature and IPCC default values where direct measurements were not available. Mean values represent average tourist behavior, while standard deviations capture variability across respondents.

Table 1. Core model parameters

Parameter	Unit	Mean	Std. Dev.	Sample Size (n)	Source
Daily travel distance per tourist	km/tourist/day	18.5	6.2	100	Survey
Fuel consumption rate	L/km	0.08	–	Literature	
Emission factor (fuel)	kgCO₂e/L	2.31	–	IPCC	
Electricity consumption	kWh/tourist/day	3.6	1.1	100	Survey + conversion
Room occupancy rate	person/room	2.3	0.7	100	Survey
Solid waste generation	kg/tourist/day	0.72	0.2	100	Survey
Wastewater generation	kg/tourist/day	95	25	100	Survey + literature
Methane emission factor (waste)	kgCH₄/kg waste	0.06	–	IPCC	
Nitrous oxide emission factor	kgN₂O/kg waste	0.004	–	IPCC	

2.5 General emission accounting framework

For each emission source, GHG emissions are calculated as:

$$E_g = AD \times EF_f \quad (1)$$

where E_g represents emissions of gas g, AD is the activity data, and EF_f is the emission factor for the respective gas. Total emissions expressed as CO_2 equivalents are calculated as:

$$CO_{2e} = \sum_g \left(E_g \times GWP_g \right) \quad (2)$$

where GWP_g denotes the global warming potential of gas g.

2.6 Solid waste emissions

Methane emissions from solid waste are modeled following the IPCC conceptual approach, accounting for methane recovery and oxidation:

$$CH_{4,emitted} = CH_{4,\, generated} \times \left(1-R\right) \times \left(1-OX\right) \quad (3)$$

where R is the methane recovery rate, and OX is the oxidation factor. The methane emissions are converted to CO_2 equivalents as:

$$CO_{2,esw} = CH_{4,emitted} \times GWP_{CH4} \quad (4)$$

2.7 Wastewater and leachate emissions

Methane emissions from wastewater and leachate are estimated based on total organic load:

$$CH_4 = TOW \times EF \times (1-R) \times (1-OX) \quad (5)$$

where TOW is total organic load, EF: emission factor, R: methane recovery rate, and OX: oxidation factor.

Nitrous oxide emissions from wastewater are calculated as:

$$N_2O_{ww} = N_{effluent} \times EF_{N2O} \quad (6)$$

The total CO_2 equivalent emissions from wastewater are then given by:

$$CO_{2e\, ww,\, total} = CH_4 \times GWP_{CH4} + N_2O \times GWP_{N_2O}) \quad (7)$$

2.8 System boundary definition

The system boundary of this study is defined at the destination level, focusing on tourism-related activities occurring within the Sembalun ecotourism area of Mount Rinjani National Park. The analysis includes three main emission sectors: transportation, electricity consumption, and waste management. Transportation emissions are limited to local mobility within and around the destination, such as travel from entry points to accommodation and tourism activity sites, while long-distance transportation to reach Lombok (e.g., air travel, inter-island ferry, or long-distance bus) is excluded. Electricity consumption is primarily treated as indirect (Scope 2) emissions associated with grid-based electricity use in tourism facilities. Where applicable, additional on-site energy use, such as diesel generators or liquefied petroleum gas (LPG), is included as part of operational energy consumption. Waste management emissions encompass both solid and liquid waste generated within the destination, including methane and nitrous oxide emissions from decomposition processes. However, downstream processes beyond the destination boundary, such as external waste transportation and final disposal outside the study area, are not explicitly considered. This boundary definition ensures a consistent and policy-relevant assessment of tourism-related emissions at the destination scale while maintaining compatibility with the system dynamics modeling framework.

3. RESULTS AND DISCUSSION

3.1 System dynamics structure of tourism carbon emissions

The system dynamics framework is a powerful tool for modeling complex interactions within systems involving multiple interlinked subsystems, such as those found in tourism. Specifically, the case of tourism activities along the Sembalun route is indicative of how carbon emissions are influenced by key subsystems: transportation, electricity use, and waste generation. This framework highlights the significance of CLDs in understanding these dynamics, positioning total tourism-related CO_2e emissions as a critical outcome affected by various reinforcing and balancing feedback mechanisms (Figure 2).

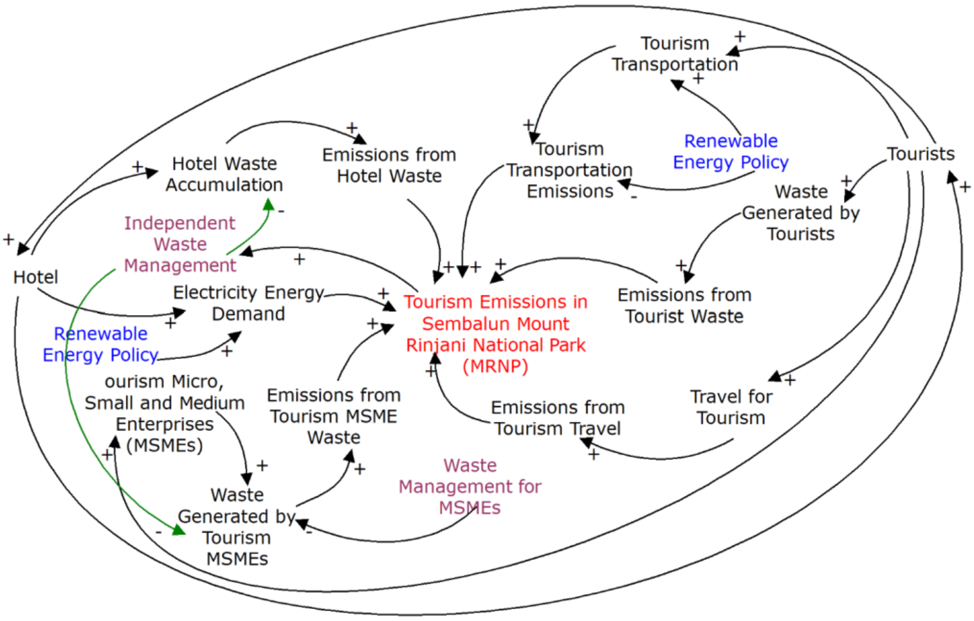


Figure 2. Causal Loop Diagram (CLD) of the tourism carbon footprint system in the Sembalun route, Mount Rinjani National Park

Tourist arrivals, service demand, and corresponding resource consumption exhibit interlinked subsystems that intensify emissions under typical business-as-usual (BAU) conditions. As the influx of tourists increases, there is a proportional rise in transportation demands and increased electricity consumption for hospitality services. For instance, Liu and Meng [27] demonstrated the economic benefits of tourism alongside CO_2 emissions, indicating that greater tourism intensity correlates with heightened environmental impact. Additionally, Khan et al. [29] emphasized the role of transportation services in driving emissions, spotlighting the need for sustainable practices in tourism development. Furthermore, Pan et al. [19] strengthened this perspective by arguing that the coordination between tourism carbon emissions and economic development is crucial for low-carbon pathways, which aligns with the potential outcomes depicted in the CLD. Central to this discussion is the reinforcing feedback loop where increased tourist numbers amplify service demands that subsequently surge emissions, showcasing the delicate balance between economic growth and environmental sustainability.

In opposition to the amplifying effects of tourism development, balancing loops can be introduced through policy interventions aimed at renewable energy adoption and effective waste management practices. Zheng et al. [30] outlined how subsidy policies in tourism can foster economic growth while mitigating environmental impacts, thereby providing insights into policy frameworks that can counteract excessive emissions. This suggests that strategic investments in renewable energy sources can significantly dampen the growth of emissions over time. Moreover, the work by Zha et al. [31] supported this notion by investigating decomposition analysis to understand the drivers of tourism CO_2 emissions. They highlight that while tourism contributes to rising emissions, focused efforts on adopting renewable energy can lead to substantial reductions in carbon output. This interplay of factors points to the importance of integrating sustainability into tourism planning, reinforcing the relevance of these balancing loops in managing future growth sustainably. The findings presented by Djalilov et al. [32] corroborate this idea by revealing that as renewable energy consumption increases, there is a notable decline in CO_2 emissions across nations with high tourism intensity. This evidence aligns with the assertion that proactive frameworks focusing on renewable sources and improved waste management are effective strategies for mitigating emissions related to tourism.

3.2 Transportation sector emissions and scenario analysis

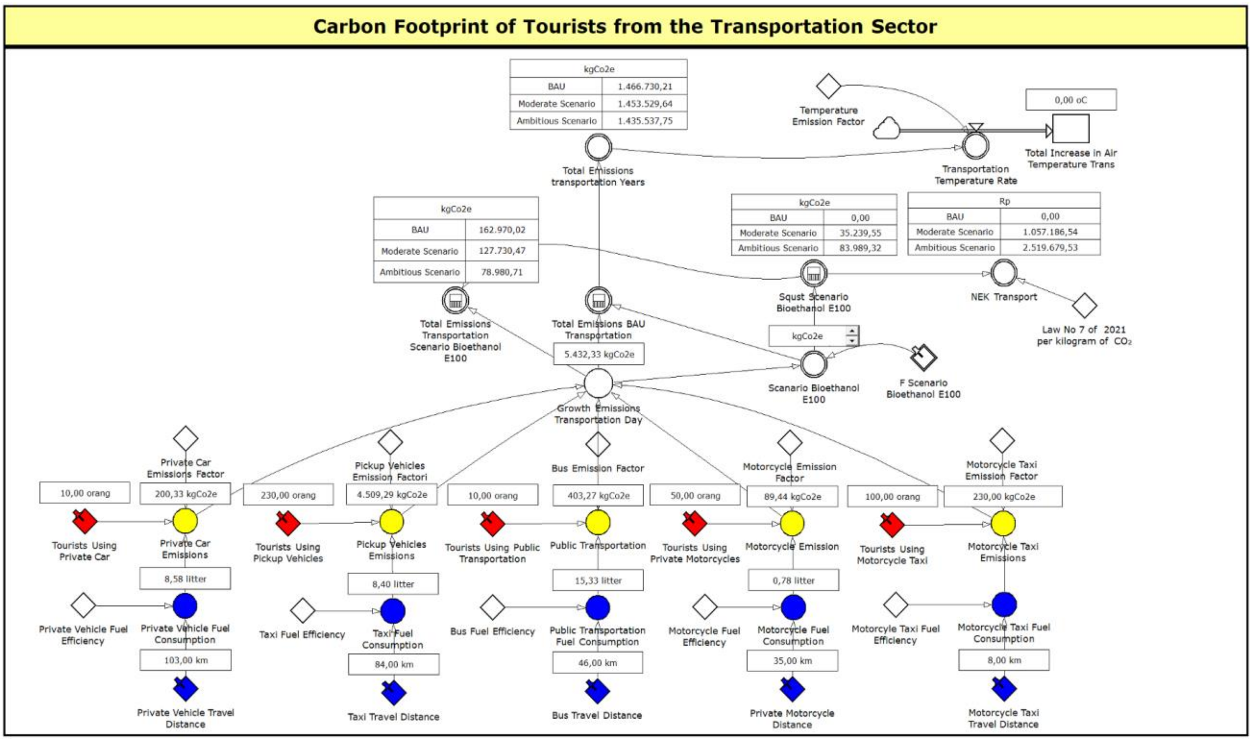
The transportation sector is a significant contributor to GHG emissions, particularly carbon dioxide (CO_2). Within this sector, several dynamics influence emissions, such as modal choice, fuel consumption, and the resulting accumulation of emissions over time. The stock-flow model for the transportation sector captures these complexities, illustrating tourist flows, fuel use, and subsequent emissions [33]. Under BAU conditions, cumulative transportation emissions are projected to reach approximately 162,970.02 kgCO_2e over a 30-day simulation period, reflecting the ongoing reliance on traditional fossil fuel sources.

Figure 3 shows the stock–flow structure for the transportation sector.

The emission reduction results under moderate and ambitious scenarios are derived based on specific intervention parameters applied within the transportation sector. In this study, mitigation is represented by the substitution of conventional fossil fuel with E100 bioethanol at defined replacement rates, while vehicle fuel economy is assumed to remain constant across all scenarios. These parameter settings ensure that the observed emission reductions are attributable solely to fuel substitution effects, thereby enabling transparent and auditable scenario analysis within the system dynamics framework.

The introduction of alternative fuels, such as E100 bioethanol, shows promise in altering the emissions trajectory of the transportation sector. For instance, implementing a moderate intervention—corresponding to partial fuel substitution—reduces cumulative emissions to approximately

127,730.47 kgCO₂e, representing a 21.62% reduction relative to the BAU scenario over the 30-day simulation period. More ambitious scenarios, characterized by higher levels of E100 penetration, further reduce emissions to 78,980.71 kgCO₂e (−51.54%) [34]. The efficacy of biofuels such as E100 is supported by their ability to displace fossil fuels in vehicle fleets, as demonstrated in previous studies focusing on lifecycle emissions and CO_2 reduction potential [35, 36]. In evaluating mitigation strategies, it is crucial to consider the dominance of specific vehicle types, such as pickup-based taxis, which are responsible for a significant share of daily emissions. Their high usage rates and fuel intensity make them key leverage points for decarbonization initiatives within the transport sector [30]. Transitioning from conventional fossil fuel vehicles toward cleaner alternatives, including biofuel-based and electrified systems, has the potential to substantially reshape emission patterns.



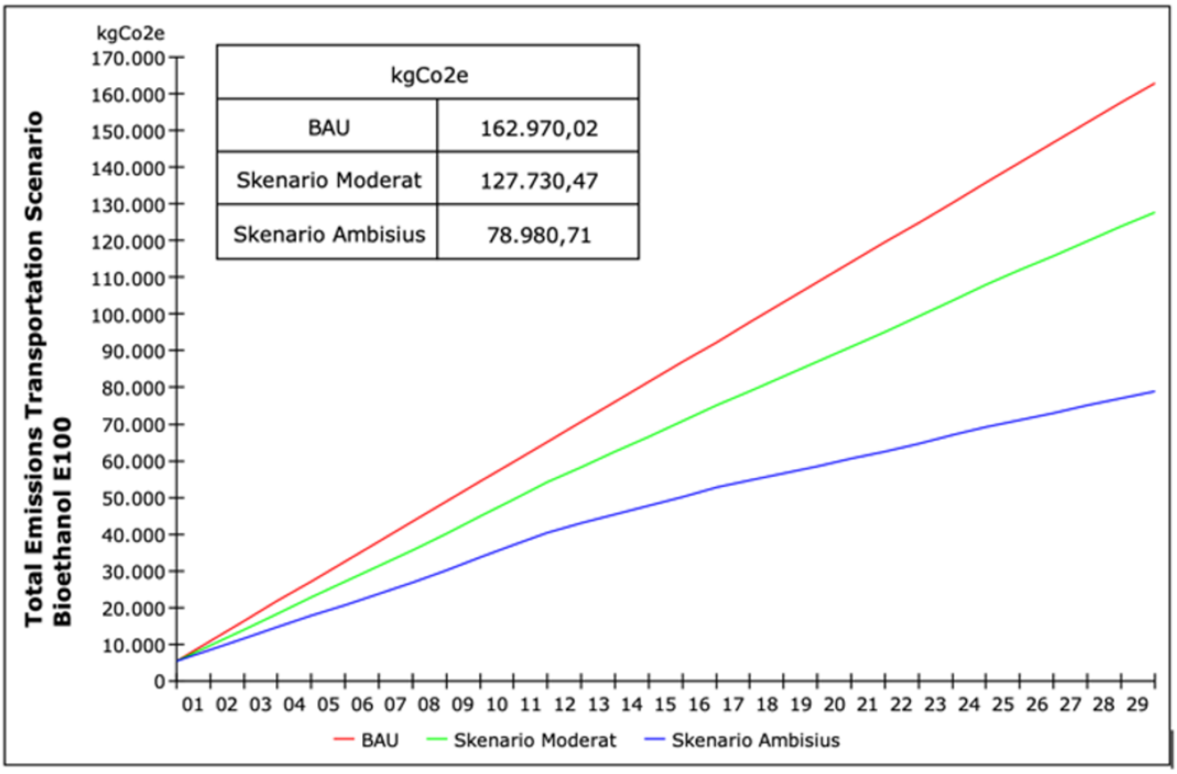
kgCo2e	
BAU	1.466.730,21
Moderate Scenario	1.453.529,64
Ambitious Scenario	1.435.537,75

kgCo2e	
BAU	162.970,02
Moderate Scenario	127.730,47
Ambitious Scenario	78.980,71

kgCo2e	
BAU	0,00
Moderate Scenario	35.239,55
Ambitious Scenario	83.989,32

Rp	
BAU	0,00
Moderate Scenario	1.057.186,54
Ambitious Scenario	2.519.679,53

Figure 3. Stock–flow diagram of the transportation sector



kgCo2e	
BAU	162.970,02
Skenario Moderat	127.730,47
Skenario Ambisius	78.980,71

Figure 4. Cumulative transportation-sector emissions under business-as-usual (BAU), moderate, and ambitious scenarios

Scenario results (Figure 4) clearly indicate that the introduction of E100 bioethanol significantly alters the emissions trajectory. The moderate intervention reduces cumulative emissions to 127,730.47 $kgCO_2e$ (−21.62%), while the ambitious scenario further lowers emissions to 78,980.71 $kgCO_2e$ (−51.54%), both relative to the BAU baseline over the defined simulation period. Pickup-based taxis dominate daily emissions due to their high usage rate and fuel intensity, reinforcing their role as the primary leverage point for transport-sector decarbonization.

The difference in emission reduction between the moderate (22–25%) and ambitious (up to 50%) scenarios is primarily driven by the level of intervention coverage and its nonlinear impact on system behavior. In the moderate scenario, partial implementation of mitigation measures—such as limited adoption of E100 bioethanol, moderate penetration of photovoltaic (PV) systems, and partial coverage of self-managed waste treatment—results in incremental emission reductions. In contrast, the ambitious scenario applies substantially higher intervention levels across all sectors, leading to compounded effects and greater disruption of emission-generating processes. This is particularly evident in the transportation sector, where higher biofuel substitution rates significantly reduce fossil fuel use, and in the waste sector, where broader coverage of treatment reduces methane emissions more effectively.

However, achieving the ambitious scenario presents notable technical and economic challenges. High levels of biofuel substitution require sufficient supply chains, vehicle compatibility, and supporting infrastructure. Similarly, expanding PV penetration depends on initial capital investment, land availability, and grid integration capacity. Waste management improvements require institutional coordination, community participation, and operational capacity. These factors imply that while the ambitious scenario demonstrates substantial emission reduction potential, its implementation may involve higher upfront costs and logistical complexity compared to moderate interventions.

Therefore, moderate scenarios may represent more immediately feasible policy options, while ambitious scenarios provide a long-term target for progressive transition toward low-carbon tourism systems. This highlights the importance of phased implementation strategies that balance emission reduction potential with technical feasibility and economic considerations. The key parameter settings used to define each mitigation scenario are summarized in Table 2.

Table 2. Key parameters for mitigation scenarios

Sector	Parameter	Business-as-Usual (BAU)	Moderate Scenario	Ambitious Scenario	Unit
Transportation	E100 replacement rate	0%	30%	70%	% fuel substitution
Transportation	Vehicle fuel economy	Constant	Constant	Constant	L/km
Electricity	PV penetration rate	0%	25%	50%	% electricity replaced
Electricity	Total electricity demand	Baseline	Same as BAU	Same as BAU	kWh
Waste	Self-managed waste treatment coverage	0%	40%	70%	% of total waste
Waste	Methane reduction efficiency	0%	30%	60%	% reduction

3.3 Electricity use and renewable energy integration

The modeling of electricity-related emissions presents a crucial understanding of how grid electricity consumption and renewable energy sources can be incorporated effectively within energy systems. This is particularly significant in the context of tourism facilities, which often experience stable daily electricity demand that can lead to steady cumulative emissions. A stock–flow diagram provides a systematic representation of how emissions evolve under different scenarios, such as Business as Usual (BAU) and varying levels of renewable energy integration (Figure 5).

The BAU trajectory forecasts a cumulative emission of 8,292 $kgCO_2e$ over 30 days. This trend reflects a sustained demand for electricity in tourism sectors, highlighting the environmental impacts of consistent energy consumption. However, integrating renewable energy sources shows a substantial potential for emission reduction. For instance, partial solar photovoltaic (PV) integration could lower cumulative emissions to 6,826.53 $kgCO_2e$, representing a reduction of 17.67% compared to the BAU scenario. More ambitious implementations of solar PV systems can further reduce emissions to 5,034.63 $kgCO_2e$, achieving a remarkable 39.28% decrease (Figure 6). These findings align with the research conducted by Hossain et al., who noted the simultaneous benefits of renewable energy for reducing emissions while meeting electricity demands in various sectors, including tourism [37].

A critical component of energy consumption in these scenarios is the continuous operation of refrigerators, which constitutes a significant portion of the base load. The predominance of this appliance explains the near-linear emissions growth pattern observed within the considered time frame. Research by Shahabi et al. emphasizes the importance of integrating efficient demand-side measures alongside renewable energy supplies to mitigate emissions effectively. Raugei et al. [38] further argued that optimizing the deployment of appliance load profiles can lead to a more efficient energy system that supports lower emissions. Studies suggest that integrating renewable energy sources with demand-side efficiency measures can create a synergistic effect, leading to more substantial reductions in emissions. For example, measurement and modeling approaches highlight that augmented solar power generation can supply energy precisely when demand peaks, particularly in scenarios where electric vehicles and appliances converge in usage [38]. This synergy is critical, especially in sectors like tourism, where energy demand can be unpredictable and fluctuating.

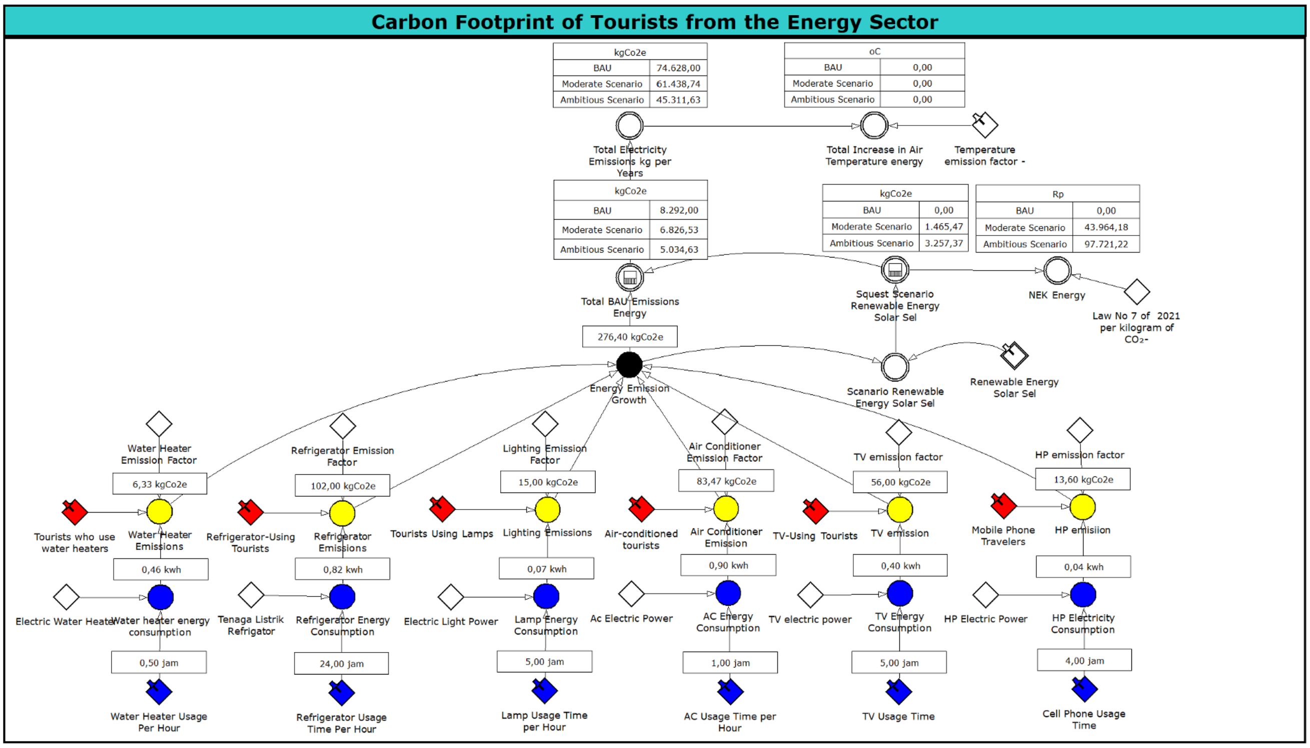


Figure 5. Stock–flow diagram of the energy (electricity) sector

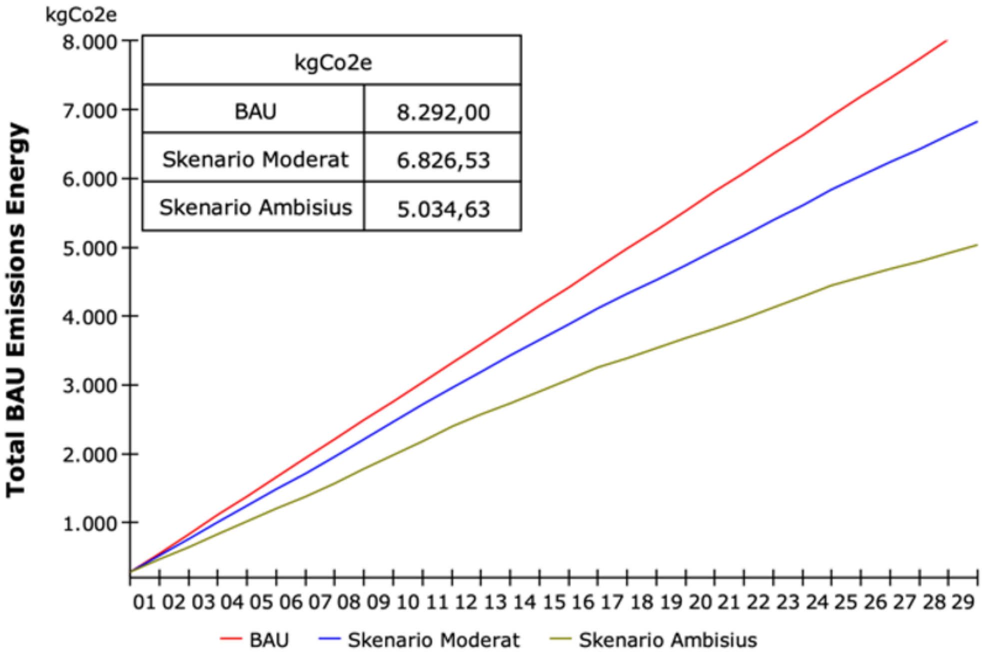


Figure 6. Cumulative electricity-sector emissions under Business-as-Usual (BAU), moderate, and ambitious scenarios

Moreover, the assessments conducted by Lima et al. [39] reaffirm that the strategic integration of renewable energy systems, like solar power, is essential for any long-term emissions reduction strategy, particularly in regions with constant energy demands. They conclude that targeted policies focusing on renewable energy integration can support a more sustainable energy future.

3.4 Waste sector dynamics and emission dominance

The dynamics of the waste sector significantly influence GHG emissions globally, especially in the context of tourism. This analysis explores the contributions of solid waste and wastewater to total emissions and discusses various mitigation scenarios aimed at decreasing these emissions. Figure 7 illustrates the waste-sector stock–flow diagram.

Figure 8 shows the cumulative waste-sector emissions under BAU, moderate, and ambitious scenarios. The waste-sector stock–flow diagram illustrates the pathways of solid waste and wastewater generation, various treatment processes, and the resulting methane emissions.

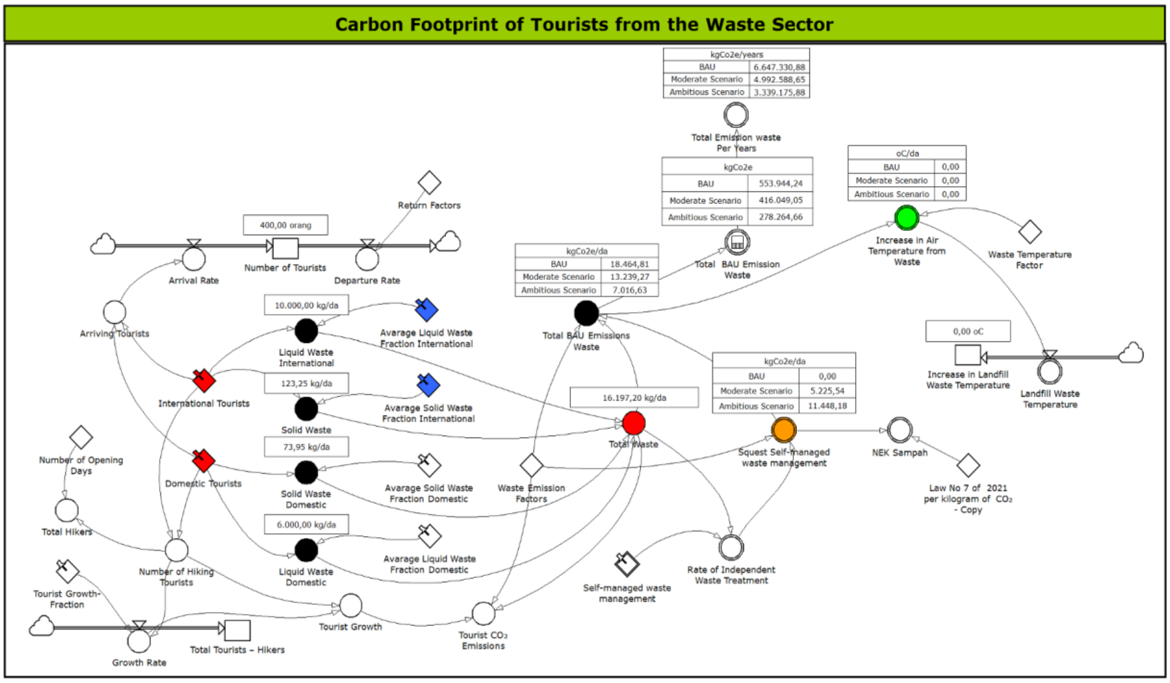


Figure 7. Stock–flow diagram of the waste sector

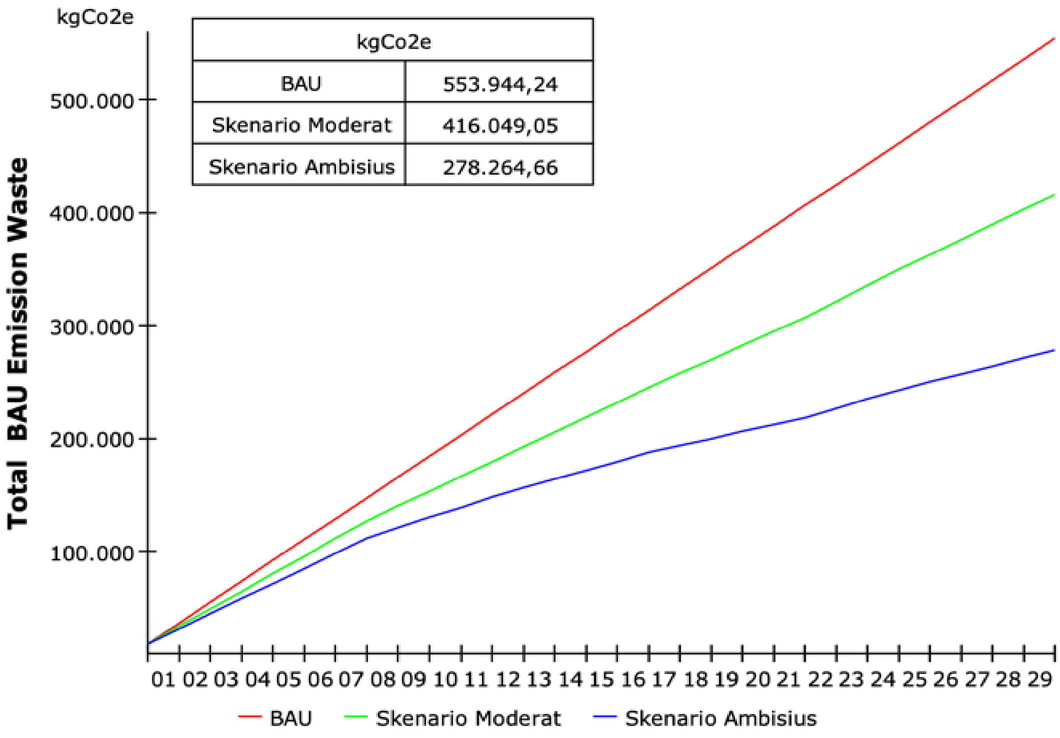


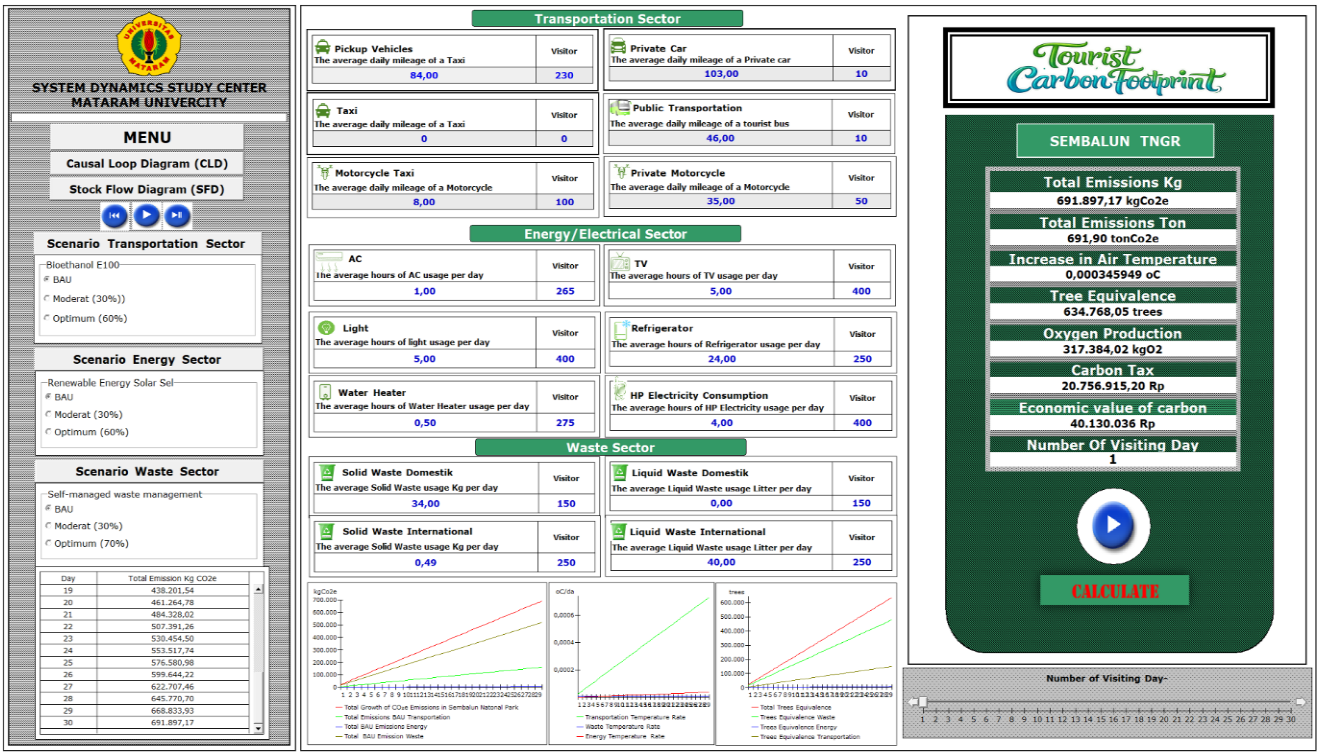
Figure 8. Cumulative waste-sector emissions under Business-as-Usual (BAU), moderate, and ambitious scenarios

Under BAU conditions, cumulative emissions from the waste sector are projected at 553,944.24 kgCO₂e over 30 days, highlighting the waste sector as a leading contributor to total tourism emissions [23]. Scenario analyses indicate that self-managed waste interventions can significantly cut emissions. In a moderate intervention scenario, emissions are reduced to 416,049.05 kgCO₂e, which represents a reduction of 24.89%, while more ambitious management strategies can lead to reductions of 278,264.66 kgCO₂e (−49.77%). Research demonstrates that liquid waste, particularly from international tourists, is a major driver of emissions in the tourism sector. Strategies focused on wastewater management are essential for promoting low-carbon tourism destination management [40]. The dominant role of methane in the waste sector cannot be understated. Research indicates that landfills are a significant source of methane emissions, which is particularly concerning as these emissions can contribute substantially to global warming. The evolution of sewage treatment plants (STPs) into systems capable of energy recovery and emissions reduction highlights their importance in tackling GHG emissions. Furthermore, investigations show that combined approaches involving anaerobic digestion and resource recovery not only reduce emissions but also convert waste into energy, enhancing sustainability. It is important to note that the cumulative emissions presented in Figures 4, 6, and 8 represent time-dependent outputs from the system dynamics model, where emissions are continuously accumulated over the 30-day simulation period. These results incorporate dynamic interactions such as tourist inflow, service demand, and feedback mechanisms across sectors. Therefore, the reported values (e.g., 162,970 kgCO₂e for transportation, 8,292 kgCO₂e for electricity, and 553,944 kgCO₂e for waste) reflect total system-level emissions over time, rather than emissions from a fixed number of tourists.

When aggregated, the cumulative emissions from the transportation, electricity, and waste sectors reach approximately 725.3 tCO₂e over the 30-day simulation period. However, this value should not be directly compared with the MRV-based emission estimate, as the system dynamics model assumes continuous tourist arrivals and cumulative emission growth, rather than a fixed population. The model captures temporal accumulation and feedback effects, resulting in higher total emissions compared to static calculations.

3.5 Integrated tourism carbon footprint and measurement, reporting, and verification implications

The development of a system dynamics-based measurement, reporting, and verification (MRV) carbon footprint calculator for the Sembalun ecotourism area of Mount Rinjani National Park presents essential insights into the carbon emissions associated with tourism. The dashboard constructed for this purpose integrates critical input variables, dynamic simulations, and output indicators that together quantify GHG emissions generated by tourism activities. Specifically, it assesses the carbon footprint for a defined scenario involving 500 tourists with an average length of stay of two days, yielding total emissions estimates of 17.46 tCO₂e. This value represents a static, scenario-based estimate within a fixed system boundary, where the number of tourists and duration are predefined, and no temporal accumulation is considered. Figure 9 highlights a significant carbon footprint attributable to even short-duration tourism activities, underscoring the need to address sustainability in emerging tourism destinations such as Sembalun.



Scenario Transportation Sector

Bioethanol E100
● BAU
○ Moderat (30%))
○ Optimum (60%)

Scenario Energy Sector

Renewable Energy Solar Sel
● BAU
○ Moderat (30%)
○ Optimum (60%)

Scenario Waste Sector

Self-managed waste management
● BAU
○ Moderat (30%)
○ Optimum (70%)

Day	Total Emission Kg CO2e
19	438.201,54
20	461.264,78
21	484.328,02
22	507.391,26
23	530.454,50
24	553.517,74
25	576.580,98
26	599.644,22
27	622.707,46
28	645.770,70
29	668.833,93
30	691.897,17

Transportation Sector

		Visitor
Pickup Vehicles	The average daily mileage of a Taxi	
	84,00	230
Private Car	The average daily mileage of a Private car	
	103,00	10
Taxi	The average daily mileage of a Taxi	
	0	0
Public Transportation	The average daily mileage of a tourist bus	
	46,00	10
Motorcycle Taxi	The average daily mileage of a Motorcycle	
	8,00	100
Private Motorcycle	The average daily mileage of a Motorcycle	
	35,00	50

Energy/Electrical Sector

		Visitor
AC	The average hours of AC usage per day	
	1,00	265
TV	The average hours of TV usage per day	
	5,00	400
Light	The average hours of light usage per day	
	5,00	400
Refrigerator	The average hours of Refrigerator usage per day	
	24,00	250
Water Heater	The average hours of Water Heater usage per day	
	0,50	275
HP Electricity Consumption	The average hours of HP Electricity usage per day	
	4,00	400

Waste Sector

		Visitor
Solid Waste Domestik	The average Solid Waste usage Kg per day	
	34,00	150
Liquid Waste Domestik	The average Liquid Waste usage Litter per day	
	0,00	150
Solid Waste International	The average Solid Waste usage Kg per day	
	0,49	250
Liquid Waste International	The average Liquid Waste usage Litter per day	
	40,00	250

Total Emissions Kg: 691.897,17 kgCo2e
Total Emissions Ton: 691,90 tonCo2e
Increase in Air Temperature: 0,000345949 oC
Tree Equivalence: 634.768,05 trees
Oxygen Production: 317.384,02 kgO2
Carbon Tax: 20.756.915,20 Rp
Economic value of carbon: 40.130.036 Rp
Number Of Visiting Day: 1

Figure 9. Monitoring, Reporting, and Verification (MRV) dashboard for monitoring the tourism carbon footprint in the Sembalun route

The dashboard reveals that emissions are generated across three primary sectors: transportation, energy consumption, and waste management. Importantly, transportation-related activities are identified as the major contributor to carbon emissions within the dynamic system behavior. This aligns with findings from prior studies, which indicate that tourist mobility, both to and within destinations, significantly escalates fuel consumption and GHG emissions [41]. The simulation results confirm this trend by showing a strong relationship between increasing tourist numbers and transportation-related emissions. Following transportation, energy consumption emerges as the second-largest contributor, primarily driven by electricity usage in accommodations and tourism-related facilities, including cooling, lighting, and appliance operation. This observation is consistent with broader tourism studies highlighting the energy-intensive nature of tourism infrastructure. Meanwhile, waste management, although representing a smaller proportion in the dynamic contribution, captures important emissions from the decomposition of solid and liquid waste, reflecting the environmental consequences of tourism activities.

The dashboard further translates carbon emissions into ecological and economic equivalency indicators, providing a meaningful interpretation of the environmental burden imposed by tourism activities in Sembalun. For instance, the estimated emissions are equivalent to the carbon absorption capacity of approximately 212,891 trees, representing a substantial ecological service provided by local forest ecosystems. The equivalent number of trees required to offset the estimated carbon emissions was calculated using a standard carbon sequestration factor. An average absorption rate of approximately 82 $kgCO_2$ per tree per year was adopted based on commonly reported values for tropical tree species in the literature. The number of trees was estimated by dividing the total emissions (expressed in $kgCO_2e$) by the annual carbon absorption capacity per tree. In this formulation, the total emissions represent the carbon footprint generated by tourism activities, while the absorption factor reflects the average sequestration capacity of an individual tree. This approach provides an approximate ecological interpretation of the carbon footprint and is intended for illustrative and comparative purposes rather than precise carbon offset accounting [36].

Additionally, the economic compensation value associated with these emissions, quantified at IDR 523,712.33, highlights the financial implications of tourism-related carbon footprints. This value was calculated by converting the estimated carbon emissions into a monetary equivalent using an assumed carbon price. Specifically, the compensation value was obtained by multiplying the total emissions (17.46 tCO_2e) by an assumed carbon price of approximately IDR 30,000 per tCO_2e. This estimation provides an indicative economic interpretation of the tourism-related carbon footprint and is intended for comparative and policy-oriented purposes rather than as an exact market-based offset cost. These indicators not only illustrate the magnitude of environmental impact but also emphasize the importance of sustainable forest management as a carbon offset strategy [42]. Moreover, although the temperature change indicator appears relatively small, it reflects the cumulative climatic impact of repeated tourism activities over time, consistent with studies emphasizing the long-term climate implications of sustained tourist inflows [43, 44].

It is essential to highlight that the MRV-based estimate (17.46 tCO_2e) represents a static snapshot of emissions corresponding to a predefined tourist scenario, whereas the system dynamics simulation outputs (Figures 4, 6, and 8) capture cumulative emissions that evolve over time under continuous tourist inflow and feedback-driven system interactions. As such, these two results are inherently not directly comparable, since they reflect fundamentally different analytical approaches—namely, a static scenario-based estimation versus a dynamic system-level accumulation. Recognizing this distinction is crucial for accurately interpreting both the magnitude and the functional role of emissions within the tourism system. Within this framework, it is important to clarify that the reported sectoral contribution shares—waste (55%), transportation (40%), and electricity (5%)—originate from the MRV-based static scenario, which is defined by a system boundary consisting of 500 tourists over a two-day period. These values, therefore, represent proportional contributions under fixed conditions without incorporating temporal accumulation effects. In contrast, the system dynamics simulation results discussed in the manuscript represent time-dependent emission accumulation, influenced by continuous tourist arrivals and internal feedback mechanisms. Under these dynamic conditions, transportation becomes the dominant driver of long-term emission growth, while the waste sector remains a substantial contributor, particularly in short-term conditions and high-density tourism scenarios.

Accordingly, the observed difference in sectoral dominance between the MRV results and the system dynamics outputs should be understood as reflecting two complementary analytical perspectives: a static distribution of emissions under controlled conditions (MRV) and a dynamic representation of emission behavior over time (system dynamics simulation).

Furthermore, the model outcomes are strongly influenced by several key parameters, particularly tourist volume, emission factors, and waste generation rates. Among these, tourist volume emerges as the most sensitive variable, as total emissions scale proportionally with the number of visitors and amplify system-wide impacts through increased transportation demand, energy use, and waste production. Emission factors, especially those related to fuel combustion and waste decomposition, also significantly influence the calculated emission magnitude, although their effects are generally linear and less dynamic compared to fluctuations in visitor numbers.

Waste generation rates play a critical role in shaping sectoral emission contributions, especially in scenario-based analyses where waste-related emissions dominate under short-term conditions. Variations in waste generation coefficients can substantially alter the relative importance of the waste sector, particularly under conditions of high tourist density. Similarly, electricity consumption parameters contribute to total emissions; however, their overall influence remains secondary compared to transportation and waste dynamics in the present study.

Overall, the findings indicate that emission outcomes are most responsive to changes in tourist volume and transportation-related parameters, while waste-related variables primarily affect the distribution of emissions across sectors. This suggests that policy interventions focusing on visitor management and transport decarbonization are likely to produce the most substantial emission reductions. The integration of these parameters within the system dynamics framework enables flexible scenario analysis and supports more robust and informed decision-making for sustainable tourism management.

4. CONCLUSIONS

This study developed a system dynamics–based MRV framework to quantify and simulate tourism-related carbon emissions in the Sembalun ecotourism area of Mount Rinjani National Park. The integrated model demonstrates that tourism activities generate substantial GHG emissions even in conservation-oriented destinations. For a defined scenario of 500 tourists staying two days, total emissions reached 17.46 tCO_2e, with waste (55%) and transportation (40%) identified as the dominant sources based on the MRV static scenario estimation, while electricity contributed a smaller share (5%). In contrast, the system dynamics simulation results indicate that transportation acts as the primary driver of emissions growth over time due to continuous tourist inflow and reinforcing system interactions. This distinction reflects the different analytical perspectives between static scenario-based estimation and dynamic system-level accumulation and is essential for the consistent interpretation of the results. Under BAU conditions, emissions increase progressively due to reinforcing interactions between tourist arrivals, service demand, and resource consumption. Scenario analysis confirms that coordinated mitigation strategies significantly reduce emissions. Moderate interventions achieved reductions of approximately 22–25% in cumulative emissions over the 30-day simulation period, whereas ambitious strategies lowered cumulative emissions by up to 50%, relative to the BAU scenario. These findings highlight the effectiveness of integrated low-carbon policies targeting waste management, transport decarbonization, and renewable energy adoption. The study contributes to the field by providing a dynamic, policy-oriented carbon accounting framework tailored to protected-area ecotourism. Despite these contributions, several limitations should be acknowledged. First, the analysis is limited to direct emissions within the defined system boundary and focuses on a specific case study area, which may limit the generalizability of the results to other tourism destinations. Second, the system dynamics model was not formally validated using independent datasets; therefore, the results should be interpreted as scenario-based simulations rather than predictive forecasts. Third, although a sensitivity-oriented discussion was included, a comprehensive quantitative uncertainty analysis—such as Monte Carlo simulation or systematic single-parameter sensitivity testing—was not performed. Future research should address these limitations by incorporating empirical validation using observed data, expanding the model to include indirect and lifecycle emissions, and applying probabilistic approaches to better capture uncertainty in key parameters such as tourist behavior, emission factors, and waste generation rates. These improvements would enhance the robustness, accuracy, and broader applicability of system dynamics–based carbon footprint models for sustainable tourism management.

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NOMENCLATURE

AD	Activity data (unit dependent on sector)
EF_g	Emission factor for gas g (kg gas per unit activity)
E_g	Emissions of gas g (kg gas)
CO_2e	Carbon dioxide equivalent (kg or t CO_2e)
GWP_g	Global Warming Potential of gas g (100-year time horizon)
R	Methane recovery rate (fraction)
OX	Oxidation factor for methane (fraction)
CH_4	Methane
N_2O	Nitrous oxide
CO_2	Carbon dioxide
tCO_2e	Metric tons of carbon dioxide equivalent
$kgCO_2e$	Kilograms of carbon dioxide equivalent
BAU	Business-as-usual scenario
MRV	Monitoring, Reporting, and Verification
CLD	Causal Loop Diagram
SFD	Stock–Flow Diagram
PV	Photovoltaic (solar power system)
E100	100% bioethanol fuel
STP	Sewage Treatment Plant
IPCC	Intergovernmental Panel on Climate Change
TNGR	Taman Nasional Gunung Rinjani (Mount Rinjani National Park)