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RESEARCH ARTICLE

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SUSTAINABLE RIVER TRANSPORT IN THE AMAZON: INTEGRATING SOLAR ENERGY INTO THE PUBLIC TRANSPORTATION SYSTEM OF THE MANAUS METROPOLITAN AREA

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RESUMO

River transportation is an important mode of transport in the Amazon, especially in the Manaus Metropolitan Region, where rivers and waterways play a fundamental role in connecting communities and municipalities. However, the predominant use of fossil fuels in watercraft contributes to high operating costs, pollutant emissions, and environmental impacts. In this context, the integration of solar energy into public river transportation presents itself as an alternative for promoting more sustainable mobility. The objective of this study is to analyze the potential for integrating solar energy into the public river transportation system of the Manaus Metropolitan Region, considering environmental, technological, economic, and social aspects. The methodology adopts a mixed-methods approach—exploratory, descriptive, and propositional in nature—combining a literature and document review with the administration of a structured questionnaire to 105 participants in the Manaus Metropolitan Region, supplemented by direct observation and qualitative analysis of the results. The results indicate that the use of electric propulsion systems combined with solar power generation can contribute to reducing fossil fuel consumption, atmospheric emissions, and the operating and maintenance costs of vessels. However, the implementation of this technology presents challenges related to initial investment, charging infrastructure, energy storage, vessel adaptation, and technical training. It can be concluded that the integration of solar energy into river transportation has the potential to strengthen sustainable mobility in Manaus and its metropolitan municipalities, provided it is accompanied by public policies, infrastructure investments, technological innovation, and integrated planning, taking into account the environmental and territorial characteristics of the Amazon.



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I. INTRODUCTION

Urban mobility constitutes one of the main challenges for the sustainable development of contemporary cities, especially in regions where geographical characteristics shape the population's patterns of movement. In the Amazon, rivers play a fundamental role in territorial, economic, and social organization, serving as important transportation routes for people, goods, and services [1], [2].

In this context, river transport represents not only a mobility alternative but also an essential element for the integration of communities and municipalities. In the Manaus Metropolitan Region, this reality is even more significant due to the extensive hydrographic network and the presence of localities whose connection with the capital depends, to varying degrees, on water transportation. However, the predominant use of fossil fuels in vessels contributes to the emission of air pollutants, noise generation, high operating costs, and environmental impacts [3], [4]. From a regional perspective, Manaus occupies a strategic position in the Western Amazon, concentrating economic, industrial, commercial, educational, and service activities. Its Manaus Industrial Pole (PIM) serves as a reference in sustainable development for Brazil and the world. Its location on the banks of the Negro River, the largest tributary of the Amazon River, and its proximity to important waterways favor the development of river transportation as a component of regional mobility [5].

Despite this potential, conventional water transportation systems still face challenges related to energy efficiency, environmental quality, port infrastructure, and technological modernization. Given this scenario, the use of renewable energy sources, especially solar energy, emerges as a possibility for energy diversification and for reducing dependence on fossil fuels in public river transportation [6], [7]. The research problem of this study is related to the following question: *How can the integration of solar energy into the public river transportation system contribute to more sustainable mobility in the Manaus Metropolitan Region?* This question involves not only the technical feasibility of using electric propulsion systems powered by solar energy but also economic, environmental, social, and institutional aspects that may influence their implementation and public acceptance [8]. The relevance of this research is associated with the need to seek transportation alternatives compatible with the environmental characteristics of the Amazon and with the principles of sustainable development.

The gradual replacement of conventional technologies with solutions based on renewable energy can contribute to reducing atmospheric emissions, fuel consumption costs, and environmental impacts resulting from transportation activities [6], [9]. Furthermore, the adoption of clean technologies can stimulate innovation and strengthen public policies aimed at energy transition and sustainable mobility. As a contribution, the study seeks to expand the scientific discussion on the application of solar energy in river transportation within the Amazonian context, providing support for researchers, public managers, and companies in the sector to evaluate technological alternatives appropriate to regional conditions. The analysis may also contribute to the planning of pilot projects and the formulation of strategies for modernizing public river transportation. Thus, the integration of solar energy and river mobility represents a promising perspective for promoting greater energy efficiency, environmental sustainability, and territorial integration in the Manaus Metropolitan Region.

II. THEORETICAL FRAMEWORK

II.1 ENERGY CONSUMPTION, URBANIZATION AND ENVIRONMENTAL IMPACTS

Urban growth and the intensification of economic activities have significantly increased energy consumption in cities, making urban systems important centers of energy demand and greenhouse gas emissions. According to [10], urban areas account for more than two-thirds of global energy consumption and a significant share of carbon emissions. This relationship depends on factors such as urban density, economic development, technological efficiency, and consumption patterns. Although urban growth may increase energy intensity, denser and more technologically advanced cities can achieve efficiency gains and partially reduce the relationship between economic growth and emissions [11], [12]. Urban energy consumption should therefore be analyzed from a systemic perspective, considering the interdependence among transportation, industry, residential areas, commerce, and public infrastructure. According to [13], the energy footprint of cities extends beyond their territorial boundaries, involving indirect flows associated with food, fuels, and construction materials. Therefore, urban sustainability requires consideration of both direct consumption and external energy and emission supply chains.

Dependence on fossil fuels remains one of the main environmental challenges due to the emissions and impacts associated with the use of oil, coal, and natural gas [14]. In this context, the transition to renewable energy sources is essential to reduce emissions and promote sustainable energy systems. In Brazil, the transportation sector accounts for approximately 32% of CO₂ emissions [15], highlighting its relevance to the energy transition. In Manaus, these challenges are intensified by territorial characteristics and the predominance of rivers, combined with limited road integration. The Manaus Industrial Pole (PIM) increases energy demand, while urban growth raises residential and commercial consumption. The regional energy matrix also remains significantly dependent on fossil fuels, particularly in isolated systems, despite the potential for renewable sources such as solar energy and biomass. The transportation sector constitutes an important driver of energy consumption and emissions due to the use of diesel and gasoline in road and river transportation systems.

The industrial sector, driven by the PIM, presents high energy demand, especially in the electronics, chemical, and two-wheeled vehicle segments, reinforcing the need for greater efficiency and the incorporation of renewable energy sources [16]. The residential and commercial sectors also contribute to the increase in electricity demand, influenced by population growth, urban expansion, and the intensive use of air-conditioning equipment resulting from equatorial climatic conditions [15]. Urban infrastructure, including public lighting, water supply, and sanitation systems, represents another relevant component of energy consumption and presents opportunities for improving efficiency [10]. Thus, Manaus's energy challenges result from the interaction among mobility, industry, residential consumption, commerce, and infrastructure. In this context, integrated policies focused on energy efficiency, diversification of the energy matrix, and the incorporation of renewable technologies are essential to promote a sustainable energy transition while considering the environmental, economic, and territorial specificities of the Amazon.

II.2 ENERGY TRANSITION AND RENEWABLE ENERGY

The energy transition constitutes one of the main contemporary challenges, characterized by the gradual replacement of fossil fuel sources with renewable energy, the decentralization of energy generation, and the incorporation of new technologies into energy systems. This process involves technological, institutional, economic, and social transformations.

According to [17], energy transitions result from the interaction among innovation, public policies, and market dynamics. Globally, efforts to meet the climate targets established under the Paris Agreement have driven the expansion of renewable energy sources. According to [18], the installed capacity of these sources has experienced significant growth, supported by declining technology costs and decarbonization policies. Brazil stands out in this scenario due to its energy matrix, which has a high share of renewable sources, particularly hydropower, biomass, wind energy, and solar energy. The country's geographical and climatic conditions favor the expansion of these alternatives, with particular emphasis on solar and wind energy [19]. Despite this advantage, challenges remain regarding the integration of decentralized energy sources, the modernization of transmission networks, and the regional distribution of energy production [20]. At the same time, regulatory and financial instruments, such as renewable energy auctions and green financing mechanisms, have contributed to expanding sustainable investments [21]. In this context, the Brazilian energy transition should be understood as a hybrid process that combines well-established renewable sources, such as hydropower, with emerging technologies, particularly solar and wind energy. This transformation requires integrated planning, innovation, and public policies capable of promoting greater efficiency, energy security, and reduced environmental impacts.

Table 1: General classification of energy sources.

Sources		Primary Energy	Secondary Energy
Non-renewable	Fossils	Mineral Coal	Thermoelectricity, Heat, Fuel for Transportation
		Oil	
		Natural gas	
	Nuclear	Fossil Materials	Thermoelectricity, Heat
Renewables	Traditional	Primitive Biomass: Firewood from Deforestation	Heat
	Conventional	Medium and Large Scale Hydraulic Potentials	Hydroelectricity
		Small-Scale Hydraulic Potentials	
	"News"	"Modern" Biomass: Replanted Firewood, Energy Crops (Sugarcane, Vegetable Oils)	Biofuels (Ethanol, Biodiesel) Thermoelectricity, Heat
		Others	Heat, Photovoltaic Electricity
			Heat and Electricity
			Electricity
		tidal and wave power	

Source: [22].

Non-renewable energy sources, such as coal, oil, natural gas, and nuclear energy, are characterized by high energy density but also by significant environmental impacts and the finite nature of their resources. Renewable energy sources, on the other hand, range from traditional forms, such as primitive biomass, to modern technologies, such as solar, wind, and geothermal energy, which constitute the central axis of the contemporary energy transition [23].

II.2.1 Biomass

Biomass constitutes one of the most relevant renewable energy sources in the Brazilian context due to its abundance and diversity of applications. It refers to the biodegradable fraction of organic materials originating from agriculture, forests, and urban and industrial waste, as defined in European Directive 2001/77/EC. This component is also highlighted by [24], which states that the prospects for the use of biomass as an energy source are increasingly promising, generating approximately US\$2 billion worldwide. Table 2 describes some of the types of biomass:

Table 2: Types of biomass and examples.

Types of Biomass	Examples
Lignocellulosic	Wood and cellulosic plants
Oilseeds	Soybeans and rapeseed
Sugar Crops	Sugar beets, sugarcane, and sugarcane
Starch Crops	Corn and wheat
Green Biomass	Grass, alfalfa, and clover
Aquatic Crops	Algae, aquatic weeds, and water hyacinth
Bio-waste	Agricultural residues and byproducts, straw, municipal and household waste, sewage sludge, wastewater containing organic matter, used vegetable oils, and animal fats

Source: [25].

The use of biomass offers significant advantages, including the reduction of net carbon emissions, since the CO₂ emitted during combustion is offset by its absorption during the growth of organic matter. In addition, biomass enables the energy recovery of waste, contributing to the circular economy [26]. The main conversion processes include combustion, gasification, and liquefaction. Gasification, in particular, stands out as a promising technology in the energy transition, enabling the conversion of biomass into fuel gas with high efficiency [27]. Additionally, biogas production through anaerobic digestion represents an effective solution for the treatment of organic waste, with potential applications in both urban and rural contexts.

II.2.2 Solar Energy

Solar energy is one of the main sources in the energy transition process due to its abundance and increasing competitiveness. Brazil has high generation potential, with favorable solar irradiation levels across virtually the entire territory. Photovoltaic technology is based on the direct conversion of solar radiation into electricity, while thermal systems use heat for energy generation or heating purposes. According to [28], the expansion of solar energy in Brazil has been driven by public policies, cost reductions, and technological advances. In the Amazonian context, solar energy is particularly relevant, especially in isolated areas. Studies indicate that photovoltaic systems can significantly reduce dependence on fossil fuel sources and improve access to energy in riverside communities [29].

II.3 SYNTHESIS OF THE ENERGY TRANSITION AND IMPLICATIONS FOR URBAN SYSTEMS

The energy transition is not limited to replacing fossil fuels with renewable sources; rather, it constitutes a systemic process involving changes in production, distribution, and consumption models. According to [17], it is a complex sociotechnical process shaped by technological, institutional, economic, and social factors, requiring integrated and long-term planning. In Brazil, the transition has particular characteristics due to the historically significant participation of renewable sources, especially hydropower. However, challenges related to climate variability, growing energy demand, and the need to diversify the energy mix remain relevant [15]. The expansion of solar, wind, and biomass energy demonstrates advances driven by technologies, public policies, and sustainable financing mechanisms [18],[21]. In urban systems, the energy transition must consider the organization of cities, mobility systems, and socioeconomic dynamics. This requires coordination among transportation, industry, buildings, and infrastructure, as well as the modernization of electricity grids and the adoption of decentralized solutions, such as distributed generation and hybrid systems [11],[30]. In Manaus, the potential for solar energy and biomass stands out, alongside limitations related to infrastructure, logistics, and dependence on fossil fuels. River transportation is strategically important due to its high energy demand and the emissions associated with the sector. The incorporation of renewable energy sources into this system can reduce environmental impacts and promote sustainable mobility in the Amazon. In addition to technical and economic feasibility, the transition depends on the social and institutional acceptance of new technologies [31]. Therefore, investigating renewable solutions applied to river transportation in Manaus can contribute to promoting energy efficiency, urban sustainability, and cleaner mobility models.

II.4 INTEGRATED RENEWABLE ENERGY AND URBAN SYSTEMS

The increasing complexity of cities requires integration among urban planning, energy systems, and environmental sustainability. In this context, energy production, consumption, and management are related to spatial organization, infrastructure, and mobility patterns. The International Energy Agency emphasizes that urban energy planning should be carried out in an integrated manner, seeking efficiency, resilience, and sustainability [30]. Traditionally, urban planning focused on land use and city expansion, but it has increasingly incorporated environmental, energy, and social dimensions in response to climate change, population growth, and increasing energy demand [32]. In Brazil, instruments such as the City Statute (Law No. 10.257/2001) and the Metropolis Statute (Law No. 13.089/2015) provide guidelines for sustainable development and integrated management [33], [34]. The integration of energy technologies has become strategic for smart and sustainable cities, involving distributed generation, smart grids, energy storage, and electric mobility [35], [18]. Mobility plays a central role due to the contribution of transportation to energy consumption and urban emissions [11]. In Manaus, the extensive river network and limited road infrastructure make the integration of renewable energy and river mobility a strategic priority, contributing to energy efficiency, emissions reduction, and urban sustainability in the Amazon.

II.5 SUSTAINABLE DEVELOPMENT

Sustainable development constitutes a fundamental paradigm for addressing challenges related to economic growth, urbanization, and environmental degradation. Although industrial and technological advancement has contributed to improving living conditions, it has also been associated with the intensive exploitation of natural resources, resulting in climate change, biodiversity loss, and resource scarcity [36]. In this context, sustainability seeks to balance economic development, environmental protection, and social equity. According to [37], there is a need to preserve the conditions that sustain life, associating environmental conservation with social justice and human development. The Brundtland Report consolidated the concept of sustainable development as development capable of meeting present needs without compromising the ability of future generations to meet their own needs [38]. This concept evolved into an integrated approach represented by the “triple bottom line,” which brings together the economic, social, and environmental dimensions [39]. This perspective is particularly relevant in cities, where population growth, energy consumption, and resource use intensify environmental impacts. The 2030 Agenda reinforces this approach through the 17 Sustainable Development Goals (SDGs), highlighting clean energy (SDG 7), sustainable cities (SDG 11), and climate action (SDG 13) [39]. Within this process, the energy sector plays a strategic role. Dependence on fossil fuels increases greenhouse gas emissions, making the transition to renewable energy sources essential [30]. In Manaus, technologies such as solar energy, biomass, and decentralized systems can improve energy efficiency, reduce environmental impacts, and contribute to a sustainable urban model adapted to the characteristics of the Amazon region.

III. MATERIALS AND METHODS

Over the past decades, the concept of sustainable development has evolved from a predominantly environmental approach toward an integrated perspective encompassing the economic, social, and environmental dimensions, consolidated in what is known as the “triple bottom line” [39]. This perspective is particularly relevant in urban contexts, where population growth, energy consumption, and resource management intensify environmental challenges. At the international level, the United Nations 2030 Agenda has established sustainable development as a global priority. Its 17 Sustainable Development Goals (SDGs) highlight areas such as clean energy (SDG 7), sustainable cities (SDG 11), and climate action (SDG 13), reinforcing the integration of energy, urban, and environmental policies [40].

The energy sector plays a strategic role in this process, as dependence on fossil fuels is directly associated with greenhouse gas emissions. Therefore, the transition to renewable energy sources constitutes an essential instrument for achieving sustainability targets [30]. In cities, where a significant share of energy consumption and emissions is concentrated, integrated planning and efficiency strategies are fundamental [11]. In Brazil and, particularly, in the Amazon region, sustainable development faces challenges associated with urban growth, the exploitation of natural resources, and infrastructure limitations. In Manaus, dependence on fossil fuels in certain sectors reinforces the need for more sustainable energy alternatives. The adoption of solar energy, biomass, and decentralized systems can reduce environmental impacts, increase energy efficiency, and improve access to energy in isolated areas. In addition to technological solutions, urban sustainability depends on changes in consumption patterns and behavior, encouraging environmental conservation practices and social responsibility [41]. Thus, sustainable development should integrate public policies, technological innovation, and social participation. In this context, the application of renewable energy to river transportation in Manaus represents an opportunity to reduce emissions, improve energy efficiency, and promote a more balanced and sustainable mobility model in the Amazon region.

III.1 RESEARCH CONTEXT

The present study was conducted in the city of Manaus, the capital of the state of Amazonas, located in the northern region of Brazil. Manaus is a city of great economic and cultural importance, situated in the heart of the Amazon Rainforest. It serves as a connection point for the northern region of the country and plays a strategic role as an economic, logistical, and cultural center of the Amazon. Its economy is largely driven by the Manaus Industrial Complex (PIM) within the Manaus Free Trade Zone, which concentrates activities in the electronics, two-wheel vehicle, thermoplastics, and information technology industries, generating employment and stimulating the regional economy [16]. The city's geographical location, surrounded by an extensive hydrographic network, makes river transportation an essential mode for the movement of people and goods. From a territorial perspective, the municipality covers an area of approximately 11,401 km² and is located at coordinates 3°06'07" S and 60°01'30" W, near the confluence of the Negro and Solimões rivers. In demographic terms, the resident population was estimated at 2,063,689 inhabitants according to the 2022 Census [42], making Manaus the main metropolis in the northern region of Brazil. Figure 1 presents the geographical location of the municipality within the context of the state of Amazonas.

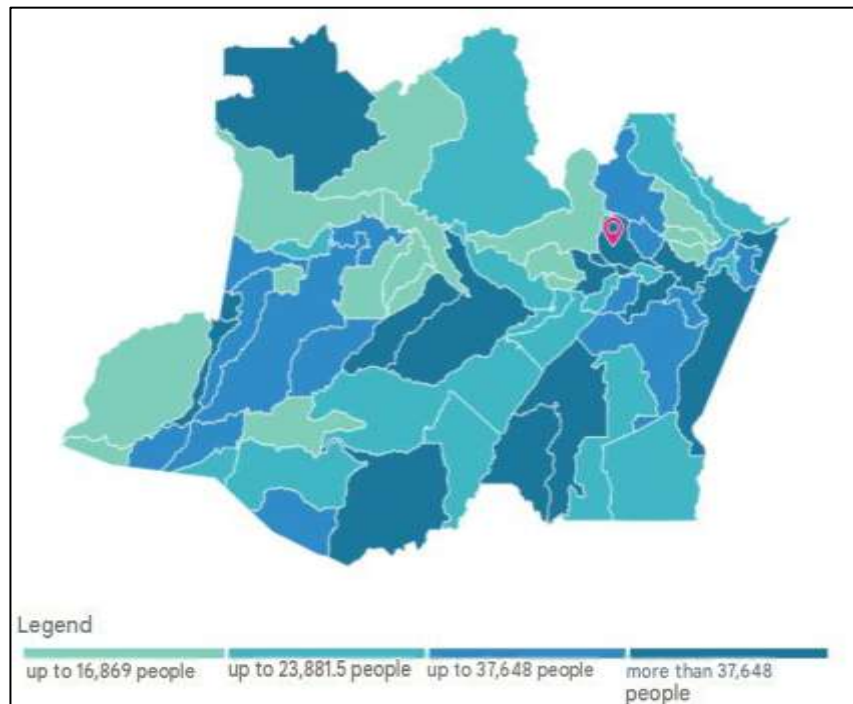


Figure 1: Population by Municipality in Amazonas.

Source: [42].

Manaus has a population density of 181.01 inhabitants/km², reflecting a relatively dispersed population distribution across an extensive territory characterized by concentrated urbanization in certain areas [42]. This pattern contrasts with capitals such as Recife, with 6,803.60 inhabitants/km², and São Paulo, with 8,035 inhabitants/km² [42], highlighting the more extensive urbanization characteristic of Amazonian cities. From an international perspective, Manaus has a larger territorial area than capitals such as Paris (105 km²) and Lisbon (100 km²), which have much higher population densities, exceeding 20,000 and 6,500 inhabitants/km², respectively [43]. This comparison highlights the differences between compact urban models and the dispersed settlement pattern of Manaus. The Municipal Human Development Index (MHDI) of Manaus was 0.737, classified as high [44]. However, socio-spatial inequalities related to income and access to services persist. The municipality's GDP per capita reached approximately BRL 45,782.75 in 2022 [42], reflecting the municipality's economic importance, although income distribution remains unequal. Manaus has 63 officially recognized neighborhoods distributed across six administrative zones: North, South, East, West, Central-South, and Central-West. In addition to these areas, there are informal regions integrated into the urban fabric, although they are not officially recognized by the municipal administration.

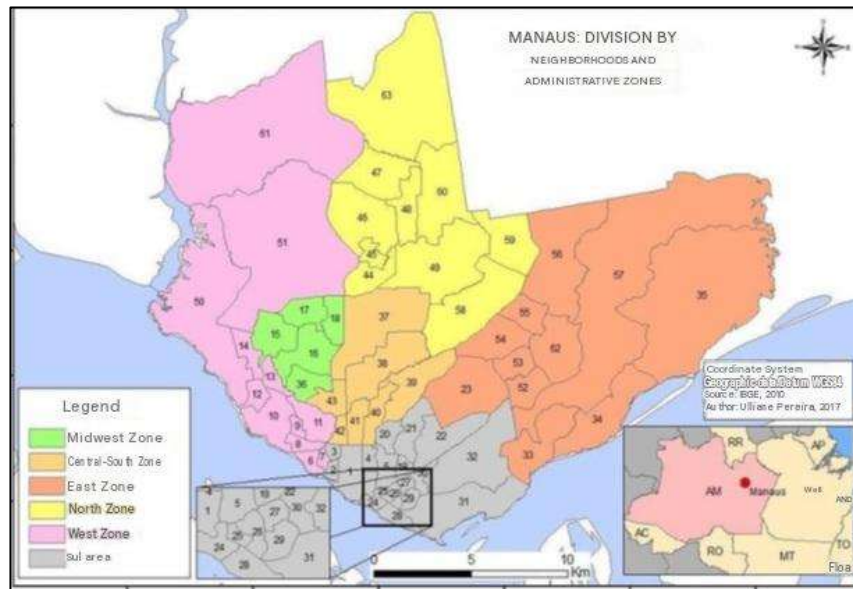


Figure 2: Manaus – Breakdown by neighborhoods and administrative zones.
Source: [45].

Manaus has a humid equatorial climate (Af), with average temperatures ranging from 26 °C to 28 °C, high humidity, and annual precipitation exceeding 2,300 mm [46]. The rainy season, predominantly occurring between December and May, influences mobility and urban infrastructure, potentially causing flooding and operational difficulties in transportation. The terrain is predominantly gently undulating, with elevations ranging from 30 to 100 meters, as well as streams and floodplain areas. Soil sealing increases vulnerability to flooding. The extensive hydrographic network constitutes an important natural resource and a structuring element of regional mobility, particularly river transportation. The municipal economy has a strong industrial base, with the Manaus Industrial Complex (PIM) standing out in the electronics, two-wheel vehicle, thermoplastics, and information technology sectors. According to [16], the PIM generates more than 80,000 direct jobs. Commerce, services, logistics, river transportation, and tourism also play significant roles. Manaus has a relatively young population, with a concentration between 20 and 39 years of age (IBGE, 2023), but socio-spatial inequalities in income and access to higher education persist [44]. Mobility is characterized by the predominance of road and river transportation. The road transportation system has approximately 1,300 buses and depends on major road corridors, facing traffic congestion and infrastructure limitations [47]. River transportation is essential for connecting Manaus to inland areas and riverside communities, although its integration with the road transportation system remains limited. This context reinforces the potential for sustainable solutions, particularly the integration of river transportation with solar energy.

III.2 RESEARCH METHODOLOGY

The present research is applied in nature and adopts a mixed-methods approach, combining quantitative and qualitative techniques. This strategy makes it possible to analyze behavioral patterns and individual perceptions, contributing to an integrated understanding of the challenges and opportunities associated with implementing a solar-powered public river transportation system in the Manaus Metropolitan Region [48], [49]. Regarding its objectives, the study is characterized as exploratory, descriptive, and propositional. It is exploratory because it investigates the integration of renewable energy into river transportation; descriptive because it identifies behaviors, perceptions, and trends related to mobility; and propositional because it develops a conceptual solution based on empirical results and scientific literature [50]. The methodological strategy is based on a single-case study focused on Manaus, considering its dependence on river transportation, infrastructural and energy limitations, and potential for the use of renewable energy sources [51]. The quantitative stage was conducted through structured questionnaires designed to identify usage patterns, satisfaction levels, and perceptions regarding sustainability. The qualitative approach involved direct observation and documentary analysis, allowing an understanding of urban conditions and practices related to river transportation. The integration of these procedures provides broader coverage in the interpretation of the results [52]. The procedures sought to identify mobility problems, assess the feasibility of solar energy, analyze public perceptions, and propose sustainable solutions. Methodological triangulation, standardized instruments, descriptive statistics, and qualitative analysis were employed [53], [54]. It is recognized that non-probability sampling limits the generalizability of the results. Thus, the research design combines theoretical foundations, empirical evidence, and the proposition of solutions for sustainable river mobility.

III.3 POPULATION AND SAMPLE

The research population corresponds to the population residing in Manaus, including potential users of public transportation, particularly river transportation. Different social groups were considered, with diversity in age, gender, income, location, and frequency of transportation use. Manaus had an estimated population of 2,063,689 inhabitants [42]. Due to the size of the population and the operational limitations of data collection, non-probability convenience sampling and voluntary participation were adopted. This approach is suitable for exploratory studies aimed at identifying trends and perceptions, without the intention of achieving statistical generalization [51], [55]. Additionally, stratification can enhance the representation of heterogeneous subgroups and reduce sampling errors. Convenience sampling is also appropriate when access to the population is limited. The strata considered were defined based on sociodemographic variables related to the use of river transportation:

- a) Age group: 18–29, 30–44, 45–59, and ≥ 60 years;
- b) Gender: female, male, and other;
- c) Monthly income: up to 1 minimum wage, 1–3 minimum wages, 3–5 minimum wages, and above 5 minimum wages;
- d) Residential area: North, South, East, West, Central-South, and Central-West;
- e) Frequency of river transportation use: daily, weekly, occasional, and never used but potentially willing to use.

These groups made it possible to distribute the sample proportionally according to the composition of the population of Manaus. The finite population formula was used only as a reference parameter to determine a desirable minimum sample size, rather than as the basis for probabilistic selection of participants. The sample actually obtained followed, as described below, the criteria of convenience and voluntary participation, which are appropriate to the exploratory nature of the study. The preliminary determination of the sample size used the finite population formula:

$$n = \frac{N \cdot Z^2 \cdot p(1-p)}{e^2 (N-1) + Z^2 \cdot p(1-p)} \quad (1)$$

Where:

- n = desired sample size;
- N = 2,063,689 inhabitants;
- Z = 1.64 (90% confidence level);
- p = 0.5 (maximum variability);
- e = 0.08 (8% margin of error).

To distribute the participants proportionally among the strata, the following was used:

$$n_h = n \cdot \frac{N_h}{N} \quad (2)$$

Where:

- n_h = number of respondents in stratum h ;
- N_h = population of the stratum;
- N = total population (2,063,689).

The sample consisted of 105 participants who voluntarily responded to the questionnaire administered through a digital platform. This number was considered adequate for descriptive statistical analyses, allowing the identification of patterns and trends related to perceptions of urban mobility and sustainable river transportation. Data collection took place between April and May 2025, seeking to include different participant profiles and locations within Manaus. Variables such as age group, gender, residence in the Central, North, East, and West zones, socioeconomic profile, and frequency of use of public and river transportation were considered. This diversity made it possible to gather different perspectives on the urban mobility system. Initially, the use of stratified probability sampling was considered. However, logistical, temporal, and operational limitations, including the lack of comprehensive databases and the territorial dispersion of the population, led to the adoption of non-probability sampling, which was considered more appropriate for the exploratory nature of the research [56]. The sample composition sought to ensure participant heterogeneity, including different age groups, socioeconomic conditions, and levels of public transportation use. According to [57], samples of this nature can be used in exploratory studies and descriptive analyses aimed at understanding perceptions. However, non-probability sampling limits the generalizability of the results to the entire population of Manaus. Therefore, the data obtained should be interpreted as indicative and exploratory, contributing to an understanding of participants' perceptions regarding sustainable river mobility.

III.4 DATA COLLECTION PROCEDURES

Data collection for the present investigation was conducted through a multimethod strategy, combining a systematic literature review, structured questionnaires, and direct on-site observation. This approach enables the triangulation of information sources, contributing to increased robustness and reliability of the results [52]. The structured questionnaire was administered in several stages, using different techniques to ensure a comprehensive understanding of the phenomenon under study, including literature review, structured questionnaires, and direct observation and on-site visits. Standardized questionnaires were administered to collect statistical data and capture nuances and perceptions regarding how the population of the Manaus metropolitan region perceives the implementation of a solar-powered public river transportation system.

III.4.1 Literature Review

The literature review was conducted systematically, using defined criteria for searching, selecting, and analyzing sources, with the aim of identifying the state of the art regarding urban sustainability, renewable energy, river transportation, and energy transition, with a focus on the Amazonian context. The Scopus, Web of Science, SciELO, and ScienceDirect databases were consulted, considering publications from 2010 to 2024. The searches used descriptors in Portuguese, English, and Spanish, including “energia renovável,” “sustentabilidade urbana,” “transporte fluvial,” “transição energética,” “renewable energy,” “urban sustainability,” “fluvial transport,” “smart cities,” and “Amazon region,” combined using the Boolean operators AND and OR. Peer-reviewed articles, theses, dissertations, and technical documents from recognized institutions, such as EPE, SEEG, IEA, IPCC, and ANEEL, were included, as well as empirical studies on Amazonian cities. Publications without peer review, except official documents, studies not directly related to the topic, and duplicate works were excluded. The process resulted in relevant references that provided a foundation for the theoretical discussion and contributed to understanding the evolution of urban sustainability, river mobility, and the energy transition in the Amazon.

III.4.2 Structured Questionnaires

The main technique for collecting primary data was the administration of a structured questionnaire consisting of 22 predominantly closed-ended questions, including multiple-choice questions. Questionnaires are widely used instruments in quantitative studies because they enable the systematic collection of data and statistical analysis of responses [53]. The questionnaire was made available through the Google Forms platform, facilitating access and participation by respondents. Distribution was carried out through digital channels, including email and social media, allowing participants from different areas of the city to be reached. Before completing the questionnaire, participants were informed about the objectives of the research and invited to provide informed consent through the Free and Informed Consent Form, ensuring compliance with ethical research principles, particularly voluntary participation, anonymity, and data confidentiality [58]. The questionnaire items were organized to address:

- use and evaluation of public transportation;
- perceptions of urban mobility;
- importance of environmental sustainability;
- feasibility of using solar energy in vessels;
- acceptance of new river transportation solutions.

III.4.3 Summary of Data Collection Procedures

The combination of the three techniques—literature review, structured questionnaires, and direct observation—enabled the collection of diverse and complementary data, allowing for an integrated analysis of the phenomenon under study. This multimethod approach is particularly appropriate for applied research in complex urban contexts such as Manaus, where social, territorial, and energy-related factors are interconnected [59].

III.5 DATA ANALYSIS

The analysis of the data obtained in the present investigation was conducted based on descriptive statistics, complemented by qualitative interpretation of the results, allowing an integrated assessment of the observed patterns and participants' perceptions.

III.5.1 Quantitative Analysis

The data obtained from the structured questionnaires were initially organized, coded, and tabulated in a digital environment and subsequently processed using descriptive statistics. This approach allows large volumes of data to be summarized clearly and objectively and is suitable for exploratory studies aimed at identifying patterns and trends [54], [60]. The main techniques used included:

- calculation of absolute and relative frequencies (percentages);
- analysis of response distributions;
- identification of predominant trends in the data;
- comparison among different response categories.

The choice of descriptive statistics is justified by the exploratory nature of the investigation and the characteristics of the sample, allowing for a consistent analysis without the need to apply complex inferential models [57]. The results were presented using pie charts, as illustrated in the Results section (Figures 9 to 28). This type of graphical representation is particularly suitable for demonstrating the relative proportions of categories within a set of responses, facilitating the visual interpretation of the data [60].

The use of graphs contributed to:

- improving the communication of results;
- facilitating the identification of patterns;
- supporting comparative analysis among variables.

III.5.2 Summary of Data Analysis

Overall, the data analysis was structured to:

- Identify patterns of public transportation use and perceptions;
- Assess the level of acceptance of sustainable solutions;
- Understand the main challenges and opportunities associated with urban mobility in Manaus;
- Support the development of the conceptual proposal presented in the Results section.

Thus, the combination of descriptive statistics and qualitative interpretation enabled a consistent analysis, aligned with the objectives of the investigation and appropriate to the context of the study.

III.6 LIMITAÇÕES METODOLÓGICAS

Despite the methodological rigor adopted, this investigation presents limitations that should be considered when interpreting the results and generalizing the conclusions. The main limitation concerns the use of non-probability convenience sampling and voluntary participation. Although appropriate for exploratory studies and the analysis of social perceptions, this strategy limits the statistical generalizability of the results to the entire population of Manaus [50], [48]. The sample size ($n = 105$) is also relatively small given the municipality's population size. However, in exploratory and mixed-methods research, the emphasis is on understanding phenomena and trends rather than exclusively on statistical representativeness [49], [60].

Another limitation is related to the structured questionnaire, whose self-reported responses may be subject to biases arising from subjective perceptions, interpretation of the questions, or social desirability [53]. The digital administration through Google Forms may also have restricted the participation of individuals with limited access to the internet or digital literacy, potentially resulting in selection bias [56]. The single-case study, centered on Manaus, enables an in-depth analysis of the local context but limits generalization to other cities. According to [51], case studies favor analytical rather than statistical generalization. In addition, the investigation focused on the feasibility and social acceptance of renewable solutions for river transportation and did not address large-scale implementation. Aspects such as operating costs, technical performance, maintenance, and detailed economic feasibility remain potential areas for future research. Despite these limitations, the combination of quantitative and qualitative methods, data triangulation, and theoretical grounding contributes to the consistency and validity of the results [59], [51].

IV. RESULTS AND DISCUSSION

IV.1 CASE STUDY

This section analyzes the Manaus case study, exploring the relationship between urban mobility, energy consumption, and the integration of renewable energy, with a focus on river transportation. The analysis seeks to understand the challenges and opportunities associated with the energy transition in Amazonian urban contexts. Manaus presents unique territorial and environmental characteristics, marked by an extensive hydrographic network that plays a fundamental role in regional mobility. River transportation is strategic for the movement of people and goods, but it also has significant energy and environmental implications due to its dependence on fossil fuels. In this context, theoretical foundations and empirical evidence are brought together, considering the urban and energy characteristics, mobility problems, and social acceptance of renewable technologies. First, the urban context and transportation system are presented; subsequently, the main energy-related issues and the results of the survey conducted with the population are analyzed. Next, the results are discussed in light of the theoretical framework, making it possible to assess perceptions and expectations regarding the use of renewable energy in river transportation. Finally, a proposal based on the integration of solar energy into vessels is presented, considering technical, environmental, economic, and social aspects as an alternative for more sustainable river mobility in Manaus.

IV.2 CONTEXTUALIZATION OF THE CASE STUDY: MANAUS AND RIVER MOBILITY

Urban mobility constitutes one of the main challenges facing contemporary cities, being closely related to energy consumption, environmental quality, and territorial organization. In Amazonian cities, this issue presents particular characteristics resulting from their geographical and hydrographic configuration. In Manaus, therefore, mobility must consider not only the road transportation system but also the strategic role of river transportation. Public transportation promotes collective mobility and can reduce per capita energy consumption and emissions compared with individual motorized transportation [30]. However, dependence on fossil fuels remains a challenge, making the adoption of clean technologies, such as solar-powered electric systems, increasingly relevant [18]. In the Amazon, rivers constitute important transportation corridors. In Manaus and the metropolitan region, river transportation connects riverside communities to urban centers, ensuring access to services such as healthcare, education, and commerce [61]. Among the main types of vessels are high-speed boats, known as “ajatos,” and “line boats.” The former are faster and have lower passenger capacity, while the latter operate regular routes and transport both passengers and cargo. According to [62], “ajato” boat routes can be classified into primary, secondary, and tertiary flows, with approximate capacities of 130, 65, and 27 passengers, respectively. In Manaus, the Manaus Organized Port (POM) and the Manaus Moderna Port (PMM) constitute important embarkation and disembarkation points on the Negro River [61]. However, the predominance of diesel engines contributes to emissions and air pollution. In this context, the integration of renewable energy into river transportation represents an opportunity to reduce environmental impacts, promote technological innovation, and strengthen the sustainability of mobility in the Amazon.



Figure 3: “Ajato” speedboats, also known as “express boats”.

Source: [62].

According to [62], “ajato” speedboats are classified into primary, secondary, and tertiary flows. Primary flows depart from Manaus and have greater infrastructure, while secondary flows connect intermediate cities to inland areas. Tertiary flows serve dispersed riverside communities, using smaller vessels. Capacities vary according to the route, reaching up to 130 passengers on primary flows, 65 on secondary flows, and 27 on tertiary flows. This diversity demonstrates the adaptation of river transportation to the different territorial conditions of the Amazon. The Balsa Amarela constitutes an important pier for access to “ajato” speedboats.



Figure 4: Express boat docked at the ferry known as “Amarela”.
Source: [63].

In the context of river transportation in the Amazon, intermunicipal or interstate line boats (Figure 5) are essential due to the region’s geographical characteristics [62].



Figure 5: Intercity or interstate ferry boats.
Source: Authors, (2026).

These boats enable long-distance journeys, connecting major ports such as Manaus to other cities, for example, Belém, located in the state of Pará, approximately 1,650 km away and requiring five days of river travel. Historically, river navigation has been used for trade and the movement of people throughout the Amazon, with different types of vessels, such as *paquetes* and *gaiolas*, which were adapted to the conditions of the region’s rivers [61]. Figure 6 presents the Manaus Organized Port.



Figure 6: Boats docked for cargo and passenger transport at the Organized Port of Manaus (POM).
Source: Authors, (2026).

The Manaus Organized Port (POM) and the Manaus Moderna Port (PMM) constitute important embarkation and disembarkation points for vessels in the region. Located along the banks of the Negro River, these ports connect Manaus to several municipalities in the state of Amazonas, performing essential commercial, social, and cultural functions for regional integration [61]. The integration of river transportation with the road transportation system is essential for improving mobility efficiency, reducing travel times, and increasing accessibility. In this context, the incorporation of solar energy into river vessels emerges as an innovative and sustainable alternative.

In addition to reducing pollutant emissions and dependence on fossil fuels, this solution can lower operating costs, increase energy autonomy, and contribute to improving the quality of life of riverside populations. Finally, it is important to emphasize that adapting the river mobility system to renewable energy sources represents not only a technological innovation but also an opportunity to enhance the cultural and territorial practices of the Amazon region. By integrating tradition and innovation, it becomes possible to develop sustainable solutions adapted to local specificities, contributing to balanced regional development.

IV.3 CHARACTERIZATION OF THE CURRENT SYSTEM AND IDENTIFIED PROBLEMS

The analysis of urban and river mobility in Manaus highlights challenges related to the territorial characteristics of the Amazon, infrastructure limitations, and dependence on fossil fuels. In the urban area, road transportation predominates and is characterized by traffic congestion, high fuel consumption, and greenhouse gas emissions. Strategies based exclusively on road expansion present economic and environmental limitations in the long term [64]. At the same time, river transportation is strategic for connecting Manaus to inland municipalities and riverside communities. The Negro and Solimões rivers constitute important transportation corridors, used by “line boats” and high-speed “ajato” boats. Despite their importance, these services face operational limitations and dependence on fossil fuels. The predominance of diesel engines contributes to emissions and environmental impacts, while river seasonality affects navigability, routes, and travel times [15]. Port infrastructure, particularly the Manaus Organized Port and the Manaus Moderna Port, also presents limitations in terms of capacity, organization, and multimodal integration. In this context, five central problems stand out: dependence on fossil fuels, limited infrastructure, low modal integration, river seasonality, operating costs, and environmental impacts. As an alternative, the use of solar-powered electric vessels is proposed, taking advantage of existing ports and docking facilities. This solution could reduce emissions, maintenance costs, and dependence on fossil fuels, while also improving mobility and reducing congestion. However, its implementation requires studies on batteries, motors, vessel weight, solar availability, charging infrastructure, and economic feasibility. Thus, solar-powered river transportation has the potential to provide sustainable mobility adapted to the conditions of Manaus.

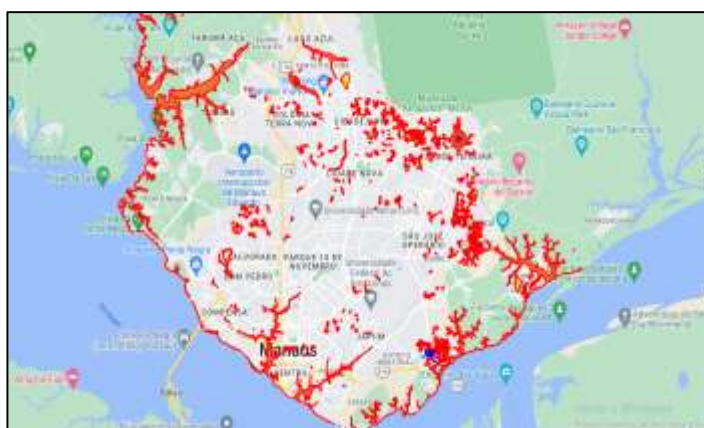


Figure 7: Map of the city of Manaus showing neighborhoods along the banks of the Rio Negro.

Source: [42].

For the introduction of solar-powered river vessels into public transportation (Figure 8), the average cost per vessel is approximately EUR 122,000 [65] (see Appendix – solar passenger boats of approximately 9 m in length and a capacity of 20 passengers, PASSENGERS 9.0 model, with and without cabin, manufactured by Sun Concept²). Converting this amount into Brazilian currency based on the EUR/BRL reference exchange rate of the Central Bank of Brazil in 2024 (approximately BRL 6.28 per euro), the cost would be approximately BRL 766,600.42. The quoted layout provides 20 passenger seats, in addition to the crew. This CAPEX value is below the average acquisition cost of an electric bus reported for Brazilian public transportation, suggesting potential economic competitiveness of the solution. However, a more accurate comparison depends on specific studies considering the operating, maintenance, and infrastructure costs of both modes of transportation.

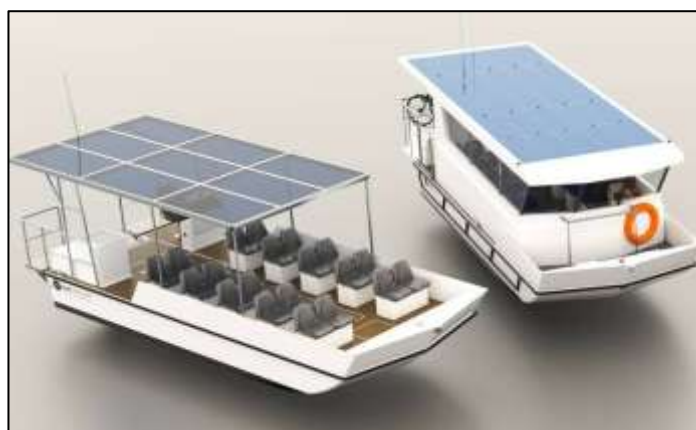


Figure 8: Solar-powered passenger boats approximately 9 meters long and designed to carry 20 passengers, the EVO PASSENGERS 9.0 model with and without a cabin, manufactured by Sun Concept².

Source: [65].

In addition to the initial investment, solar-powered vessels have the potential to reduce operating costs through the use of a renewable energy source and lower dependence on fossil fuels. This technology can also stimulate investment, research, and innovation in clean energy, in addition to strengthening sustainable tourism in the Amazon and serving as a reference for other regions with similar characteristics. Sun Concept provides electric-propulsion vessels characterized by low maintenance costs, reduced noise, and lower environmental impact. According to the manufacturer, the version for 20 passengers and crew uses two 12 kW motors, 27.8 kWh batteries, and solar panels for charging, according to the configuration adopted [65]. In the Manaus Metropolitan Region, the predominance of road transportation places a significant burden on road infrastructure. According to [64], the expansion of overpasses and road infrastructure alone is not a sufficient solution, making collective and sustainable alternatives necessary. The state of Amazonas has particular logistical characteristics, with many municipalities accessible primarily by rivers. In this context, the seasonality of floods and droughts directly influences navigation and route planning. The expansion of solar-powered river transportation will depend on passenger demand, distances between docking facilities, vessel speed, and range. Historically, recreational boats were used, characterized by long journeys and lower-powered engines. Subsequently, faster vessels emerged, such as the “Expresso” or “Ajato,” which reduced travel times, although they provide less passenger comfort.

IV.4 EMPIRICAL RESULTS (SURVEY)

The survey analysis sought to understand participants’ perceptions of urban and river mobility in the Manaus Metropolitan Region, as well as to assess acceptance of the use of renewable energy in transportation [11][30]. The questionnaire was organized into four dimensions: (i) main mobility problems; (ii) climatic and technological conditions for the use of solar energy in vessels; (iii) social acceptance of solar-powered river transportation; and (iv) technical, logistical, and economic aspects of implementation. Data were collected through a structured questionnaire administered via Google Forms to public transportation users. The sample was non-probabilistic, consisting of 105 voluntary participants with diverse age, socioeconomic, and territorial profiles. This strategy is appropriate for exploratory research aimed at understanding social perceptions and behaviors [50][55]. The data were analyzed using descriptive statistics, allowing the identification of transportation usage patterns, environmental perceptions, and levels of acceptance of the sustainable river mobility proposal [60].

IV.4.1 Urban Mobility in the Manaus Metropolitan Region

Initially, participants were asked whether they currently use or have regularly used public transportation in the Manaus Metropolitan Region. The results are presented in Figure 9. The majority of respondents (78%) reported that they use or have used public transportation, highlighting the relevance of the collective transportation system to local urban mobility. This result is consistent with studies indicating that bus-based public transportation is the main means of urban travel in Manaus, despite its operational and structural limitations [66], [67]. On the other hand, 22% of respondents indicated that they do not use public transportation, which may reflect the use of alternatives such as individual motorized transportation, bicycles, or walking. Such modal diversity is common in cities with fragmented transportation systems and varying levels of accessibility [11].

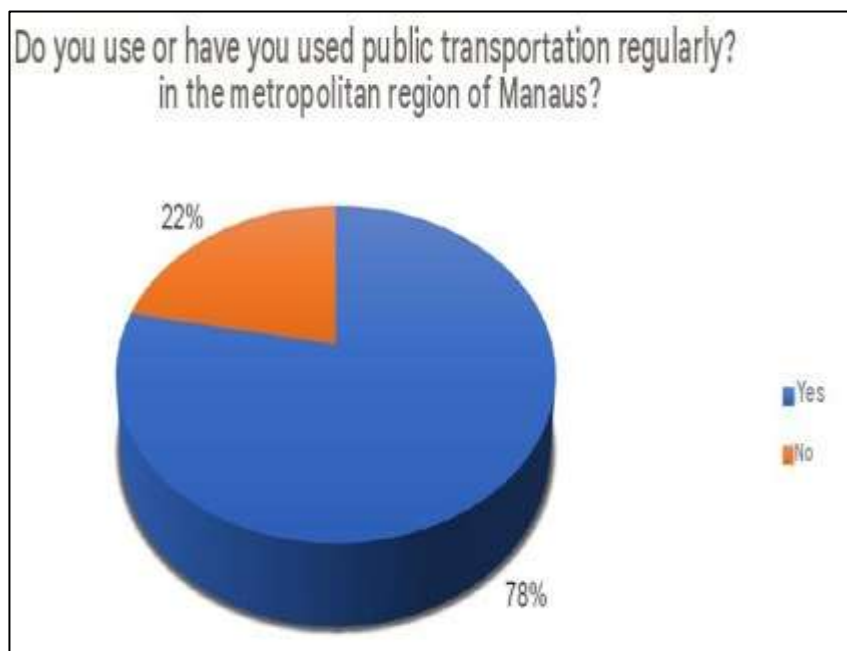


Figure 9: Do you currently use or have you ever used public transportation regularly in the Manaus metropolitan area?

Source: Authors, (2026).

Next, participants were asked about the efficiency of the current public bus transportation system powered by internal combustion engines (Figure 10). The results indicate that 65% of respondents consider the system inefficient, while 31% classify it as partially efficient, and only 4% consider it efficient. These data reveal a widespread perception of dissatisfaction, corroborating previous studies that identify structural problems in urban mobility in Manaus, including uncontrolled urban growth and inadequate planning [67].

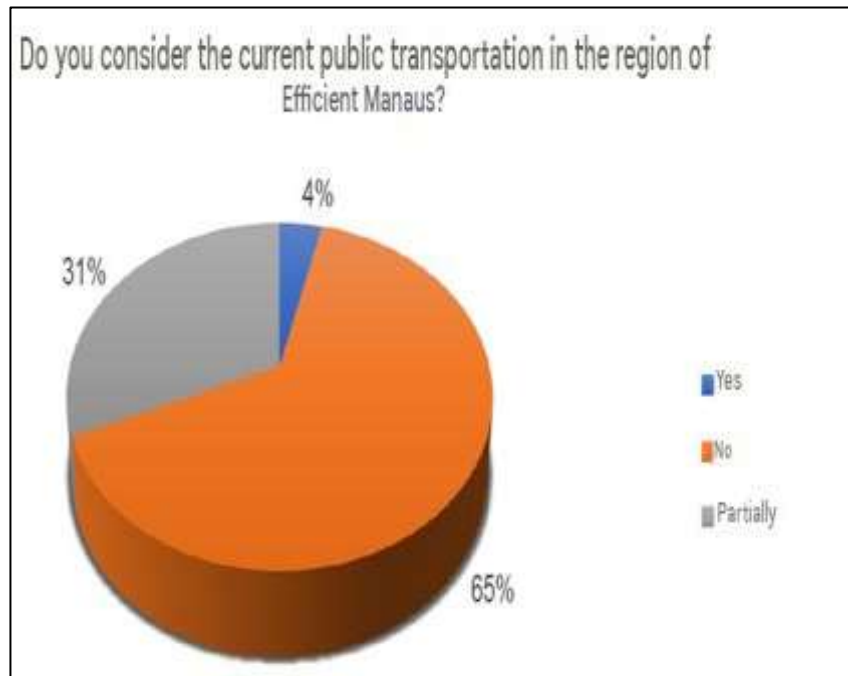


Figure 10: Do you consider the current public transportation system in the Manaus region to be efficient?
Source: Authors, (2026).

Next, the importance attributed by participants to reducing the environmental impact of public transportation was analyzed (Figure 11). The results show that 98% of respondents consider this reduction important, demonstrating a high level of environmental awareness. This finding is consistent with the literature on sustainable mobility, which highlights the growing appreciation of low-carbon solutions in urban transportation systems [68], [18]. Only 2% of respondents did not consider reducing the environmental impact relevant, which may reflect different levels of information or individual priorities. Nevertheless, the overwhelming majority consensus reinforces the relevance of public policies aimed at decarbonizing urban mobility.

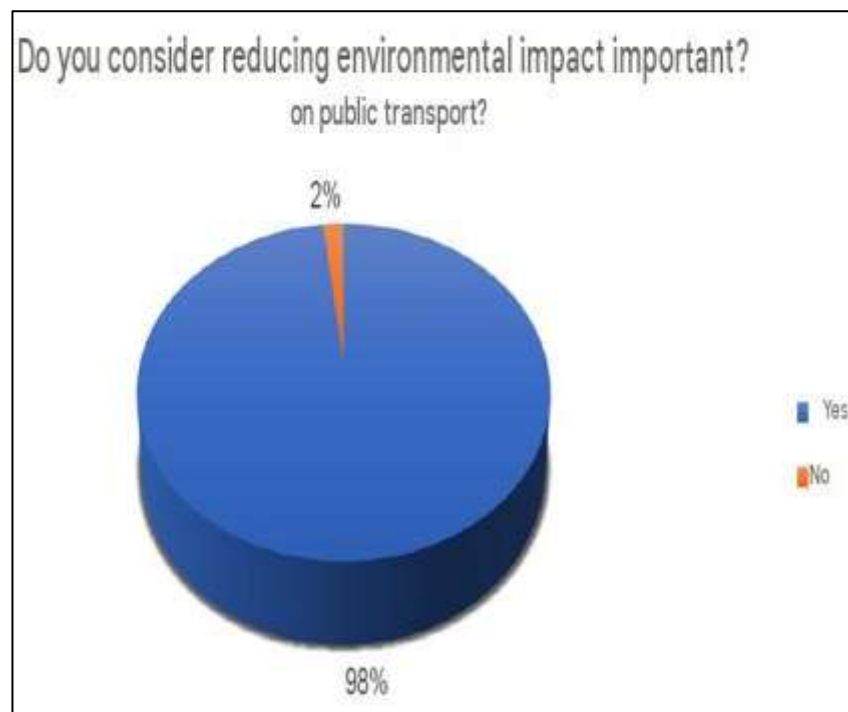


Figure 11: Do you consider it important to reduce the environmental impact of public transportation?
Source: Authors, (2026).

Subsequently, participants were asked about the main problems affecting public transportation in Manaus (Figure 12). The results indicate that overcrowding (22%), lack of safety (20%), inadequate vehicle conditions (17%), and low territorial coverage (13%) are the main problems identified. Lack of punctuality (13%) and high fares (12%) were also identified as relevant factors. These results confirm previous assessments of urban mobility in Manaus, which identify long waiting times, overcrowding, and poor service quality as recurring factors contributing to dissatisfaction [67]. The literature also highlights that inefficient urban transportation systems directly affect quality of life and productivity in cities [11].

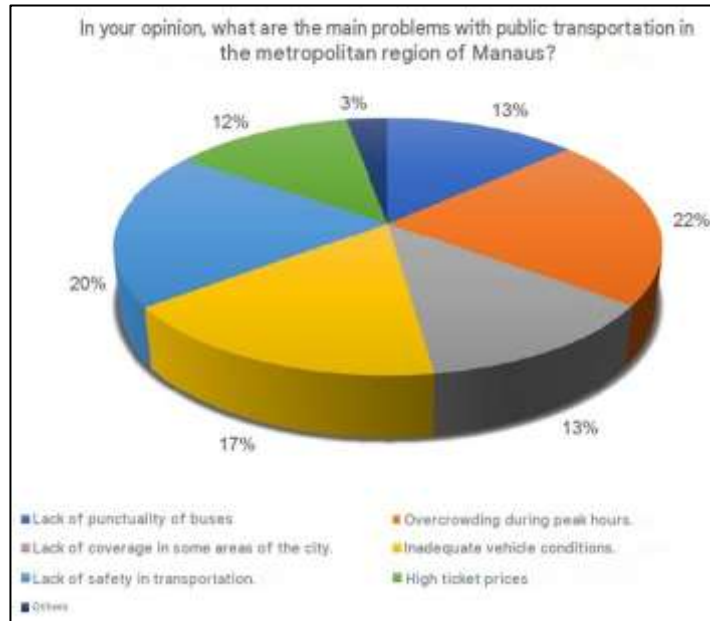


Figure 12: In your opinion, what are the main issues facing public transportation in the Manaus metropolitan area?
Source: Authors, (2026).

In the overall assessment of public transportation quality (Figure 13), 39% rated the system as unsatisfactory and 32% as poor, totaling 71% negative evaluations. Only 1% considered the system good, indicating that, despite widespread criticism, there are aspects of public transportation that some users consider adequate. However, the extremely low percentage of positive evaluations highlights the urgent need for reforms and significant improvements to raise the standard of service provided to the population of Manaus. This result reinforces the need for structural reforms and is consistent with studies indicating that public transportation in Manaus performs below that of other Brazilian state capitals. The study by [69], conducted over a five-year period, had already reported that the quality of public transportation in the Manaus region is considerably lower than that of major Brazilian capitals, given that urban mobility lacks sustainable technologies and planning capable of meeting the needs of the population of Amazonas. Furthermore, the unplanned growth of the city of Manaus makes it difficult for public policies to adequately meet the social demand for public transportation.

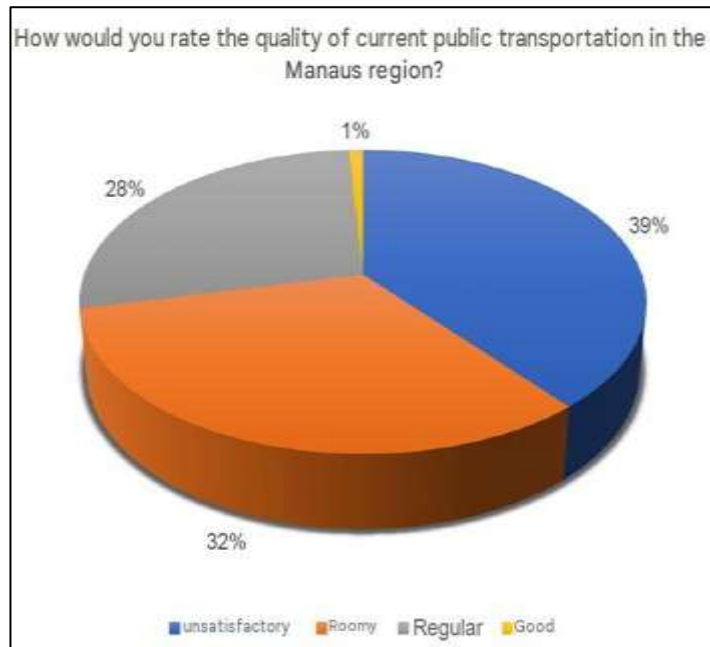


Figure 13: How would you rate the quality of public transportation in the Manaus region today?
Source: Authors, (2026).

Regarding the improvements needed (Figure 14), the following stand out: safety (21%), use of technology (19%), fleet expansion and improved maintenance (16%), modal integration (15%), and fare reduction (12%). Integration with other modes of transportation, such as bicycles and vessels, can expand mobility options, facilitate access to different areas, and promote the use of more sustainable means of transportation. The relevance of modal integration is particularly important for this research, as it indicates users' openness to solutions that connect different modes of transportation, including river transportation. This finding is consistent with contemporary approaches to sustainable urban mobility, which advocate for integrated and multimodal systems [35]. Furthermore, according to [67], the lack of transportation alternatives, such as metro systems or Bus Rapid Transit (BRT), limits citizens' options and places additional pressure on the current system.

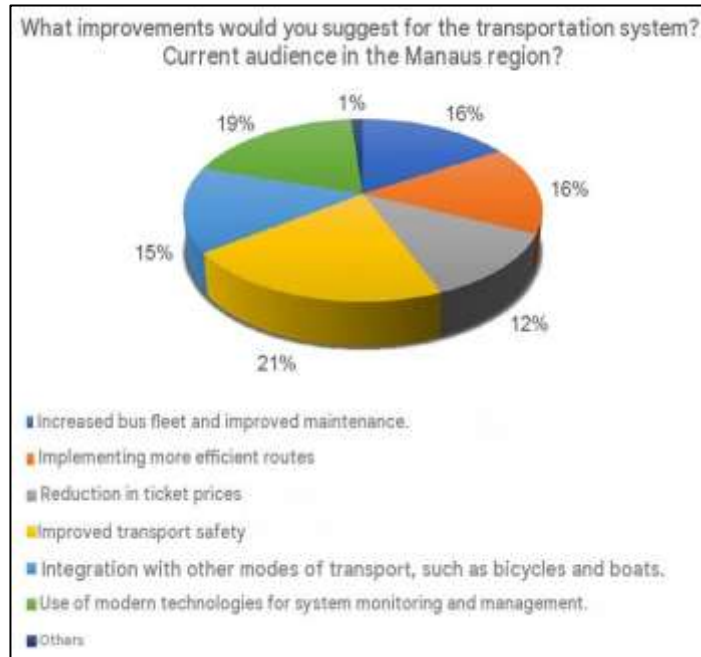


Figure 14: What improvements would you suggest for the current public transportation system in the Manaus region?
Source: Authors, (2026).

Finally, the use of river vessels was analyzed (Figure 15). The results indicate that 80% of respondents had previously used this mode of transportation, highlighting its importance for regional mobility. This finding confirms the literature on the Amazon, which emphasizes river transportation as a structuring element of the regional urban network [61]. However, 20% of respondents had not used this mode of transportation. This group may include individuals who live in areas with easier access to other modes of transportation or who simply have not had the need or opportunity to use river vessels. The results underscore the relevance of river vessels in the region and the need to continue investing in improvements and innovations, such as the implementation of solar energy systems, to increase the efficiency and sustainability of river transportation. The high usage rate suggests that any improvements in this sector could have a significant and positive impact on the lives of a large portion of the population.

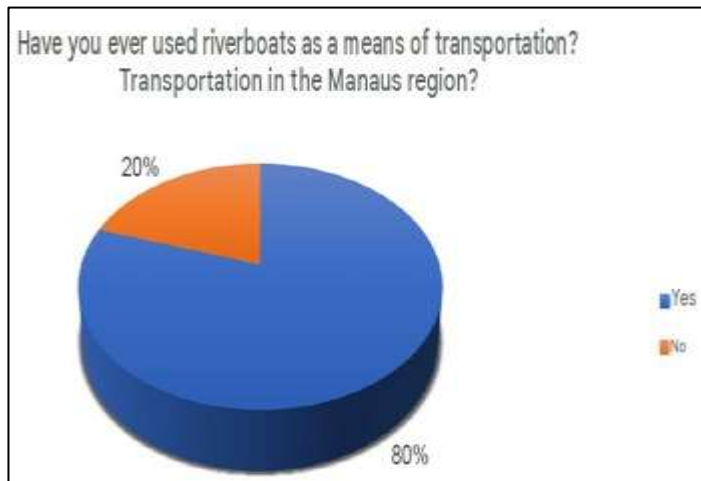


Figure 15: Have you ever used riverboats as a means of transportation in the Manaus region?
Source: Authors, (2026).

IV.4.2 Climatic and technological conditions in the region to determine the feasibility and efficiency of using solar energy in river vessels

Participants' perceptions regarding the feasibility of using solar energy in river vessels were analyzed (Figure 16). The results indicate that 96% consider this technology feasible, demonstrating a high level of social acceptance. This finding is consistent with studies on solar energy potential in the Amazon region, which highlight the technical feasibility of photovoltaic energy in regions with high solar irradiation [28], [18]. The 4% who disagreed may point to concerns related to costs, maintenance, and efficiency under adverse climatic conditions. These concerns are recurrent in the literature on the adoption of energy technologies and reinforce the importance of considering technical and economic factors when implementing sustainable solutions [31]. The reasons for this disagreement may include concerns about the high initial implementation costs, the maintenance and durability of solar energy systems, as well as energy efficiency during periods of low solar irradiation, such as rainy or cloudy days. Thus, while the majority perceive solar energy as a promising solution, it is essential to address the concerns of those who still have doubts to ensure a fair and effective transition toward sustainable technologies. Therefore, the results demonstrate not only the technical potential of solar energy in the region but also strong social acceptance, a fundamental factor for the success of energy transition initiatives in the transportation sector.

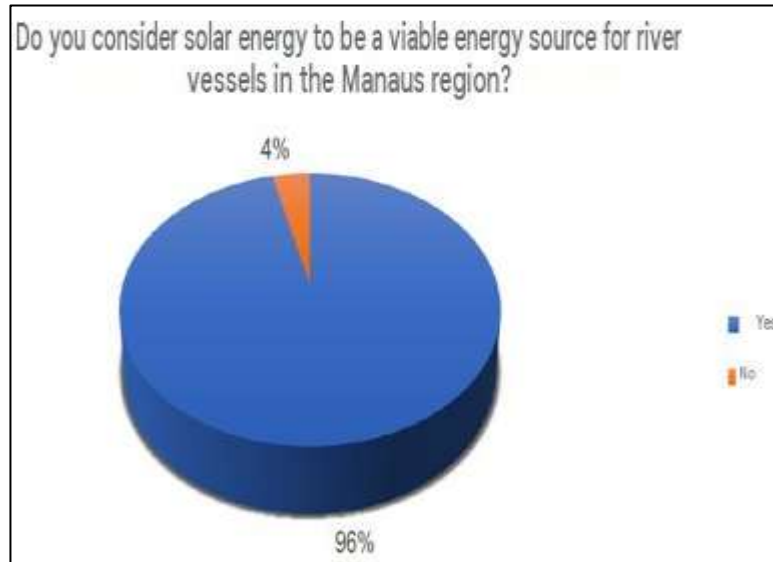


Figure 16: Do you consider solar energy to be a viable energy source for river vessels in the Manaus region?
Source: Authors, (2026).

Subsequently, participants were asked to assess the technical feasibility of using solar energy in river vessels in the Manaus region (Figure 17). The results indicate that 61% of respondents gave the highest rating (score 5), demonstrating a strongly positive perception of the technical feasibility of the proposed solution. Additionally, 20% assigned a score of 4, reinforcing the favorable trend. These data suggest a high level of confidence in photovoltaic technology, which is consistent with studies indicating the technological maturity and increasing competitiveness of solar energy in mobility applications [18], [28]. On the other hand, 12% assigned a score of 3, indicating a moderate perception, possibly associated with uncertainties regarding operational efficiency under real-world conditions. Meanwhile, 7% of respondents assigned low scores (1 and 2), revealing skepticism or a lack of information about the technology. This behavior is consistent with the literature on technology acceptance, which indicates that the adoption of new energy solutions depends on users' level of knowledge and confidence [31]. These results highlight the need for awareness-raising and information dissemination initiatives, as well as pilot projects demonstrating the feasibility of the technology under real-world conditions, thereby contributing to increasing public confidence. The combination of high acceptance and areas of skepticism provides a solid basis for developing strategies to promote the broader and more efficient adoption of solar energy in river vessels in the region.

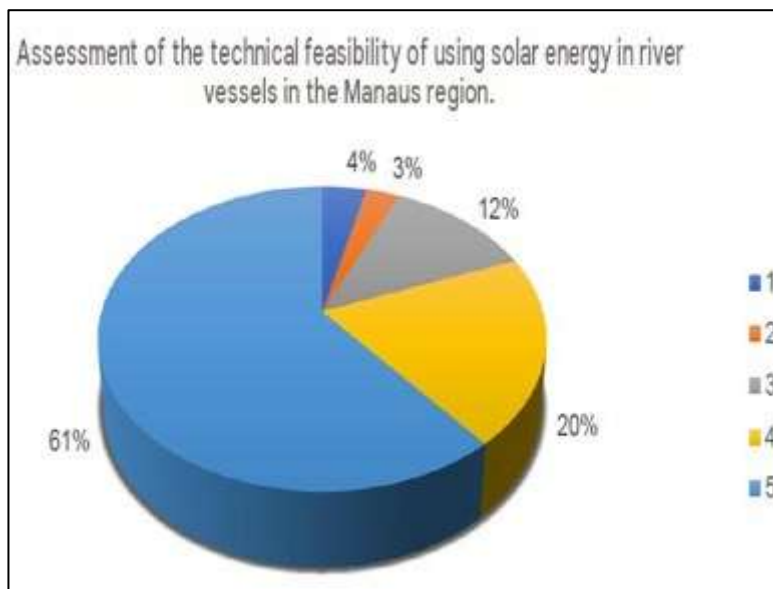


Figure 17: How do you assess the technical feasibility of using solar energy in river vessels in the Manaus region?
Source: Authors, (2026).

Subsequently, participants were asked about the main logistical challenges associated with implementing solar-powered vessels (Figure 18). The installation of charging infrastructure was identified by 21% of respondents as the main challenge, highlighting the importance of establishing support systems for vessel operations. The literature on electric mobility reinforces that infrastructure availability is one of the main factors influencing the adoption of new energy technologies [30]. Adaptation to climatic conditions was mentioned by 17% of participants, reflecting concerns about the environmental variability of the Amazon region. Indeed, although the region has high solar energy potential, factors such as cloud cover and precipitation may affect system efficiency [18]. Travel regularity (16%) and vessel construction/maintenance (16%) were also identified as relevant challenges, indicating the need for robust technical solutions and efficient system management. Travel regularity is considered essential for user confidence and the planning of daily activities.

Ensuring that solar-powered vessels can maintain their schedules consistently requires efficient energy management and rigorous logistical planning. The training of specialized personnel (12%) reinforces the importance of local capacity building, an element frequently identified as critical to the implementation of innovative energy technologies [31]. The operation and maintenance of solar-powered vessels require specific technical knowledge that may not be widely available in the region. Therefore, investing in qualification and specialized training programs is essential to overcoming this obstacle.



Figure 18: In your opinion, what are the main logistical challenges for the implementation of solar-powered river vessels?
Source: Authors, (2026).

Other factors (2%), such as river seasonality and vessel characteristics, highlight the complexity of the Amazonian context and the need for solutions adapted to local conditions. In this context, the seasonal variation between low- and high-water periods is particularly relevant, as are the production of inputs in the Manaus Industrial Complex, issues related to vessel size and materials, and whether off-grid or hybrid systems will be used. These additional factors highlight the complexity and multifaceted nature of the challenges involved in implementing a solar-powered river transportation system.

IV.4.3 Local Community Perception

To assess the community's perception of the implementation of solar-powered river vessels, participants were asked whether this system could improve urban mobility (Figure 19). The results indicate that 80% of respondents believe that the solution would contribute to improving mobility, demonstrating strong social support. This finding is consistent with studies that identify sustainable mobility as a key element in improving urban quality of life [11]. The 19% who answered "maybe" indicate the need for greater clarification regarding the practical feasibility of the proposed solution. These respondents may still have doubts or require more information about the feasibility and effectiveness of a solar-powered river transportation system, while only 1% expressed rejection. This small group may have specific concerns regarding the technical, financial, or logistical challenges that could arise during the transition to a solar-powered transportation system.

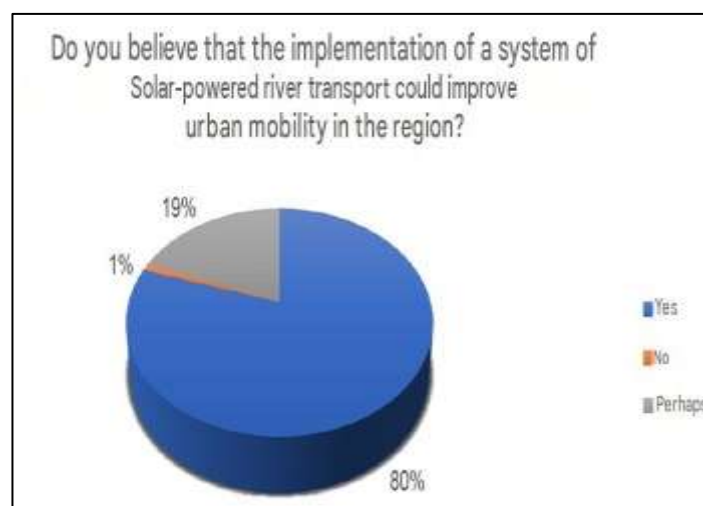


Figure 19: Do you believe that implementing a solar-powered river transportation system could improve urban mobility in the region?
Source: Authors, (2026).

Regarding willingness to use the system (Figure 20), 90% of respondents stated that they would use solar-powered vessels. This finding is particularly relevant because it demonstrates a high potential for adoption, a critical factor for the success of sustainable mobility policies [31]. The willingness to use this mode of transportation suggests that there is significant potential for its successful integration into the urban mobility system of Manaus. On the other hand, only 10% of respondents stated that they would not be willing to use solar-powered river vessels, which may be related to issues such as reliability, comfort, convenience, or simply resistance to change.

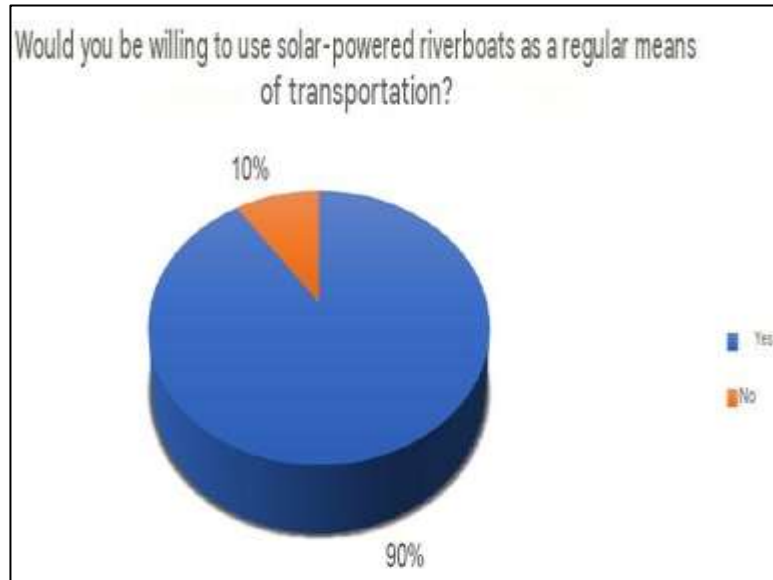


Figure 20: Would you be willing to use solar-powered riverboats as a regular means of transportation?
Source: Authors, (2026).

When asked about the community's reaction (Figure 21), the results show a diversity of perceptions: 33% condition their support on the existence of tangible improvements, while 30% express enthusiasm. Other groups raise concerns related to costs, reliability, and changes in transportation habits. A total of 15% of respondents expressed concern about the initial costs. Additionally, 9% believe that the community would react with skepticism due to the novelty of the technology. The introduction of new technologies may raise doubts about their effectiveness and reliability, particularly if the population is not familiar with the benefits and operation of solar-powered vessels. On the other hand, 7% of respondents stated that the community's reaction would be one of resistance due to changes in transportation habits. Meanwhile, 6% responded that the community would react with indifference, perceiving no major changes. This group may not fully understand the significant impact on their daily routines or may be less interested in environmental and technological issues. This behavior is consistent with the literature on technological innovation, which highlights that social acceptance depends on the perception of tangible benefits, confidence in the technology, and cultural adaptation [35].

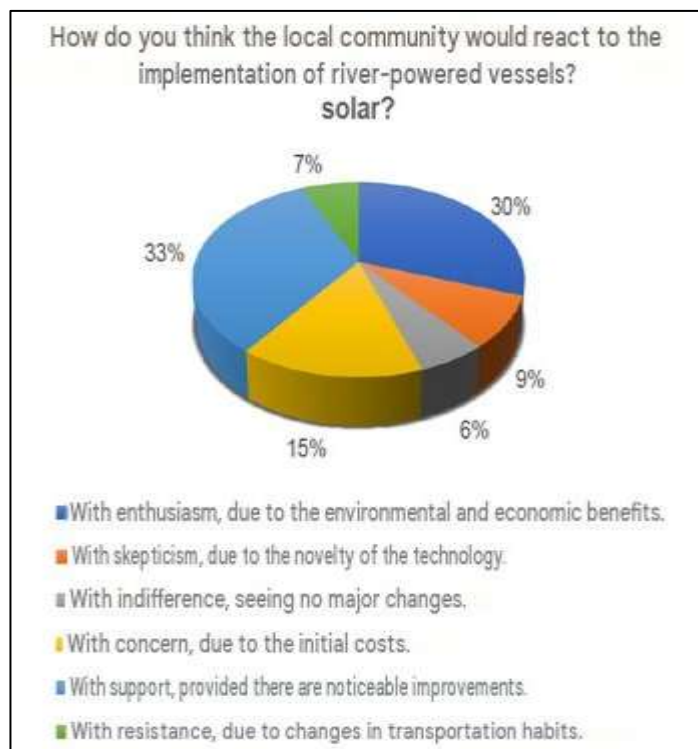


Figure 21: How do you think the local community would react to the introduction of solar-powered riverboats?
Source: Authors, (2026).

Regarding concerns (Figure 22), the initial cost (26%) emerges as the main factor, followed by maintenance (18%), climate dependence (17%), and operational capacity (16%). These results reinforce that the feasibility of renewable energy projects depends on a balance between technical and economic factors [18]. Analyzing the response groups in greater detail, 18% stated that maintenance and vessel durability are concerns, given the need to ensure that the vessels are reliable and sustainable in the long term, with maintenance costs that do not compromise the economic feasibility of the project.

Meanwhile, 17% of respondents highlighted dependence on the region's climatic conditions as a concern, since the efficiency of solar energy systems can be affected by climatic factors such as periods of rainfall and cloud cover, which are common in the Amazon region. For 16%, transportation capacity and trip frequency are concerns, as it is necessary to ensure that the vessels can meet the population's demand, with sufficient capacity and frequent schedules to ensure acceptance and the success of the transportation system. Another 14% expressed concerns about acceptance by the local community itself, highlighting apprehension regarding public receptiveness to new technologies and the changes required in transportation habits.

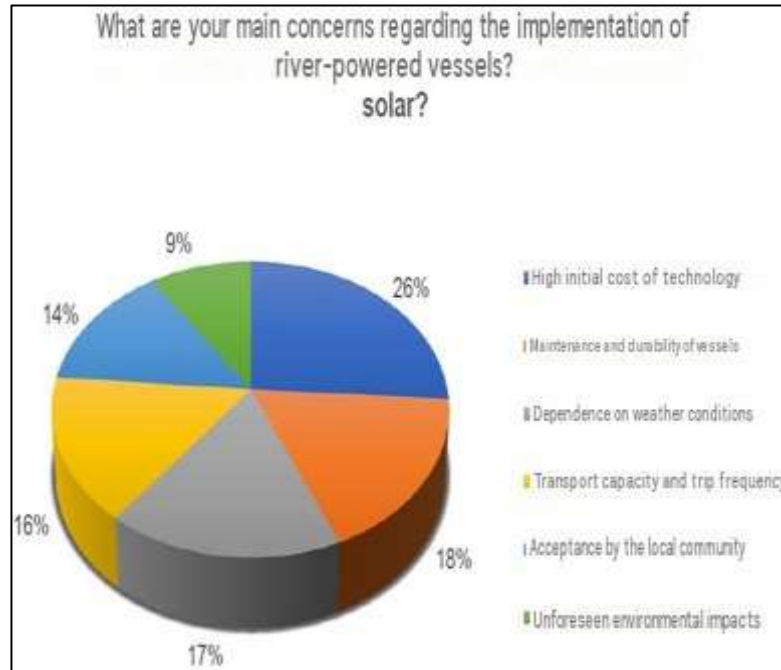


Figure 22: What are your main concerns regarding the implementation of solar-powered river vessels?
Source: Authors, (2026).

IV.4.4 Technical, Logistical, And Economic Aspects

Regarding perceptions of costs (Figure 23), 87% of respondents believe that the use of solar-powered vessels could reduce transportation costs. This finding reflects a positive expectation among residents that the adoption of sustainable and renewable technologies would not only contribute to environmental preservation but also provide economic benefits. Reductions in operating costs, such as fuel and maintenance expenses, could be passed on to users in the form of more affordable fares, making river transportation more economical and attractive. This expectation is consistent with studies indicating that renewable energy-based systems have lower long-term operating costs due to reduced fossil fuel consumption [18]. On the other hand, 13% expressed skepticism, reflecting concerns about the initial investment and economic feasibility, aspects frequently highlighted in the literature as barriers to the adoption of clean technologies [31]. This group may have concerns about the initial investments required for the installation of solar technologies, support infrastructure, or specialized maintenance that may be necessary. In addition, there may be doubts regarding the operational efficiency and long-term financial return of these vessels.

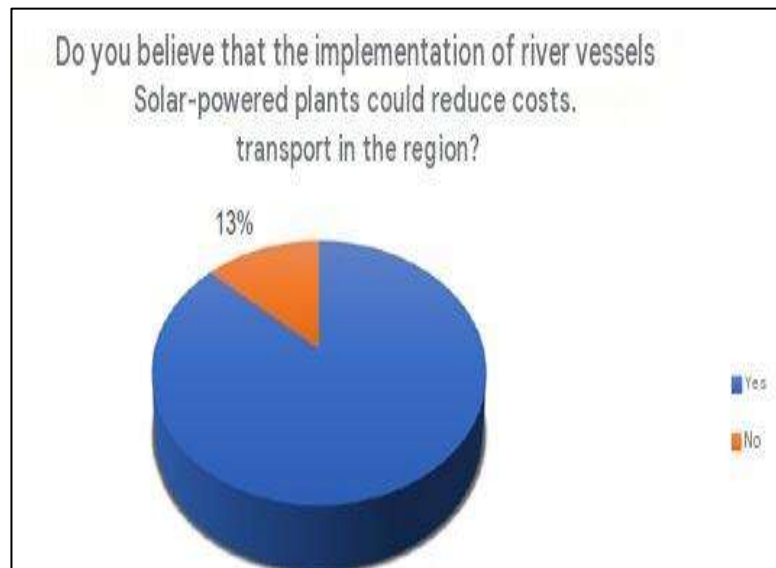


Figure 23: Do you believe that the introduction of solar-powered river vessels could reduce transportation costs in the region?
Source: Authors, (2026).

Regarding the impact on tourism (Figure 24), 90% of participants believe that the implementation of solar-powered vessels could attract more visitors. This finding suggests that sustainability can act as a factor of territorial differentiation, contributing to local economic development. The adoption of solar-powered vessels not only demonstrates a commitment to sustainability and environmental preservation but also offers visitors a distinctive and environmentally friendly experience. The implementation of these vessels could become an additional attraction, positioning Manaus as a destination that combines natural beauty with technological innovation. On the other hand, 10% of respondents stated that they do not believe that solar-powered vessels would attract more tourists. This group may have concerns about the vessels' reliability and comfort, or may believe that other factors, such as tourism infrastructure, services, and promotion, are more decisive in increasing tourism in the region.

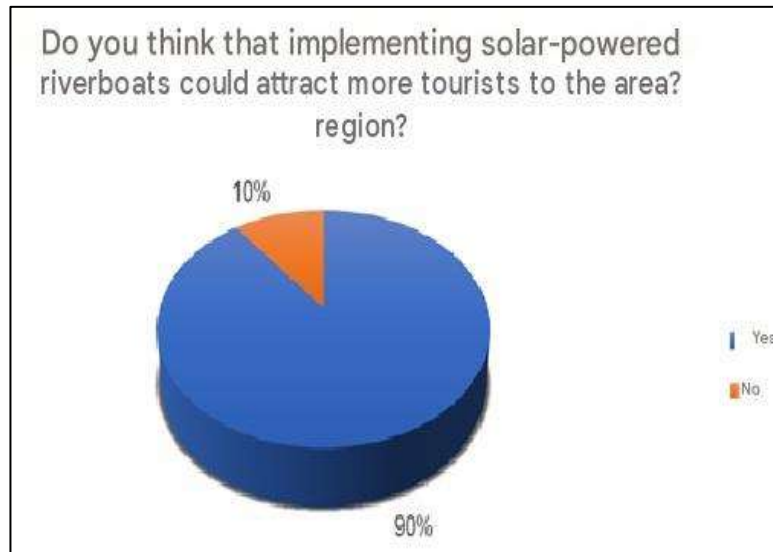


Figure 24: Do you think that the introduction of solar-powered riverboats could attract more tourists to the region?
Source: Authors, (2026).

Regarding the willingness to pay more (Figure 25), 78% of respondents expressed acceptance, indicating that they value the environmental benefits. The willingness to pay an additional amount suggests that the population recognizes long-term benefits, such as reduced pollution and the promotion of a greener economy, and is committed to environmental preservation. This behavior is consistent with studies on sustainable consumption, which indicate a growing willingness to pay for environmentally responsible solutions [41].

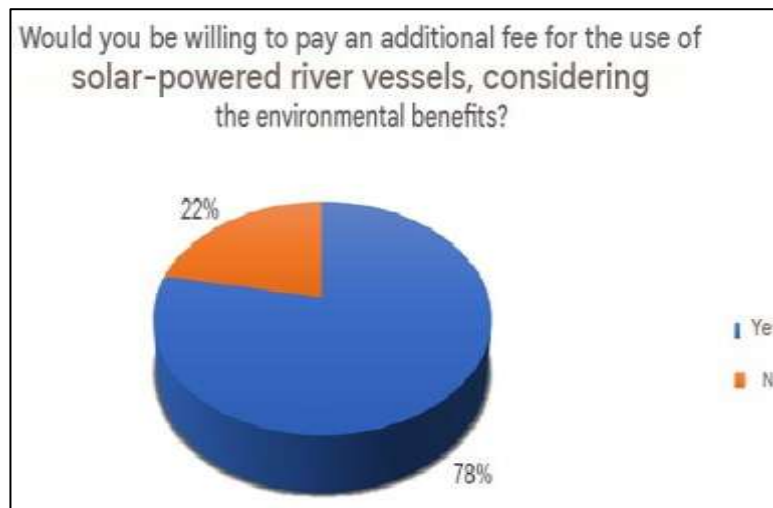


Figure 25: Would you be willing to pay extra to use solar-powered riverboats, given the environmental benefits?
Source: Authors, (2026).

However, 12% of respondents stated that they would not be willing to pay an additional amount, which may be related to financial constraints or the need to maintain affordable fares for the population. This finding demonstrates that sustainability must be associated with economic feasibility and social inclusion. Among the main perceived environmental benefits (Figure 26), the following stand out: the use of renewable energy (21%), reduction in emissions (19%), and promotion of sustainability (19%). These results demonstrate participants' recognition of the environmental benefits of solar energy, which is considered important for mitigating climate change [70]. In addition, 16% highlighted reduced dependence on fossil fuels, such as diesel and gasoline, while 13% pointed to reduced water pollution and 12% to noise reduction. These benefits are particularly relevant in the Amazonian context, where the preservation of rivers and ecosystems is a fundamental concern. Overall, the results demonstrate a high level of environmental awareness among participants, who associate solar energy with pollution reduction, natural resource conservation, and the promotion of sustainable practices. According to [70], the use of renewable energy sources contributes to reducing dependence on fossil fuels and greenhouse gas emissions, promoting cleaner and more sustainable energy systems.

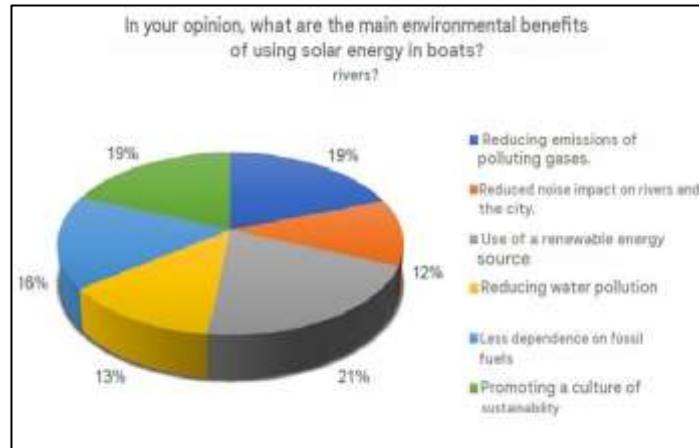


Figure 26: In your opinion, what are the main environmental benefits of using solar energy on river vessels?
Source: Authors, (2026).

Finally, the perceived economic impact was analyzed (Figure 27), reinforcing the finding that the population associates the implementation of sustainable technologies with local economic development.



Figure 27: How do you think the introduction of solar-powered river vessels might impact the local economy?
Source: Authors, (2026).

According to Figure 27, respondents perceive positive impacts from the implementation of solar-powered river vessels on the local economy. 20% highlighted the attraction of investment in sustainable technologies, while 19% pointed to an increase in sustainable tourism. The creation of direct and indirect jobs was mentioned by 16%, particularly in the shipbuilding, maintenance, operation, and tourism sectors [18]. Another 15% highlighted the reduction in operating costs associated with lower fossil fuel consumption, while 10% indicated an improvement in quality of life due to reduced pollution and noise. These results reinforce the potential of sustainability as a factor in regional development and tourism attraction [71]. Regarding the impacts on urban mobility (Figure 28), 33% considered that the main contribution would be more efficient and sustainable transportation [11]. 23% highlighted the diversification of transportation options, and 22% pointed to improved traffic flow. Another 13% identified a reduced need for road infrastructure expansion, 6% an increase in urban connectivity, and 3% a reduction in travel time. Thus, the results demonstrate a favorable perception of the potential of solar-powered river transportation to promote sustainability, economic development, and improved mobility in Manaus.

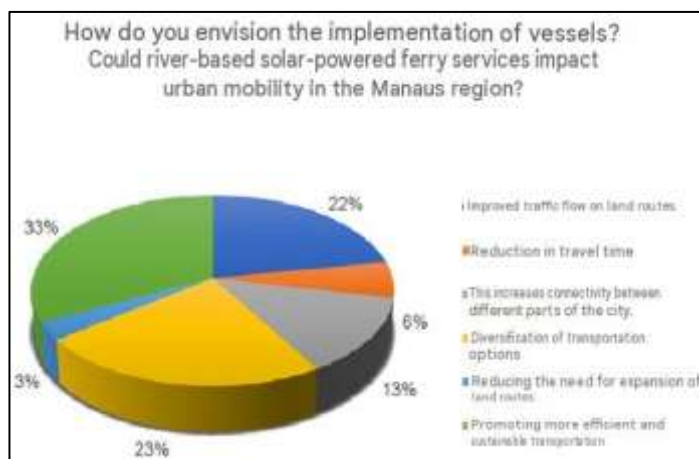


Figure 28: How do you think the introduction of solar-powered riverboats might impact urban mobility in the Manaus region?
Source: Authors, (2026).

The results presented demonstrate a broadly favorable perception among the population regarding the implementation of renewable energy-based mobility solutions, particularly solar-powered river transportation. In addition to the high level of social acceptance, the data reveal positive expectations regarding the environmental, economic, and operational impacts of the proposed solution. However, relevant concerns were also identified, particularly regarding initial costs, maintenance, infrastructure, and operating conditions. These aspects indicate that, although there is a favorable context for implementing the proposed solution, its feasibility depends on a more in-depth analysis integrating technical, institutional, and socioeconomic factors. Therefore, the following section discusses the results obtained by linking the empirical data with the theoretical framework of the research and identifying strategic implications for the development of a sustainable river transportation system in Manaus.

IV.5 DISCUSSION OF RESULTS AND IMPLICATIONS

‘The survey results demonstrate a favorable perception among the population toward the implementation of renewable energy-based mobility solutions, particularly in river transportation. This acceptance is fundamental to the energy transition, since the adoption of new technologies depends on users’ confidence and perception of their usefulness [31]. The high level of public transportation use, combined with dissatisfaction with service quality, reveals a mobility system under pressure and reinforces the need for structural and integrated solutions [67]. The importance attributed to reducing environmental impacts (98%), acceptance of solar energy (96%), and willingness to use sustainable vessels (90%) demonstrate a favorable social context for the adoption of clean technologies. However, challenges related to initial costs, maintenance, infrastructure, and climate dependence remain. Implementation requires charging stations, energy management, and coordination among technology, infrastructure, and governance [35]. Finally, the high level of river transportation use (80%) confirms its strategic importance for Manaus, reinforcing the need to modernize and integrate this mode into sustainable mobility policies [61].

IV.5.1 SWOT Analysis of the Implementation of Solar-Powered River Transportation

Based on the survey results and the literature reviewed, a SWOT analysis was developed to assess the internal and external conditions associated with implementing a solar-powered river transportation system in Manaus. This tool makes it possible to systematize factors that may facilitate or hinder the adoption of the proposed solution. Among the strengths, the extensive Amazonian river network stands out, facilitating connectivity between urban areas and riverside communities. In addition, the population’s tradition and high level of use of river transportation may facilitate the acceptance of new technologies [61]. The use of this mode can also reduce pressure on the road transportation system, contributing to the diversification of urban mobility [11]. Another favorable factor is the potential for harnessing solar energy, considering the region’s solar irradiation conditions [18]. Among the weaknesses, the limitations of port infrastructure, lack of standardization, and accessibility difficulties stand out, compromising system efficiency [72]. The predominance of fossil-fuel-powered vessels, many of them old and with low energy efficiency, also makes modernization more difficult [73].

Other challenges include the informality of some operators, limited oversight, irregular schedules, and limited integration with other modes of transportation. Regarding opportunities, advances in energy transition and decarbonization policies favor the adoption of clean technologies [30]. Integrating river transportation with electric buses, bicycle lanes, and intelligent transportation systems can contribute to more efficient mobility [35]. Sustainable tourism also represents an opportunity, as do the establishment of public-private partnerships and access to financing mechanisms aimed at infrastructure and innovation [18]. Among the main threats, extreme hydrological events, such as droughts and floods, stand out because they can affect navigability and operational regularity [74]. Competition with informal operators may compromise the safety and economic viability of the system. In addition, the high initial costs of vessels and infrastructure constitute barriers to the energy transition [31]. Finally, institutional instability and discontinuity in public policies may hinder the maintenance of long-term projects. Figure 29 highlights the main elements of the SWOT analysis discussed above.

	POSITIVE FACTORS	NEGATIVE FACTORS
External	Strengths • Extensive navigable hydrographic network, allowing high connectivity between neighborhoods, municipalities, and riverside communities. • Historical and cultural tradition of river transport in the Amazon region. • Reducing pressure on the land-based road system, thus alleviating congestion. • High potential for incorporating solar energy, given the annual radiation regime. • Capacity to serve areas with no efficient or non-existent road access.	Weaknesses • Insufficient and poorly standardized port infrastructure (terminals, piers, accessibility). • Fleet predominantly powered by diesel, with high operating costs and environmental impact. • The frequency of informal operators reduces security and institutional control. • Poor schedule regularity and lack of integrated route planning. • Old vessels, with low energy efficiency and technological limitations.
	Opportunities • National and international public policies on energy transition and decarbonization. • Intermodal integration with electric buses, bike paths, BRT tourist transport. • Expansion of ecotourism, which favors sustainable boats. • Possibility of Public-Private Partnerships (PPPs) for fleet renewal and infrastructure. • Access to international financing (IDB, World Bank, European Union) for sustainable mobility in the Amazon.	Threats • Extreme hydrological events (severe droughts or historic floods) that can compromise navigability. • Competition from illegal river transport is affecting safety and economic viability. • High initial costs for deploying solar or hybrid vessels. • Potential environmental impacts resulting from poor operating or maintenance practices. • Political instability and a lack of administrative continuity can disrupt sustainable projects.

Figure 29: SWOT analysis of the implementation of solar-powered river transportation in the Manaus Metropolitan Area.

Source: Authors, (2026).

The SWOT analysis demonstrates that implementing a solar-powered river transportation system in Manaus has significant strategic potential, supported by favorable natural conditions, social acceptance, and alignment with global sustainability trends. However, the effectiveness of this solution depends on overcoming structural, institutional, and technological challenges, as well as on the ability to coordinate different public and private stakeholders. Integration among urban mobility policies, energy planning, and sustainable development is essential to transform the identified opportunities into concrete solutions. Thus, the SWOT analysis reinforces the relevance of the proposal developed in this research, demonstrating that the transition toward sustainable river mobility systems can significantly contribute to the urban and environmental development of the city of Manaus.

IV.6 PROPOSED SOLUTION AND CONCEPTUAL MODEL

Based on the empirical results obtained and the theoretical analysis developed throughout the research, the implementation of an integrated sustainable river mobility system in the city of Manaus is proposed, based on the use of solar-powered vessels with battery storage and, as a complementary possibility to be evaluated in future studies, hybrid systems using green hydrogen. The proposal is grounded in the concept of integrated urban energy systems, in which mobility, energy production, and urban management are addressed in an integrated manner [30]. In this model, river transportation assumes a structuring role, functioning as a complementary axis to the road transportation system and contributing to reducing pressure on land-based infrastructure. The proposed conceptual model integrates four main components:

A. Sustainable River Infrastructure

- a. modernization of ports and docking facilities;
- b. creation of energy charging stations;
- c. integration with urban systems.

B. Renewable Energy System

- a. use of photovoltaic solar panels;
- b. battery energy storage;
- c. future assessment of hybrid systems using green hydrogen as a backup.

C. Integrated Mobility System

- a. coordination between river and road transportation;
- b. modal integration (buses, bicycles, etc.);
- c. intelligent route management.

D. Governance and Social Acceptance

- a. community engagement;
- b. local technical training;
- c. public-private partnerships.

V. CONCLUSIONS

This research enabled an analysis of the potential for integrating solar energy into public river transportation in the Metropolitan Region of Manaus, considering the environmental, technological, economic, and social dimensions. The results demonstrate that river transportation has strategic importance for mobility and territorial integration in the Amazon, particularly given the extensive river network and limitations of road infrastructure. However, the strong dependence on fossil fuels in vessels contributes to high operating costs, atmospheric emissions, and environmental impacts, highlighting the need for more sustainable alternatives. In this context, the use of electric propulsion systems associated with solar energy generation emerges as a promising alternative for the energy transition of the sector. Replacing conventional diesel-powered engines can reduce fossil fuel consumption, greenhouse gas emissions, air pollution, and noise levels. Additionally, lower dependence on fuels may reduce operating and maintenance costs, contributing to greater economic efficiency of vessels in the medium and long term. However, implementing this technology requires attention to the specific characteristics of the Amazonian region. Factors such as photovoltaic panel capacity, energy storage, battery autonomy, motor power, vessel weight, and route characteristics must be analyzed in an integrated manner. River seasonality, with periods of flooding and drought, is also a relevant factor for the system's sizing and operation. The results also demonstrate favorable social perceptions regarding the adoption of renewable energy in river transportation. This receptiveness represents an important condition for the implementation of new technologies, although issues related to safety, comfort, fares, accessibility, and service quality must also be considered. It can be concluded that integrating solar energy into river transportation has the potential to make a significant contribution to cleaner, more efficient, and more resilient mobility in Manaus. However, its implementation depends on public policies, infrastructure investments, technical training, financing, and integrated planning. Therefore, pilot projects and technical-economic feasibility studies are recommended to assess the actual performance of vessels under different operating conditions. In this way, solar energy may become a viable alternative for modernizing river transportation and contributing to the energy transition and sustainable development of the Amazonian region.

VI. AUTHOR'S CONTRIBUTION

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