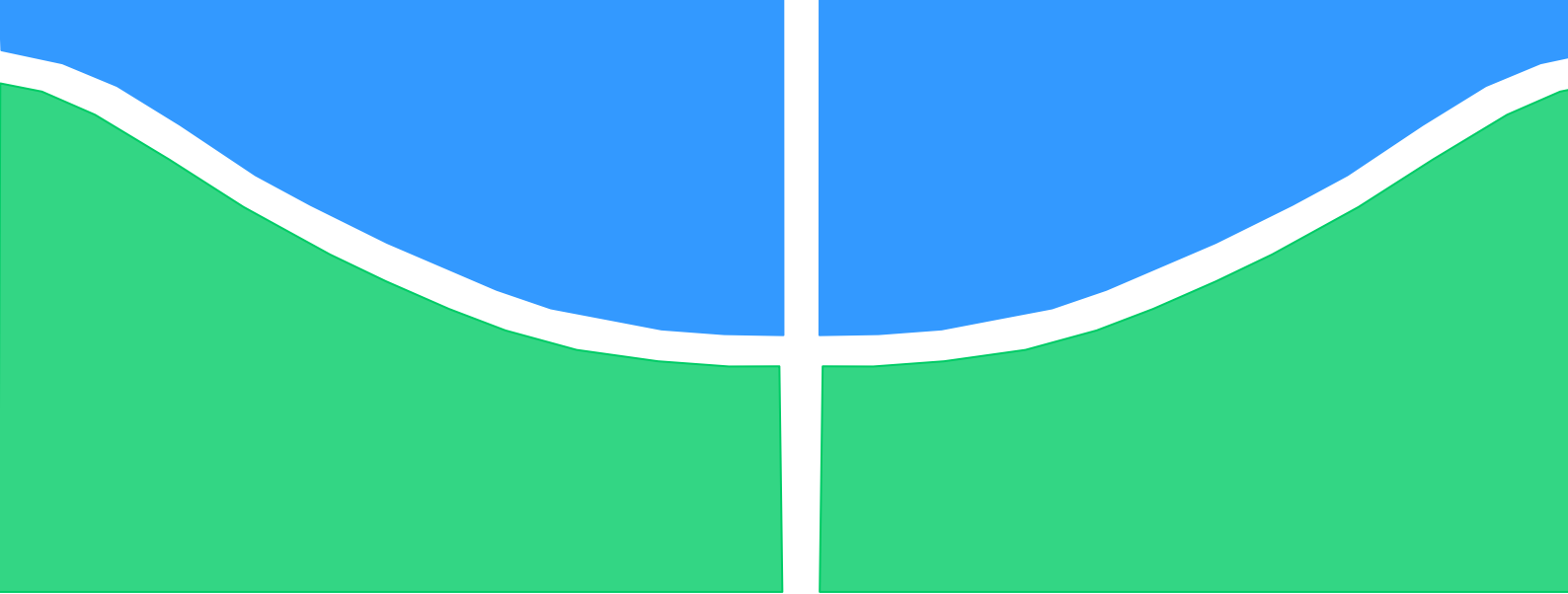




University of Brasília – UnB
Faculty of Technology
Postgraduate Program in Mechanical Sciences

**Decarbonization Pathways for Remote Amazonian
Communities: Life Cycle Assessment and Carbon
Dynamics of Wood Waste-Based Bioenergy System**

Author: Paloma Fachinelli de Oliveira
Advisor: Prof. Dr. Edgar Amaral Silveira

Brasília, DF
2025



Paloma Fachinelli de Oliveira

Decarbonization Pathways for Remote Amazonian Communities: Life Cycle Assessment and Carbon Dynamics of Wood Waste-Based Bioenergy System

Dissertation submitted as a requirement for
obtaining the Master's degree in Mechanical
Sciences.

University of Brasília – UnB
Faculty of Technology

Advisor: Prof. Dr. Edgar Amaral Silveira

**Brasília, DF
2025**

CIP – Catalogação Internacional da Publicação*

Orientação: Edgar Amaral Silveira.

Dissertação de Mestrado – Universidade de Brasília - UnB
Faculdade de Tecnologia, 2025.

1.Avaliação de Ciclo de Vida. 2. Bioenergia. 3. Sistemas Isolados. I. Prof. Dr.
Edgar Amaral Silveira. II. Universidade de Brasília. III. Faculdade de Tecnologia.
IV.

Paloma Fachinelli de Oliveira

Decarbonization Pathways for Remote Amazonian Communities: Life Cycle Assessment and Carbon Dynamics of Wood Waste-Based Bioenergy System

Dissertation submitted as a requirement for obtaining the Master's degree in Mechanical Sciences.

Prof. Edgar Amaral Silveira, UnB/ FT
Advisor

Prof. Alexandre Betinardi Strapasson, UnB/ CDS
Member

Dr. Thiago Oliveira Rodrigues, IBICT
Member

Prof. Thiago de Paula Protásio, UFLA/ DCF
Member

Brasília, DF
2025

ACKNOWLEDGMENT

I have always believed that engineering should have a purpose and a positive impact on someone's life. Therefore, developing a master's dissertation just for its own sake was never my goal. I hope that this work can impact the quality of life of communities and perhaps be a small part of the contribution to the fight against climate change.

That is why I am grateful to my advisor for having the sensibility to understand my profile and my beliefs. Thank you for listening to me and being supportive. This journey was easier with your guidance and knowledge.

To my father, thank you for all the advice. That afternoon at the bookstore was one of the decisive moments for the progress of my master's degree. I am very proud of you.

Mom, you are my role model. Without knowing, you show me what it means to persist.

To my partner, thank you so much for accompanying me when I thought about giving up because my beliefs no longer made sense. They actually do. This work is proof of that.

UM CAMINHO PARA DESCARBONIZAR COMUNIDADES REMOTAS DA AMAZÔNIA COM SOLUÇÕES DE BIOENERGIA SUSTENTÁVEIS: AVALIAÇÃO DO CICLO DE VIDA E PERSPECTIVAS DO MERCADO DE CARBONO

RESUMO

As atividades humanas perturbaram profundamente os sistemas climáticos e ecossistemas da Terra, levando a uma aceleração sem precedentes nas emissões de carbono. Este estudo analisa o modelo de desenvolvimento sustentável de Ignacy Sachs, com ênfase no conceito “*B-cube*”, biomassa, biodiversidade e biotecnologia, ao aproveitar resíduos florestais do manejo florestal sustentável (MFS) para a produção de bioenergia. O norte do Brasil, com mais de 190 sistemas isolados de energia altamente dependentes de diesel, enfrenta desafios ambientais e socioeconômicos significativos. Esta pesquisa investiga se a integração de sistemas de bioenergia em mercados emergentes de carbono pode oferecer uma solução escalável e sustentável para a descarbonização dessas regiões remotas. Usando resíduos de MFS, os sistemas de bioenergia foram avaliados em Manicoré e Lábrea por meio de uma Avaliação do Ciclo de Vida (ACV) do tipo “*gate-to-grave*”. A análise revelou que sistemas de bioenergia podem alcançar impactos de 117,39 kg CO₂-eq por MWh, em comparação com emissões de 1.200 kg CO₂-eq por MWh nos sistemas à base de diesel, destacando seu potencial para a neutralidade de carbono. Os principais resultados indicam que a integração da bioenergia em mercados de carbono, como o programa RenovaBio do Brasil, pode gerar incentivos financeiros, com valores projetados de créditos de carbono esperados de R\$ 124,06 por tonelada de CO₂-eq em 2023. No âmbito social, a transição para bioenergia poderia beneficiar mais de 1.500 famílias nas cidades de Lábrea e Manicoré, melhorando o acesso à energia e promovendo o desenvolvimento econômico local. Este trabalho demonstra que sistemas de bioenergia oferecem um caminho sustentável e escalável para descarbonizar sistemas isolados na Amazônia, ao mesmo tempo em que apresentam potencial no mercado de carbono. Abordar a desigualdade energética e aproveitar incentivos econômicos pode avançar na sustentabilidade ambiental e no alcance das metas climáticas globais.

Palavras-chave: Resíduos de madeira amazônico; Sistemas isolados; Gestão florestal sustentável; Transição energética justa; Avaliação de emissões.

ABSTRACT

Human activities have profoundly disrupted Earth's climate systems and ecosystems, leading to an unprecedented acceleration in carbon emissions. This study examines Ignacy Sachs's sustainable development model, emphasizing the "*B-cube*" concept: biomass, biodiversity, and biotechnology, by leveraging forest residues from sustainable forest management (SFM) for bioenergy production. Northern Brazil, home to over 190 isolated energy systems heavily reliant on diesel, faces significant environmental and socioeconomic challenges. This research investigates whether integrating bioenergy systems into emerging carbon markets can provide a scalable and sustainable solution for decarbonizing these remote regions. Using SFM residues, bioenergy systems were assessed in Manicoré and Lábrea through a "gate-to-grave" Life Cycle Assessment (LCA). The analysis revealed that bioenergy systems can achieve a carbon impact of 117.39 kg CO₂-eq per MWh, compared to emissions of 1,200 kg CO₂-eq per MWh from diesel-based systems, highlighting their potential for carbon neutrality. Key findings indicate that integrating bioenergy into carbon markets, such as Brazil's RenovaBio program, could generate financial incentives, with projected carbon credit values expected to rise from R\$ 124.06 per tonne CO₂-eq in 2023. On the social front, transitioning to bioenergy could benefit over 1,500 families in Lábrea and Manicoré cities by enhancing energy access and fostering local economic development. This work demonstrates the concept that bioenergy systems offer a sustainable and scalable pathway for decarbonizing isolated systems in the Amazon while also holding potential within the carbon market. Addressing energy inequity and leveraging economic incentives can advance environmental sustainability and achieve global climate goals.

Keywords: Amazon wood residues; Isolated systems; Sustainable Forest Management; Just energy transition; Emissions assessment.

LIST OF FIGURES

Figure 1. Overview of public policies and government actions in bioenergy production.....	24
Figure 2. Fossil fuel chain description and boundaries. Technological models of fossil fuel chain established on LCA for expert software for (b) Lábrea and (c) Manicoré cities.....	35
Figure 3. (a) Bioenergy chain description and boundaries. (b) Technological model of bioenergy chain established on LCA for expert software.	36
Figure 4. LCA results for (a) total, (b) transport and (c) power plants assessments.	50
Figure 5. Total emissions to air (a), soil (b), and water (c) per 1 MWh of electricity produced for the fossil fuel chain (Lábrea and Manicoré) and bioenergy systems.	53
Figure 6. Carbon balance for 1MWh in (a) Lábrea, (b) Manicoré, and (c) Bioenergy energy systems.....	55
Figure 7. Global warming potential (GWP) assessment of the biomass valorization route, detailing contributions from storage, transportation, power plant emissions, CO ₂ uptake, and avoided diesel emissions (ADE). Financial analysis (b) of carbon credits (in USD) and (c) CBIOS values (in BRL).	56
Figure A 1. Model for Manicoré system at GaBi	74
Figure A 2. Model for Lábrea system at GaBi	74
Figure A 3. Model for chemicals in diesel power plants at GaBi	75
Figure A 4. Model for bioenergy system at GaBi	75

LIST OF TABLES

Table 1. Overview of renewable energy studies in isolated systems across Latin America. ...	22
Table 2. Emissions factors for the storage stage of diesel considering de FU of 1 MWh.....	37
Table 3. Emissions factors for a thermal power plant supplied by diesel (adapted from (DE ALMEIDA et al., 2017)).	38
Table 4. Summary of the wood species and their physical and chemical characterization.....	39
Table 5. Emissions factors for the bioenergy plant.	41
Table 6. LCIA results for the fossil fuel (Diesel) chain for 1MWh.	44
Table 7. LCIA results for the bioenergy chain for 1 MWh.	46
Table A 1. Information sources for the inventory.	68
Table A 2. Size of the tanks of Atem company in Manaus.	69
Table A 3. Summary of the wood species and their physical and chemical characterization..	71
Table A 4. Results for each impact category described in detail in subcategories.....	76

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviations

Abiotic Depletion from fossil fuels	ADP _{fossil}
Acidification Potential	AP
Amazonas State Secretariat for the Environment	SEMA
Annual Plan for Energy Operation of Isolated Systems	PEN SISOL
Association of Extractive Producers of the Sardinha Colony	ASPACS
Avoid Diesel Emission	ADE
Benzene – Toluene – Ethylbenzene – Xylene	BTEX
Biodiversity- Biomass-Biotechnologies	<i>B-cube</i>
Biomass Residues	BR
Brazilian Emissions Trading System	SBCE
Brazilian Institute of Geography and Statistics	IBGE
Efficiency grade	EG
Brazil's Energy Research Company	EPE
Brazil's National Emissions Registration System	SIRENE
Business as usual	BAS
CO ₂ equivalent	CO ₂ -eq
Brazilian National Energy Policy Council	CNPE
Carbon Credit	CC
Carbon capture and storage	CCS
Sardinha Mixed Agroextractive Cooperative	COOPMAS
Cooperative of Agricultural Producers and Extractivists of	COPEMA
Natural Resources in Manicoré	
Decarbonization Credits	CBIOs
Global Warming Potential	GWP
Greenhouse Gas	GHG
Gross Domestic Product	GDP
Heavy Fuel Oil	HFO
Higher Heating Value	HHV
Human Toxicity Potential	HTP
National Institute for Space Research	INPE
International Panel on Climate Change	IPCC

Latin America	LATAM
Life Cycle Assessment	LCA
Life Cycle Cost	LCC
Life Cycle Inventory	LCI
Light for All	LPT
Manicoré Green Cooperative	CONEMA
Model Predictive Control	MPC
Monitoring and Information Portal for Isolated Systems	PASI
National Electric Energy Agency	ANEEL
National Economic Development Bank	BNDES
National Electric System	SEN
National Interconnected System	SIN
National Oil and Gas Agency	ANP
National System Operator	ONS
Plant Extraction and Forestry Production	PEVS
Program for Alternative Sources of Electricity Energy	PROINFA
Reducing emissions from deforestation and forest degradation in developing countries	REDD+
Social Life Cycle Assessment	SLCA
Social analysis	S
Sustainable Development Goals	SDGs
Sustainable Forest Management	SFM
The Electricity Trading Chamber	CCEE
Thermal Power Plant	TPP
Units of Conservation	UCs
Voluntary Carbon Markets	VCM
Worldwide Fund for Nature	WWF
<i>Symbols</i>	
Emission factors for diesel storage	$EF_{d,storage}$
Emission factor	EF_i
Surface area	A
Average tank height	H
CO ₂ uptake from biomass	$CO_2 \text{ uptake}$

Wood carbon content

Standard efficiency

Power production

Carbon conten

$\eta_{conversion}$

P

SUMMARY

ACKNOWLEDGMENT	7
Resumo	8
Abstract	9
LIST OF FIGURES.....	10
LIST OF TABLES	11
LIST OF ABBREVIATIONS AND ACRONYMS	12
SUMMARY	15
1. INTRODUCTION.....	17
1.1 Objectives.....	18
1.1.1 Main Objective.....	18
1.1.2 Specific Objectives.....	19
2. Research context	19
2.1 Energy Policies and Brazilian Law	24
2.2 Bioenergy: biomass and thermoelectric power plants	26
2.3 Life Cycle Assessment.....	27
3. CASE OF STUDY	29
3.1 Cities Description	29
3.1.1 Energy Consumption.....	32
3.1.2 Fuel Distribution	33
3.1.3 Wood Residues Availability And Potential	33
4. LIFE CYCLE ASSESSMENT	33
4.1 Goal And Scope Definition	34
4.2 System Description	34
4.3 Life Cycle Inventory.....	36
4.3.1 Fossil Fuel Chain.....	36
4.3.1.1 Diesel Storage.....	37
4.3.1.2 Diesel Transportation	37
4.3.1.3 Diesel Power Plant.....	38
4.3.2 Bioenergy Chain.....	38
4.3.2.1 Wood Residues Characteristics	39
4.3.2.2 Biomass Storage	40
4.3.2.3 Biomass Power Plant	40
4.4 Carbon Credits Potential	41
5. RESULTS AND DISCUSSIONS.....	43
5.1 Life Cycle Impact Assessment: Business as Usual	43
5.2 Life Cycle Impact Assessment: Bioenergy Chain	45
5.3 Comparison of Operation Modes	47
5.4 Carbon Balance.....	54

5.5	<i>Carbon Market</i>	55
6.	LIMITATIONS AND PROSPECTS	57
7.	CONCLUSIONS	58
	REFERENCES	60
	Appendix	67
	<i>Appendix 1</i>	67
	<i>Appendix 2</i>	68
	<i>Appendix 3</i>	69
	<i>Appendix 4</i>	70
	<i>ANNEX 5</i>	72
	<i>ANNEX 6</i>	74
	<i>ANNEX 7</i>	76

1. INTRODUCTION

According to Climate Watch data, humans have released approximately 954.33 Gt of CO₂ into the atmosphere in thirty years, an amount that nature took millions of years to store (WORLD RESOURCES INSTITUTE, 2022). Of the total anthropogenic emissions, 45% remain in the atmosphere, while oceans and forests capture the rest (PENA-VEGA, 2023). Human activity has altered natural cycles to such an extent that many scientists refer to the current era as the Anthropocene, a geological epoch defined by the significant and lasting impact of human actions on Earth's ecosystems, climate, and geological strata. This disruption of natural cycles underscores a profound disconnection between modern society and the ecological processes that sustain life on Earth.

In contrast to this unsustainable trajectory, Ignacy Sachs proposes a model of development based on the sustainable use of renewable resources, particularly through the concept of modern biomass (SACHS, 2009). Sachs advocates for a society that harnesses the potential of the “*B-cube*” – biomass, biodiversity, and biotechnology – by integrating the traditional knowledge of local communities with scientific innovations (SACHS, 2009).

Brazil hosts over 196 isolated systems, predominantly in remote Amazonian regions, such as Rondônia, Acre, Amazonas, Roraima, Amapá, and Pará. These areas, disconnected from the National Interconnected System (SIN), rely heavily on local diesel-based power generation, which accounts for 96% of their energy supply (PASI, 2024). This reliance poses significant challenges regarding energy costs, efficiency, and security, highlighting the need for localized solutions (ABRAMOVAY, 2022). This is especially pertinent for small-scale power plants, which often exhibit low efficiency and poor maintenance compared to the operational standards in other countries, such as the isolated systems in Canada (SADAGHIANI; MAFAKHERI; CHEN, 2023). These issues underline the problem of energy injustice (JENKINS et al., 2016) and may help explain the correlation between the lack of access to energy solutions and persistent poverty (HAMPL, 2024).

The concept proposed by Sachs was explored in this work using wood forest residues generated by Sustainable Forest Management (SFM) practices in the Brazilian Amazon. The region contains an immense variety of wood species and is primarily inhabited by traditional populations, including indigenous and riverside communities,

whose livelihoods are supported by forest products (NOBRE et al., 2023; SANTOS et al., 2025). SFM integrates selective logging and legal harvesting under Brazil's Forest Code (2012), promoting biodiversity conservation while balancing economic, social, and environmental benefits (MMA, 2006). Reduced-impact logging in the Amazon, a key aspect of SFM, adheres to guidelines that limit timber harvest to 30 m³ per hectare, with a 30-year cutting cycle and a minimum diameter at breast height (DBH) of 50 cm (CONDÉ et al., 2022; MMA, 2006). The sustainable extraction and utilization of timber products facilitate the development of a small-scale production chain. A significant byproduct of this process is forest residues, comprising sawdust, branches, and wood chips, which account for 65% of a tree's total mass and offer a substantial potential for bioenergy generation (LIMA et al., 2022).

Integrating bioenergy solutions into carbon markets presents a promising pathway for addressing environmental and economic challenges in remote communities. Policies such as RenovaBio, which leverage Decarbonization Credits (CBIOS) as a market-driven incentive for reducing greenhouse gas emissions, can encourage bioenergy adoption (HAMPL, 2024). These mechanisms promote sustainable energy transitions and align economic development with environmental goals.

In addition to addressing technical aspects of diesel dependency and bioenergy adoption, environmental considerations are crucial for evaluating the sustainability of bioenergy transitions. Life cycle assessment (LCA) provides a comprehensive evaluation of environmental performance by analyzing emissions and impacts across the entire lifecycle of energy systems (COCCO et al., 2014).

1.1 Objectives

1.1.1 Main Objective

This study objective is to comprehensively evaluate the potential of sustainable forest residue chains for bioenergy production in Amazonian isolated systems as an alternative to diesel-based energy systems. Therefore, the feasibility of the transition from fossil fuels in two cities in the North of Brazil is analyzed based on the potential of bioenergy production through sustainable forest residues.

Therefore, the novelty of this research lies in the following key contributions: i) Identification and analysis of two representative cities in the Amazon region for bioenergy transition, considering the logistical challenges of road and water

transportation of diesel; ii) Evaluation of diesel-powered energy systems, defined as the business-as-usual scenario, in the selected Amazonian municipalities; iii) Identification of forest residues from SFM to be utilized as biofuel in the bioenergy transition; iv) Development of a technological model for bioenergy systems and establishment of a life cycle inventory; v) Attributional LCA to compare diesel-powered systems with bioenergy alternatives in the context of isolated systems in the Amazon region, and vi) Potential prospects for carbon market considering the transient to bioenergy system.

1.1.2 Specific Objectives

The specific goals of this work are to:

1. Discuss to select two isolated systems in the Amazonas state following EPE plans.
2. Assess the potential of forest residues from SFM to generate bioenergy in the Lábrea and Manicoré systems.
3. Perform a life cycle assessment of thermal power plants in isolated systems powered by diesel and forest residues from SFM.
4. Identify the economic potential of bioenergy systems to generate carbon credits, offsets, and CBIOs in the Brazilian market.

2. RESEARCH CONTEXT

The concern for environmental issues began to gain traction following the end of World War II and the Hiroshima disaster (MACHADO, 2005). Subsequently, the intensive use of fossil fuels, such as coal, oil, and LPG, started being questioned during the Oil Crises of the 1970s, although in a simplistic and economically focused manner. In the following decade, the concept of sustainable development gained prominence, eventually driving a global shift in energy patterns.

Reports from the International Panel on Climate Change (IPCC) (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2023) underscore the critical role of reducing greenhouse gas emissions to mitigate climate change. Meanwhile, data published annually by Climate Watch reveal that (WORLD RESOURCES INSTITUTE, 2022), in the ten most polluting countries in the world, the energy sector is

the largest contributor to greenhouse gas emissions. Together, these tools strengthen the transition in energy patterns by promoting a shift from intensive fossil fuel consumption to cleaner energy sources, thereby mitigating environmental impacts.

In this context, a new energy transition regime, specifically the energy transition (ET), has emerged. According to WERNER; LAZARO, (2023) the energy transition can be described as a socio-technical transformation that recognizes changing an energy system as an opportunity to transform social, political, and economic structures rather than merely implementing a technological shift. However, NEWELL; PHILLIPS, (2016) conducted a socio-technical analysis of energy system changes in a Global South country, Kenya, and found that while adopting renewable energy diversifies technological options, it does so without disrupting existing power relations within the energy system.

In addition, SINGH; SINGH, (2019) analyzed the sustainability of bioenergy projects in the energy transition in Indian cities, aiming to evaluate environmental justice concepts within these models. The study reveals that technological solutions have been proposed in rigid, pre-packaged ways and are currently being guided by a framework of "weak sustainability," as green reforms are pursued primarily with the singular agenda of creating a profitable green energy market. Consequently, the concept of energy transition aligns more closely with the definition proposed by BRADSHAW; DE MARTINO JANNUZZI, (2019), which refers to transforming fossil fuel-based systems to ones with higher shares of renewable energy. Generally, it suffers economic, regulatory and intuitional disadvantages compared to fossil fuels.

As merely a shift in energy systems, the energy transition (ET) fails to address social inequalities deeply unless accompanied by *pro-poor* policies. This perspective critically discusses the intersection between energy transition and energy poverty. According to (SÁNCHEZ, 2024), in the 1990s, energy poverty was defined as families spending more than 10% of their income on energy. However, this concept is now considered outdated. In 2015, BOUZAROVSKI; PETROVA, (2015) proposed that energy poverty should be defined by factors such as energy accessibility, affordability, flexibility, energy efficiency, and the needs and practices of the population using this energy.

This updated definition better explains the reality of energy in some regions of the Global South, particularly in northern Brazil, where many communities experience energy poverty and struggle to meet basic needs such as energy, sanitation, education, and healthcare access (HAMPL, 2024). Most of these areas are categorized as isolated

systems. According to a report published by IRENA (IRENA, 2023), off-grid energy systems can be defined as systems that operate independently of the main power grid, typically use fossil fuels, such as diesel generators and often are customized and designed to provide specific and low energy needs.

Although fossil fuels predominantly power isolated systems, they can also use renewable energy technologies such as batteries, wind, biomass, hydropower, and solar. Opting for sustainable energy solutions can help communities reduce their reliance on costly and environmentally harmful fossil fuels (IRENA, 2023). Thus, studying energy transitions in off-grid systems is highly relevant to the literature. Table 1 provides a comprehensive state-of-the-art review of isolated systems in the Global South.

The literature presents an analysis of renewable energy for isolated systems in Brazil but only evaluates the energy potential of Amazon biomass (ARAÚJO et al., 2022; DE OLIVEIRA et al., 2023), hydro (HENRIQUE DA COSTA OLIVEIRA et al., 2021) and solar (SOLIANO PERREIRA; REIS; RÜTHER, 2024). On the other hand, two works developed an energy potential analysis of environmental impacts (DE ALMEIDA et al., 2017), and only one compared diesel with bioenergy from agricultural waste (MIRANDA; KULAY, 2023). However, no work has developed an analysis of bioenergy's energy potential and environmental impact from residues from SFM for isolated systems, with a social, environmental conservation and carbon market focus.

Table 1. Overview of renewable energy studies in isolated systems across Latin America. Source: Prepared by the author.

Source / Biome	Energy carrier	EP ^a	S ^b	E ^c	EC ^d	CC ^e	Contribution	Methodology	Country/ Year / Ref.
Solar / Amazon	Microgrid / off-grid	✗	✓	✗	✗	✗	Establishes a conceptual connection between the conservation of the Amazon and renewable energy	Literature and policy review	Brazil / 2024 / (HAMPL, 2024)
Biomass / Amazon	Renewable thermal	✓	✗	✗	✗	✗	Presents the availability and physicochemical properties of local Amazonian biomass residues and examines thermochemical conversion methods	Literature review	Brazil / 2022 / (ARAUJO et al., 2022)
Plywood and pinewood / Energy forest	Waste-to-energy	✓	✓	✓	✓	✗	Provides crucial evidence for policymakers, businesses, and civil society, supporting sustainable energy and water supplies by assessing the potential of CHP	LCA, LCC ^f , SLCA ^g	Mexico/ 2022 / (MARTINEZ-HERNANDEZ et al., 2022)
Diesel, Natural Gas / Amazon	Thermal power plant	✓	✗	✓	✗	✗	The first study to assess the environmental impacts of a bio-fuel thermal power plant in the Brazilian Amazon using the LCA approach and based on primary data collection. In addition, it sets a benchmark for future sustainability research in the region	LCA	Brazil / 2017 / (DE ALMEIDA et al., 2017)
Manure and straw / Amazon	Biogas	✓	✗	✓	✗	✗	Benchmarking with medium and large-scale biogas power plants worldwide to design a biogas plant tailored to the Brazilian Amazon	LCA	Brazil / 2023 / (MIRANDA; KULAY, 2023)
Solar / Amazon	Solar energy	✗	✓	✗	✗	✗	Review of public policies for isolated systems since 2000. Identify gaps in the national program and how technologies could solve them.	Survey and policy analysis	Brazil / 2024 / (SOLIANO PERREIRA; REIS; RÜTHER, 2024)
Hydro / Amazon	Small hydroelectric	✓	✗	✗	✗	✗	Framework to differentiate between theoretical, geographic, technical, and market potential for hydrokinetic energy	HK Assessment	Brazil / 2021 / (HENRIQUE DA COSTA OLIVEIRA et al., 2021)
Solar and diesel / Amazon	Power plant and photovoltaic	✓	✗	✗	✗	✗	Evaluation of the proposed system in the Amazon region of Ecuador under different load and generation scenarios	Model Predictive Control (MPC)	Ecuador / 2024 / (ARCOS-AVILES et al., 2024)
Agriculture residues / Amazon	Bioenergy	✓	✗	✗	✗	✗	Evaluates the potential of small steam turbines to reuse residual biomass from local agricultural activities	Experimental analysis	Brazil / 2023 / (DE OLIVEIRA et al., 2023)

Diesel and Amazon forest residues / Amazon	Power plants and bioenergy	✓	✗	✓	✗	✓	Comprehensive analysis of the environmental impacts, energy potential, and carbon market dynamics associated with the bioenergy and diesel supply chain. Additionally, it examines the social implications of transitioning isolated systems towards more sustainable energy solutions.	LCA	Brazil / Study
--	----------------------------	---	---	---	---	---	---	-----	----------------

^a EP: energy potential; ^b S: social analysis; ^c E: environment analysis; ^d EC: economic analysis; ^e CC: carbon credits ^f life cycle cost; ^g social life cycle assessment

2.1 Energy Policies and Brazilian Law

Although the energy transition heavily depends on technological development, it is closely tied to public policies, institutional dynamics, and government decisions. Brazil has made significant progress in advancing the bioenergy agenda over the last twenty years by implementing several policies, as displayed in Figure 1. WERNER; LAZARO, (2023) analyzed the cases of Brazil and Chile to reveal the key policies that facilitated the implementation of renewable energy initiatives, and the leading institutions involved. For Brazil, the main institutions identified were the Ministry of Energy and Mines (MME), the National Economic Development Bank (BNDES), the Brazilian National Energy Policy Council (CNPE), the Brazilian National Electric System Operator (ONS), the National Electric Energy Agency (ANEEL), and the Energy Research Company (EPE) (WERNER; LAZARO, 2023).

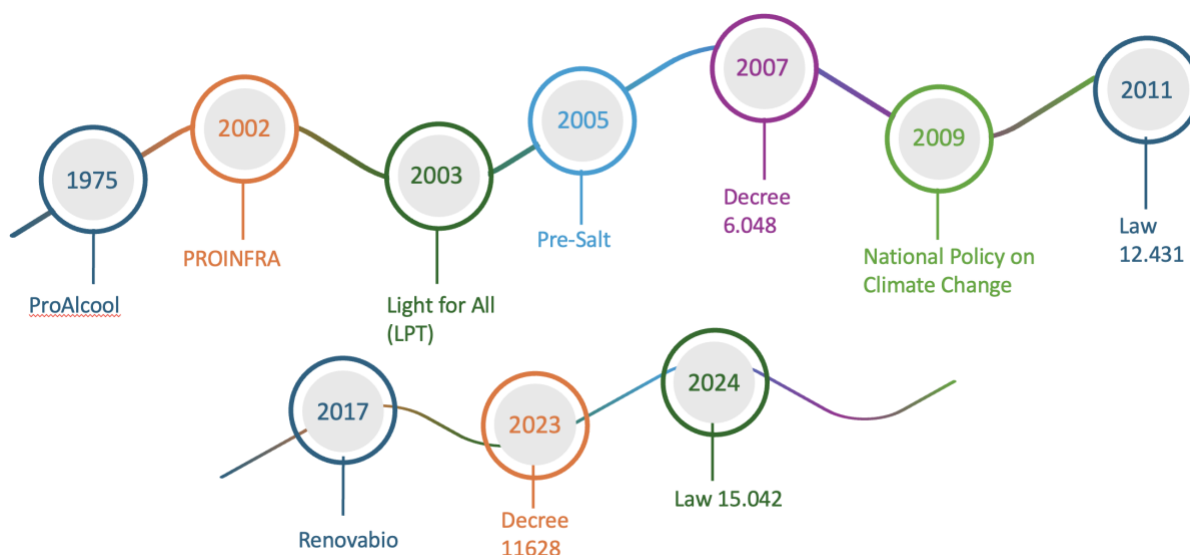


Figure 1. Overview of public policies and government actions in bioenergy production.

The laws and policies implemented by these institutions can be considered milestones in Brazil's bioenergy development. The first significant program was created after the oil crises of the 1970s as an effort to reduce Brazil's dependency on fossil fuels. This program, called "ProAlcool," was institutionalized by Decree 76.593 in 1975 and aimed to encourage ethanol production from sugarcane, cassava, or other inputs. It emphasized increasing agricultural production, modernizing and expanding existing distilleries, installing new production units (both attached to plants and autonomous), and developing storage facilities. ProAlcool is regarded as one of the key policies responsible for the successful development of the bioethanol industry in Brazil.

In the early 2000s, Brazil experienced several blackouts in the National Electric System (SIN) due to periods of drought, issues with gas supply and lack of investment in installed capacity. As an alternative, Law 10.438 of 2002 was enacted to boost the share of electricity produced by wind power, hydropower, and biomass-fueled thermal power plants. This law established the Incentive Program for Alternative Sources of Electricity Energy (PROINFA). The costs of these projects are distributed through monthly installments collected by distributors, transmission companies, and licensed cooperatives. These amounts are paid by all free and regulated consumers of the SIN, except for those classified as low-income. The program facilitated the installation of 19 biomass-fueled thermal power plants, with a total installed capacity of 533.34 MW (ENBPARG, 2024).

Moreover 2003, during the first term of the Lula government, the Light for All (LPT) program was launched to provide electricity to rural communities and areas without access to energy. The program encouraged families to return to rural areas and facilitated the regularization of properties through diesel-powered thermal power plants, thereby increasing energy demand (HAMPL, 2024). The program was successful in universalizing access to electricity in certain rural communities, but without offering quality energy. However, given the persistent challenges in achieving universal access to electricity in Brazil, particularly in remote areas of the northern region, and considering the impacts of climate change and the energy transition, the LPT Program was relaunched under Decree N°. 11,628 on August 4, 2023. The updated program introduced improvements and innovations to address the challenges faced by rural populations and those living in remote regions of the Legal Amazon. It emphasized using clean and renewable energy sources for electricity generation while promoting the preservation of the Amazon biome (MINISTÉRIO DE MINAS E ENERGIA, 2023).

A significant milestone occurred in the mid-2000s with the discovery of the Pre-Salt oil and gas reserves along the Brazilian coast, spanning Espírito Santo, Santa Catarina, Rio de Janeiro, and São Paulo. This discovery delayed investments in renewable energy in Brazil. At the time, there was hope that the revenue generated from Pre-Salt exploration would be directed toward promoting renewable energy, but this shift did not materialize (DE AREA LEÃO PEREIRA et al., 2019).

In 2007, Decree No. 6.048 established renewable energy auctions to support the growth of electricity supply from renewable sources, including wind, solar, hydro, and bioenergy. The success of this auction program is closely linked to earlier initiatives, such as PROINFA, as well as the design of the auctions, including the regulatory framework and implementation processes (TOLMASQUIM et al., 2021). Subsequently, in 2009, the government introduced

the National Policy on Climate Change (Law No. 12.1872) and, in 2015, announced its first commitment to reduce GHG emissions through the Intended Nationally Determined Contributions (iNDC). In 2016, the National Congress completed the ratification process of the Paris Agreement, officially making Brazil a signatory.

Another critical instrument is Law No. 12.431 of 2011, which established an infrastructure of debentures to implement R&D&I projects in specific sectors such as transportation, telecommunications, urban mobility, energy, and basic sanitation (WERNER; LAZARO, 2023). For the energy sector, the government compiled a list of priority projects deemed essential for energy infrastructure, including biofuels.

A significant breakthrough occurred in 2017 with the creation of the National Biofuels Policy, also known as Renovabio. This policy introduced biofuel consumption and production incentives, establishing Brazil's first carbon tax through an open market for carbon reduction credits, known as CBIOS (WERNER; LAZARO, 2023). The policy contributed to the expansion of bioenergy by promoting the cogeneration of bagasse in corn and sugar mills, which collectively added 28,246 GWh of electricity to the National Interconnected System (SIN) in 2023 (CCEE, 2024b).

2.2 Bioenergy: biomass and thermoelectric power plants

Biomass-derived from organic residues offers a sustainable alternative for thermoelectric plants, as evidenced by its prominence in literature focused on renewable energy solutions. Research conducted by FERREIRA et al., (2023) analyzed the physical and chemical properties of pellets produced from Amazonian wood residues and eucalyptus. The pellets' higher heating value (HHV) ranged from 19.52–20.39 MJ kg⁻¹. The study concluded that *Dinizia excelsa* produced pellets with higher density and lower volatile matter content, highlighting its significant potential for renewable energy generation from these residues.

Another study PEREIRA et al., (2020) investigated bioenergy production using Amazonian forest wood residues to produce metallurgical charcoal. It analyzed physical properties such as moisture content, density, calorific value, ash content, and energy density. Multivariate analysis revealed that tropical forest woods in Pará possess promising characteristics, including high basic density, high calorific value, and ash content below 1%. The HHV of the analyzed woods showed considerable variability due to the diverse age, species, and size of the trees in tropical forests and their lignin and cellulose composition.

Expanding on using residues for metallurgical charcoal production, BARROS et al., (2023) examined the impact of segregating Amazonian wood species on the quality of charcoal produced in kilns. The findings showed that segregation significantly enhances properties such as density, fixed carbon content, and calorific value. This practice optimizes energy production by improving the charcoal's efficiency as a reducing agent in blast furnaces. Additionally, segregation enhances the organization and efficiency of the production process.

Focusing on the energy potential of Amazonian residues, such as seeds and husks from bioproducts, ARAUJO et al., (2022) conducted a study to identify biomass residues suitable for generating electricity in isolated communities. Data collected from the literature were used to analyze the physicochemical properties of these residues and evaluate their potential for thermochemical conversion into electricity. The results demonstrated that sufficient biomass exists to meet the energy needs of isolated communities. However, further research and technological advancements are required to maximize the utilization of these resources. The study proposed the application of Amazonian biomass in individual microgrid projects as an alternative to diesel use, offering a sustainable solution for meeting the electricity demands of isolated communities.

Building on the concept of biomass-fired thermal power plants for isolated systems, EGBAELU; BELLO; AYODEJI, (2021) conducted a feasibility analysis evaluating six tropical wood species as feedstock. The research calculated the mass and volumetric flows of air, water, and biomass required for a 1.0 MWh steam plant. Key parameters such as boiler efficiency, air mass and volume, and steam consumption were assessed at varying air-fuel ratios. The findings demonstrated these biomass sources' energy potential and suitability for sustainable electricity generation in isolated systems.

Focusing on biomass derived from agricultural waste, such as açai seeds and sugarcane bagasse, DE OLIVEIRA et al., (2023) examined the feasibility of using small, low-pressure steam turbines to generate electricity in isolated Amazonian communities. The study analyzed the mechanical and electrical performance of turbines operating at 0.1, 0.2, and 0.3 MPa pressures. Results from a preliminary experimental survey revealed promising turbine efficiency, highlighting their potential to meet small-scale energy demands in remote regions.

2.3 Life Cycle Assessment

One way to evaluate the biomass performance for electricity generation in power plants is through the Life Cycle Assessment (LCA) tool. LCA provides a robust theoretical framework

for measuring the environmental impacts of continuous operations across processes, flows, and facilities, enabling a systemic analysis of industrial activities. In alignment with global efforts to mitigate greenhouse gas emissions, LCA has emerged as a comprehensive approach to examine the environmental aspects of product supply chains, fostering a holistic perspective that supports the formulation of public policies for effective environmental management (SILVEIRA et al., 2017). Furthermore, incorporating environmental damages within the LCA scope enhances decision-making by integrating diverse analytical perspectives (DEUTSCH et al., 2022).

The LCA for bioenergy is a well-documented approach in the literature. For instance, SILVA et al., (2022) conducted studies using pellets and briquettes in Latin America, utilizing databases such as Web of Science, Scopus, and Scielo. Despite recent growth in research, the review highlighted the region's limited studies compared to Europe and North America, identifying only eight articles from Chile, Brazil, and Mexico, countries with significant agricultural and forestry potential. Environmental impacts, such as water consumption and land-use changes, remain underexplored. Notably, the environmental impact of 1 MJ of energy production in Latin America was up to nine times lower than in Europe, reflecting differences in biomass availability, production systems, and LCA modeling.

The first LCA study on electricity generation in Mexico was conducted by SANTOYO-CASTELAZO; GUJBA; AZAPAGIC, (2011), using GaBi software to evaluate the environmental impacts of the country's electricity mix, which relies heavily on fossil fuels and accounts for 79% of total primary energy. Renewable energy sources contribute 16.5% (hydropower 13.5%, geothermal 3%, and wind 0.02%), with the remaining 4.8% from nuclear power. The analysis revealed that generating 225 TWh produces 129 million tonnes of CO₂ eq. annually, with fossil fuels responsible for 87% of emissions. The study estimated the Global Warming Potential (GWP) of Mexico's electricity mix at 571 g CO₂ eq./kWh.

A pivotal LCA study in Latin America carried out by MARTINEZ-HERNANDEZ et al., (2022) focused on the unique realities of Global South countries. The analysis evaluated two scenarios: one for a 0.5 MW plant and another for a 1 MW plant. The cost per kW of energy was lower than the current market price in Mexico. Environmentally, the study observed reductions in impact categories ranging from 20% to 95%. Additionally, the social analysis revealed potential benefits, including improved access to residential energy, treated water, basic sanitation, and job creation.

Following the LCAs in Latin America, MIRANDA; KULAY, (2023) performed an LCA in Brazil for a biogas power plant (BGPP) using agricultural residues to provide renewable

electricity to isolated Amazonian communities. The model demonstrated substantial reductions in CO₂ emissions (up to 7.7-fold) and energy consumption (71-fold) compared to diesel-based electricity generation. However, ecotoxicity remains a challenge, necessitating improved digestate management practices.

To evaluate the environmental impact of removing sugarcane straw for bioethanol production, (CALDEIRA-PIRES et al., 2018) analyzed soil carbon content in two scenarios: leaving straw in the field (RS) and exporting it for energy use (SS). The SS scenario increased impacts by 161% due to biotic emissions but reduced fossil GWP by 39%. The study emphasized that second-generation bioenergy requires optimization of straw utilization for maximum efficiency, as exporting straw for electricity cogeneration demonstrated superior environmental performance compared to the reference scenario.

Lastly, a significant LCA study forming the foundation of this work was undertaken by DE ALMEIDA et al., (2017), which assessed the environmental impacts of a bi-fuel Thermal Power Plant (TPP) in isolated systems in the Brazilian Amazon. Originally designed for Heavy Fuel Oil (HFO), the plant was adapted to operate with both HFO and natural gas. The results showed that bi-fuel operation significantly reduces local and regional impacts, with a 61.1% lower Eutrophication Potential and improvements in six impact categories compared to HFO-only operation. However, no statistically significant differences were observed for Global Warming Potential.

3. CASE OF STUDY

3.1 Cities Description

The state of Amazonas has the largest number of isolated systems, comprising 97 systems Fig. 1(a) and (b). It stands out as having the highest energy demand compared to other states in the region. It is the only state projected to remain dependent on isolated energy systems over a 10-year horizon (see Fig. 1(c)).

This study identifies bioenergy solutions as an opportunity to address these challenges, reduce deforestation, and decarbonize the state. Two cities, Manicoré and Lábrea, were selected for assessment (Fig. 1(d)). These cities are representative of regions heavily reliant on diesel-based energy systems, with considerable urban and local business activity and significant logistical and infrastructure challenges (Fig. 1(e)). Both are located within the Legal Amazon, a region renowned for hosting the world's richest biodiversity and largest freshwater reserves.

Paradoxically, these cities lie within the so-called “deforestation arc” of the Amazonas state, an area under significant environmental pressure.

The first city, Manicoré, is located at 5° 48' 47" S and 61° 17' 56" W. The city covers an area of 48,315.038 km², of which 35% is designated as Conservation Units (UCs), 16.64% as Indigenous lands, and 4.5% for sustainability extraction. The second city, Lábrea, is located at 7° 15' 36" S and 64° 47' 57" W, with a total area of 68,262.680 km², of which 53.99% are UCs, 22.93% are Indigenous lands, and 2.47% are settlements (VOIVODIC et al., 2017).

The region's economy focused on carbon-intensive, low-value-added products and mineral commodities, primarily agriculture, cattle ranching and mining sectors, bioproducts, timber, and vegetable oils (NOBRE et al., 2023).

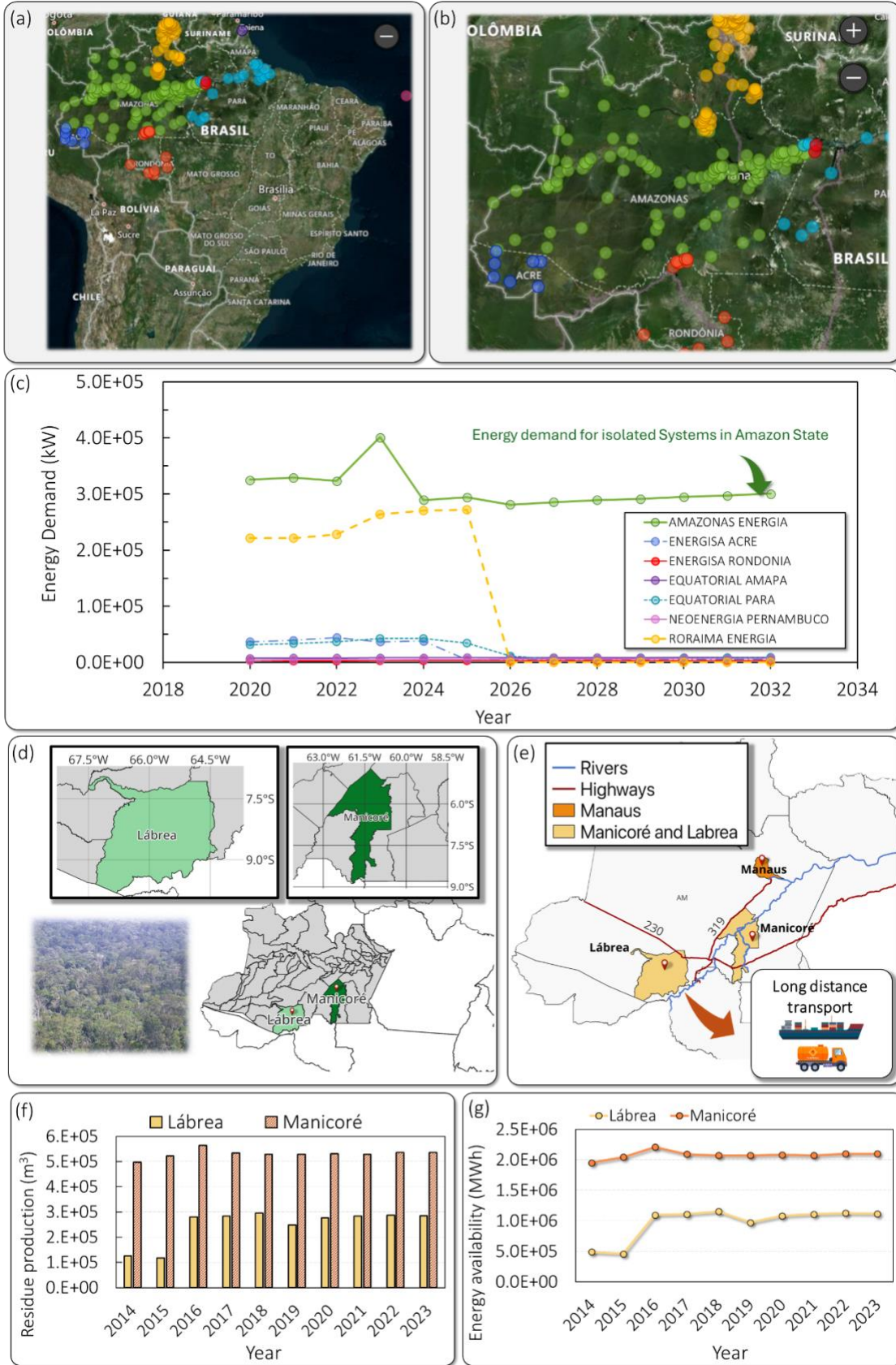


Figure 2. (a) Overview of isolated systems in Brazil, (b) isolated systems in Amazonas as mapped by the EPE platform (PASI, 2024), (c) projected energy demand of isolated systems for 2018–2034, (d) location of Manicoré and Lábrea, (e) transportation logistics, (f) residue production quantified by volume, and (g) energy availability from residues (details provided in Annex 1 in Eqs. S1 and S2).

3.1.1 Energy Consumption

Access to electricity is essential for basic sanitation and achieving Sustainable Development Goals (SDGs) 6 and 7 (MARTINEZ-HERNANDEZ et al., 2022). In both cities, most of the population resides in rural areas. In Manicoré 19.09% of households lack electricity, and 35.6% lack primary sanitation access (MARTINEZ-HERNANDEZ et al., 2022). Lábrea exhibits higher rates of energy poverty, with 21.68% of its population lacking access to electricity. The residential and commercial together account for 75.12% of total energy consumption (PASI, 2024). In 2023, the industrial sector accounted for 3.03% of energy consumption, primarily driven by sawmills, food industries, and cooperatives: ASPACS (Association of Extractive Producers of the Sardinha Colony) and COOPMAS (Sardinha Mixed Agroextractive Cooperative), which produce nuts, bioproducts and vegetal oil.

Manicoré's industrial sector is smaller, comprising only 0.79% of energy consumption in 2023 (PASI, 2024), with activities including dairy factories, sawmills, ice and furniture manufacturing and sand extraction for civil construction. The city also benefits from two cooperatives: CONEMA (Manicoré Green Cooperative) and COPEMA (Cooperative of Agricultural Producers and Extractivists of Natural Resources in Manicoré) (VOIVODIC et al., 2017). Both cities rely on bioproducts and natural solutions. Electric energy resources are crucial for processing products to meet quality standards and seals, which are prerequisites for assessing external markets and generating income (NOBRE et al., 2023).

Both cities rely on diesel for energy supply. Manicoré operates two thermal power plants with a combined installed capacity of 13.325 kW. In 2023, the city's energy demand was 7.189 kW, and consumption was 40.471 MWh. For 2027, the EPE (Brazil's Energy Research Company) projects a demand of 8.215 kW and a consumption of 45.285 MWh. Lábrea operates a single thermal power plant with an installed capacity of 19.697 kW. In 2023, its energy consumption was 41,764 MWh, with a projected consumption of 47,554 kWh and a demand of 8,455 kW by 2027 (EPE, 2022a). Amazonas Energia manages Lábrea and Manicoré's energy systems. Between January 2022 and July 2023, 18,114,512 L and 17,333,614 L of diesel were used to meet the energy demands of Manicoré and Lábrea, respectively (PASI, 2024). The efficiency of these diesel systems is low; however, data on efficiency is unavailable due to confidentiality rules. In 2023, the total technical energy losses in Lábrea reached 28.20%, while Manicoré reported a loss index of 26.49% (PASI, 2024).

3.1.2 Fuel Distribution

Most isolated systems are in the country's North, mainly due to difficulties imposed by the conventional energy infrastructure. To preserve environmental balance in these areas, it is essential to develop infrastructure centered on a robust socio-biodiversity economy, fostering the well-being of the Amazon population while respecting local territories and Indigenous forest knowledge (ABRAMOVAY, 2022).

The logistics to guarantee the energy supply are based on conventional engineering. Thus, fossil fuels power the two cities and are transported via conventional roads and rivers, which are prone to shortages during certain periods. The Amazon's rivers experience seasonal flow variations, roads suffer from poor infrastructure, and blockages occurred to rainfall (VOIVODIC et al., 2017). This scenario is expected to worsen in the coming years, based on the results from the Intergovernmental Panel on Climate Change IPCC report for tropical regions (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2023). Therefore, fossil fuel distribution must be considered in life cycle assessments (LCA) to quantify environmental impacts.

3.1.3 Wood Residues Availability And Potential

The residues used in this research come from sustainable forest management, therefore, comply with Brazilian legislation and have a low impact on the environment and local biodiversity. According to the Plant Extraction and Forestry Production (PEVS) data, in 2021, Manicoré produced 145,000 m³ of roundwood and 380,000 m³ of firewood, while Lábrea achieved 120,000 m³ of roundwood and 395 m³ of firewood (IBGE, 2022). The volume of wood residue was estimated using a two-step approach. First, the wood production volume reported by the PEVS was multiplied by 1.7, based on the literature reference (CORDEIRO, 2006). Second, the PEVS wood production was multiplied by 0.65, a coefficient provided by the CONAMA resolution No 411. This resulted in 340,750 m³ of residues for Manicoré and 282,200 m³ for Lábrea in 2021.

The electricity potential of Lábrea was calculated at 346,792.872 MWh annually, using 190,110,300 kg of residues, corresponding to 548.195 kg to generate 1 MWh. Similarly, Manicoré's electricity potential was 419,041.387 MWh annually, based on 229,716,612.50 kg of wood residues, with the same conversion ratio of 548.195 kg per MWh.

4. LIFE CYCLE ASSESSMENT

4.1 Goal And Scope Definition

The primary goal of this LCA is to compare the potential for decarbonization in two cities by evaluating the environmental and energy performance of two chains, the fossil fuel chain and the bioenergy chain, to support decision-making. Therefore, this study employs an attributional LCA, using average data to describe mass and energy flows (FINNVEDEN et al., 2009).

The alternative bioenergy chain presented here is based on thermal plants powered by biomass residues from SFM. Conversely, the fossil fuel chain currently operates with diesel engines at low-efficiency rates. The system's function for the fossil fuel and bioenergy chains is the same: electrical energy production. Therefore, the functional unit (FU) was defined as 1 MWh.

The LCA For Experts software from LCA FE (Sphera© , formerly GaBi) was utilized, and the model can be found in Annex 6. The CML 2001 methodology was applied, following the ISO 14040 series. The CML 2001 method evaluated key indicators: Global Warming Potential (GWP 100 years, kg CO₂ eq.), Abiotic Depletion (fossil) (ADP_{fossil}, MJ); Acidification Potential (AP, kg SO₂ eq.), Eutrophication Potential (EP, kg PO₄³-eq.), and Human Toxicity Potential (HTP, kg 1,4 DCB eq.). These categories were chosen due of their greater impact when compared to other categories.

4.2 System Description

Figures 2 and 3 illustrate the cradle-to-grave and gate-to-grave LCAs systems, respectively. Each phase includes inputs, such as energy, chemicals, and machinery, as well as outputs of intermediate products, emissions, and the final product. Figure 2(a) displays the fossil fuel chain in both cities, starting with upstream oil production, middle stream and downstream, followed by tankage storage. The subsequent stage involves long-distance fuel transportation by truck or ship, depending on the destination city. The final stage is the thermal power plant, where diesel is converted into electricity. The oil production represented by Figure 2(a) was accounted by the GaBi software, which accounts the impacts when “Heavy fuel oil at refinery” was chosen.

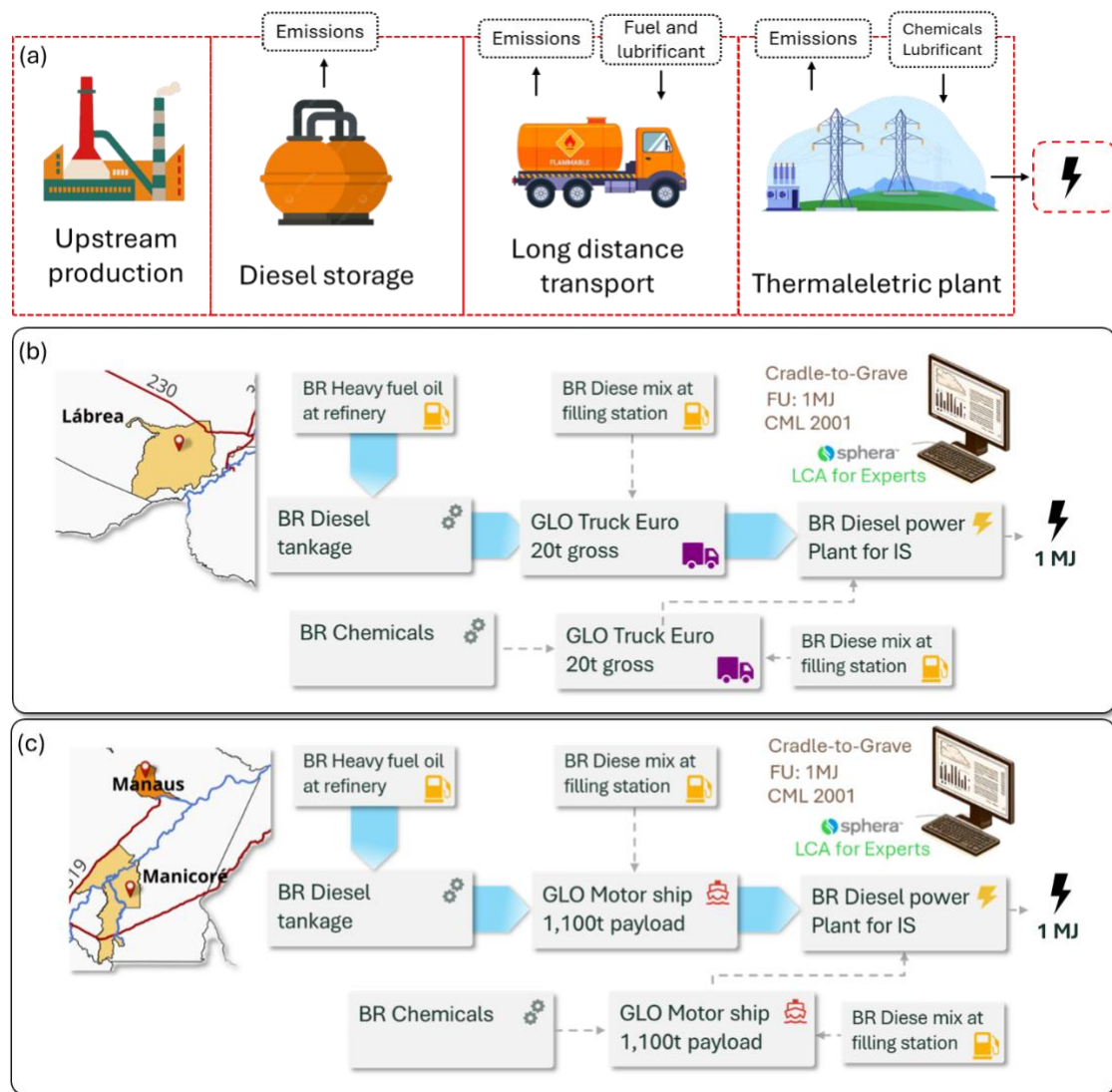


Figure 2. Fossil fuel chain description and boundaries. Technological models of fossil fuel chain established on LCA for expert software for (b) Lábrea and (c) Manicoré cities.

Figure 3(a) presents the bioenergy chain, divided into four parts: sustainable forest management, forest residue storage, short-distance transportation, and bioenergy generation at a power plant. This study considers residue storage, transport and energy conversion. The bioenergy route involved short transportation distances using diesel-powered trucks. The process concludes with a thermal bioenergy power plant producing electricity.

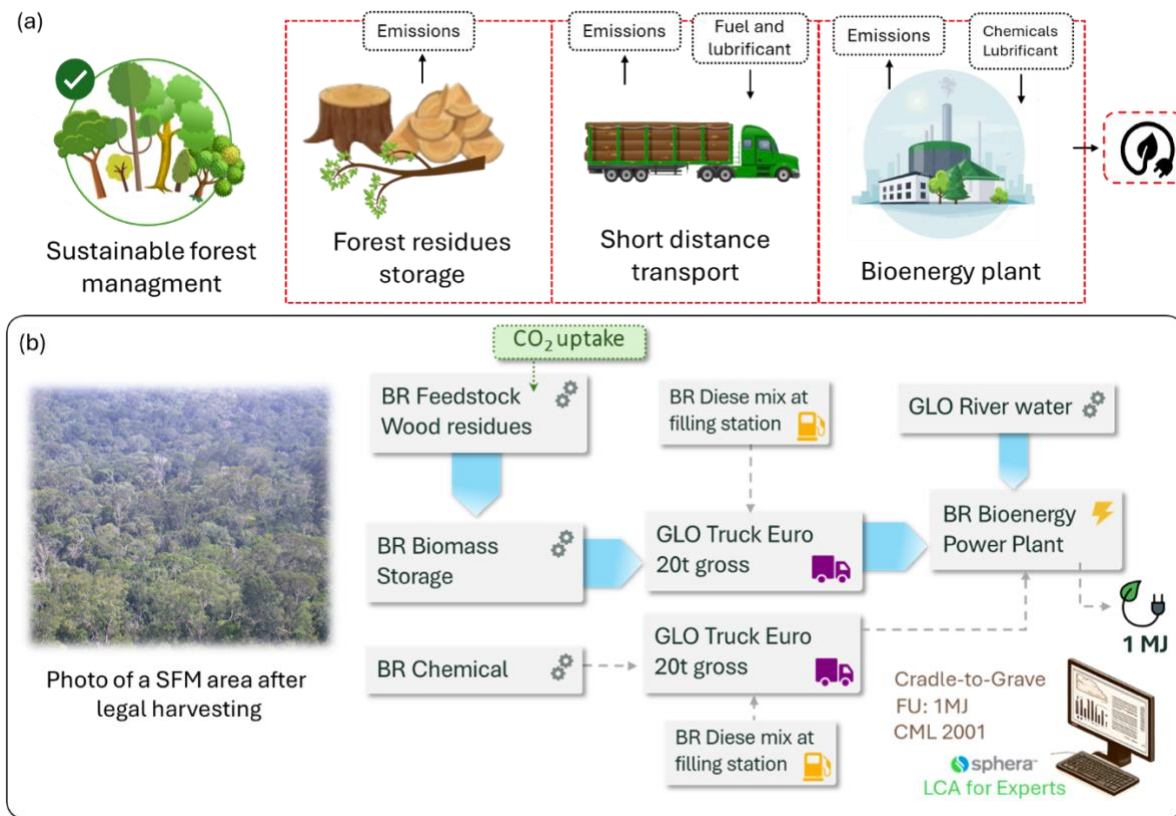


Figure 3. (a) Bioenergy chain description and boundaries. (b) Technological model of bioenergy chain established on LCA for expert software.

4.3 Life Cycle Inventory

The main objective of this section is to present the mass and energy balance information used to assess the life cycle of electricity in isolated systems. The Life Cycle Inventory (LCI) for the bioenergy and fossil fuel chains was developed using secondary data from various information sources, supplemented with information in Appendix 1, 2, 3 and 4.

The LCI was built using literature and government data (Table S1 in Appendix 2). However, information gaps were filled using reports from NGOs and local organizations. This input was crucial for the Life Cycle Impact Assessment (LCIA), providing deeper insights into the social context and local infrastructure.

4.3.1 Fossil Fuel Chain

The LCI for the fossil fuel chain primarily encompasses processes related to oil production, storage, transportation, and conversion of diesel fuel (Fig. 2). Data were derived from Brazilian government reports and a comprehensive literature review on LCA studies of thermal power plants operating in isolated energy systems.

4.3.1.1. Diesel Storage

Emission factors for diesel storage were calculated using the BTEX emissions data provided in (KUMARI et al., 2023) and information published by the ANP (National Agency of Petroleum, Natural Gas, and Biofuels) on tanking and national fuel supply (ANP, 2023). For Manicoré and Lábrea, the company responsible for the fuel supply is Atem, which operates 15 tanks with varying sizes and a total capacity of 77,105 m³. Detailed information on tanks in Manaus is available in Table S2. Emission factors for diesel storage ($EF_{d,storage}$) were derived using the vent-pipe flow model (KUMARI et al., 2023), covering BTEX emissions (benzene, toluene, ethylbenzene, o-xylene and m-p-xylene). The total emissions were calculated using Eq. (1), with emission factors displayed in Table 2.

$$EF_{d,storage} = EF_i \times A \times H \quad (1)$$

Here, $EF_{d,storage}$ is expressed in kg, EF_i is the emission factor (kg m⁻³) of a specific BTEX emission (i), A is the tank surface area (m²), calculated based on NBR standards (see Appendix), and H is the average tank height (considered as 34 m).

4.3.1.2. Diesel Transportation

Fuel transportation data were sourced from the ANP (ANP, 2023). Figure 1(e) illustrates the transportation paths to cities. According to the ANP tankage data, fuel is stored in tanks and distributed without pipelines. According to the Google Maps tool (GOOGLE, 2024), fuel is transported to Lábrea by trucks via BR-230 and BR-319 highways, covering 853 km. Due to the uncertainty linked to the practicability of Manicoré's roads, it is assumed that fuel is delivered by an inland ship along the Madeira and Amazon Rivers, spanning 464 km. EuroVI A-C trucks (14-20 tons capacity, 0.002 kg km⁻¹ diesel consumption) and Inland motor ships (1,100 tons capacity, 0.047 kg km⁻¹ diesel consumption) were used.

Table 2. Emissions factors for the storage stage of diesel considering de FU of 1 MWh.

Gas	Emission factor (kg m ⁻³) ^a	Total emissions (kg) ^b
Benzene (Emissions to air)	1.12 E-07	1.33E-01
Toluene (Emissions to air)	2.19 E-07	2.60E-01
Ethylbenzene (Emissions to air)	8.50 E-08	1.01E-01
m-p-xylene (Emissions to air)	1.04 E-07	1.23E-01
o-xylene (Emissions to air)	9.50 E-08	1.13E-01

^a from (KUMARI et al., 2023); calculated based on (ANP, 2023) and Eq. (1).

4.3.1.3. Diesel Power Plant

The inventory for the thermal power plant was sourced from (DE ALMEIDA et al., 2017), which presents an LCA for a thermal power plant in an isolated system located in Amazonas state, Manaus. This isolated system is managed by Amazonas Energia, the same company supplying electricity in Manicoré and Lábrea. Table 3 outlines the inputs and outputs for the functional unit (FU), 1MWh.

4.3.2 Bioenergy Chain

No LCI or LCA studies on electricity generation powered by local Amazonian wood biomass were identified for the bioenergy scenario in the literature. Therefore, the present work presents novel data on LCIA for bioenergy from Amazonian forest residues.

Table 3. Emission inventory for a thermal power plant supplied by diesel (adapted from (DE ALMEIDA et al., 2017)).

Inputs	Unit	Value
HFO (Heavy Fuel Oil)	kg	2.020E+02
Water	kg	3.200E+03
Lubricant oil	kg	5.270E-01
Air	kg	5.035E+05
Sodium nitrite	kg	1.420E-03
Sodium hydroxide	kg	6.710E-04
Adipic acid	kg	6.110E-06
Phosphoric acid	kg	1.220E-05
Ammonium chloride	kg	3.170E-06
Formaldehyde	kg	2.260E-05
Monoethanolamine	kg	1.580E-04
Outputs		
Oily Sludge (residue)	kg	1.390E+03
Chemical Oxygen demand	kg	6.870E-01
Biochemical oxygen demand	kg	1.340E-01
Total Phenols	kg	1.010E-03
Phosphate	kg	2.010E-02
Nitrate	kg	8.480E-03
Nitrite	kg	2.820E-01
Oils and Grease	kg	4.740E-02
Total Dissolved Solids	kg	1.820E+03
Suspended solids	kg	4.910E-01
Sedimentable solids	kg	5.060E-04

Sulfate	kg	4.070E-03
Sulfide	kg	2.180E-03
Nitrogen Monoxide (air)	kg	4.160E+01
Nitrogen oxides (air)	kg	6.430E+01
Sulfur dioxide (air)	kg	4.830E+00
Particulate matter (air)	kg	3.410E+00
Carbon dioxide (air)	kg	5.900E+02
Carbon monoxide (air)	kg	1.910E-01
Offgrid electricity	MWh	1.000E+00

Previous research suggests that technological improvements in biomass-to-electricity systems can reduce social risks in the supply chain (MARTÍN-GAMBOA et al., 2021). However, this approach may not fully reflect the realities of the Global South or traditional communities in the Amazon. According to MARTINEZ-HERNANDEZ et al., (2022a) a community-scale energy system should be simple and efficient and provide low-cost energy to poor and marginalized communities. Therefore, this work does not consider any treatment for the forest residues in a way that would complicate the system. Instead, it examines whether the proposed approach is feasible and effective.

4.3.2.1. Wood Residues Characteristics

Conservation units (UCs) typified as Sustainable Development Reserve and State Forest presents in Manicoré and Lábrea were selected for the bioenergy chain, excluding state natural parks due to their full legal protection. The selected UCs include the Amapá River, Igapó-Açú, Rio Madeira and Manicoré State Forest. The Sustainable Management Plans (SMPs) (ABDEL AZIZ et al., 2010; LUIZ; DE ANDRADE, 2014a, 2014b; PRETO, 2010) provided data on wood species, facilitating the selection of 23 common wood species (see Table S3 in Appendix 4). The averaged results, which represent the feedstock for the bioenergy plant, are provided in Table 4. In this case, the moisture content for the amazon residues biomass is 12.47% (AMARAL et al., 2014).

Table 4. Summary of the wood species and their physical and chemical characterization.

Properties	Forest Residues (Minimum and maximum values)
Basic Density (kg m ⁻³)	280 - 910
Moisture (%)	12.47
Proximate property	
Ashes (%)	0.07 – 2.80
Ultimate composition	

Sulphur Content (%)	0.01 – 0.8
Carbon Content (%)	48.53 – 50.95
Nitrogen Content (%)	0.37 – 1.58
Oxygen Content (%)	10.01 – 44.05
Hydrogen Content (%)	3.36 – 6.28
Calorific	
Higher Heating Value (MJ kg ⁻¹)	17.51 – 29.10

4.3.2.2. Biomass Storage

Forest residue storage was defined for six months at the company's yard, as the Keilla Group (Keilla Florestal) reported. Previous studies have assessed the greenhouse gas emissions associated with wood residue storage (WIHERSAARI, 2005). After six months of storage, naturally dried forest residues (with 40 wt% moisture content) were reported to emit a total of 58 kg CO₂ eq., due to CH₄ and N₂O release from carbon and nitrogen degradation during this period (WIHERSAARI, 2005). This study adopts this value to account for the kg CO₂ eq. emissions from biomass storage. In addition, it was assumed that biomass would undergo a 6.6% dry material loss over six months, as reported in (WIHERSAARI, 2005).

4.3.2.3. Biomass Power Plant

Eq. (2) was used to determine the mass of biomass residues (BR in kg) considering the power production (P) of 1MWh (FU), the higher heating value in MJ kg⁻¹ (see Table 4), and a standard efficiency ($\eta_{conversion}$) of 0.33 was adopted (FRANÇA et al., 2023).

$$P = \eta_{conversion} \times HHV \times Residues \times \frac{1h}{3600s} \quad (2)$$

Considering the bioenergy power plant emissions, data were collected from gas characterization studies during the combustion of Amazonian biomass (AMARAL et al., 2014; AMORIM et al., 2013; MAJ, 2018; SOARES NETO et al., 2011). The emission factors considered from biomass combustion were determined based on previous literature regarding the release of water vapor, CO, CO₂, NO_x, and particulate matter (AMARAL et al., 2014), SO₂ (MAJ, 2018), and CH₄ (AMORIM et al., 2013) during thermal decomposition.

An LCA study carried out on energy production from waste forest residues provided information on the chemical products used in biomass-powered thermal power plants (CORONA et al., 2020) (see Table 5).

Table 5. Emission inventory for the bioenergy plant.

Inputs	Unit	Value	Ref.
Biomass (solid)	kg	4.798 E+02	-
Combustion (Air)	kg	2.125 E+02	-
Ammonia Liquid	kg	2.314 E-03	(CORONA et al., 2020)
Lubrificant Oil	kg	1.051 E-05	
Sodium hydroxide	kg	1.727 E-03	
Sulfur	kg	2.105 E-03	
Water	kg	2.100 E+02	
Sand	kg	3.157 E-04	
Outputs			
Offgrid electricity	MWh	1.000 E+00	-
Carbon Dioxide (captured by photosynthesis)	kg	7.586 E+02	(AMARAL et al., 2014)
Carbon Monoxide [Inorganic emissions to air]	kg	2.332 E+01	(AMARAL et al., 2014)
Water vapor [Inorganic emissions to air] ^a	kg	5.986 E+01	(AMARAL et al., 2014)
Nitrogen compounds	kg	1.401 E+00	(AMARAL et al., 2014)
Particulate matter	kg	1.526 E+00	(AMARAL et al., 2014)
Methane	kg	1.535 E+00	(AMORIM et al., 2013)
Sulfur Dioxide	kg	2.882 E+01	(MAJ, 2018)
Wastewater	kg	3.083 E+01	(CORONA et al., 2020)
Waste mineral oil	kg	6.000 E-03	(CORONA et al., 2020)

^a The amount of water vapor was calculated based on the moisture content (AMARAL et al., 2014).

4.4 Carbon Credits Potential

The carbon credit potential of the transition to a bioenergy system was evaluated by calculating the total CO₂ eq. emissions from the biomass valorization route, including storage, transportation, and biomass combustion in the power plant. The CO₂ uptake during the biomass growth phase was accounted for, promoting a carbon-neutral cycle. Additionally, emissions avoided by replacing diesel fuel with bioenergy were considered, reflecting the system's efficiency in mitigating carbon emissions.

For diesel replacement, the higher heating value (HHV) of diesel was 45.008 MJ kg⁻¹ (EMPRESA DE PESQUISA ENERGÉTICA, 2023), and CO₂ equivalent (CO₂ eq.) emissions were calculated according to the IPCC methodology for the energy sector at 7.407E-02 kg MJ⁻¹ of energy released (EPE, 2022b). These values were essential for estimating the system's

efficiency in replacing fossil fuels with bioenergy, emphasizing the significant carbon mitigation potential of the biomass valorization route.

This mitigation potential underscores the need to understand the financial valuation of carbon credits, a process influenced by various factors, such as the country's regulatory framework, credit type, and quality, including project modality, year of issuance, environmental impact, and the total avoided emissions. Carbon credits from emissions trading systems (ETS) and carbon tax schemes are generally regulated by mandatory national frameworks and tend to command higher market values (S&P GLOBAL, 2024). In Latin America (LATAM), only Colombia, Mexico, and Chile have made substantial progress in establishing mandatory markets through carbon tax systems (BLANTON et al., 2024). Brazil has taken its first steps in 2024, but its carbon market is still under development. In contrast, most carbon credits in South America are derived from voluntary carbon markets (VCM), which generally have lower prices and are predominantly driven by projects to reduce emissions from deforestation and forest degradation (REDD+), with significant participation from countries like Brazil, Peru, and Colombia (BLANTON et al., 2024).

This article distinguishes between VCM and carbon tax markets to assess the financial value of carbon credits. Since Brazil does not yet have an operational carbon market, despite passing legislation to establish one, the analysis draws upon current mandatory carbon market prices from a LATAM country with a similar context, specifically the city of Yucatan in Mexico. The carbon tax in this region applies to substances generated during production processes, including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (WORLD BANK, 2024). The pricing and allocation mechanisms also allow for the reduction of up to 100% of emissions avoided or reduced through renewable energy installations and for emissions captured in forest conservation areas (WORLD BANK, 2024).

For VCM carbon credits, the market value in 2023 was considered to be \$5.77 per tonne of CO₂ eq., (ECOSYSTEM MARKETPLACE, 2023), encompassing credits from forestry/land use, renewable energy, and fuel-switching projects (see detailed formulation in Annex 5). For mandatory carbon tax markets (Yucatan in Mexico), the assumed carbon price in 2024 was \$17.69 per tonne of CO₂ eq. (WORLD BANK, 2024).

RenovaBio, Brazil's National Biofuels Policy, was established in 2017 to promote biofuel production and use as part of the country's strategy to reduce greenhouse gas emissions and transition to a low-carbon economy. It sets decarbonization targets for the fuel sector and incentivizes sustainable energy practices through market mechanisms such as Decarbonization

Credits (CBIOs). To align with Brazil's COP 21 commitments, RenovaBio aims to increase bioenergy's share to 18% of the energy matrix by 2030. Biofuel producers and importers certified by the ANP issue CBIOs, while fossil fuel distributors must purchase them to meet ANP-assigned annual targets. Each CBIO, equivalent to 1 ton of CO₂ avoided, has no expiration and is retired upon request to meet decarbonization obligations. In addition, the Renovabio is one of the most important government programs that use life cycle assessment as a base methodology. Therefore, for the Brazilian context, the CBIO credits served as the basis for financial calculations, with an average value of R\$ 113.61 per tonne of CO₂ eq. in 2023.

5. RESULTS AND DISCUSSIONS

This section presents the LCA results for the business-as-usual operation and the proposed transition to a bioenergy chain. The results for each impact category described in detail in subcategories can be found in Appendix 7. Furthermore, the consequences of this transition on social aspects are discussed throughout the text.

5.1 Life Cycle Impact Assessment: Business as Usual

Table 6 provides the results of the LCA studies for the cradle-to-grave analysis of the diesel chain. The five categories presented here are of greatest relevance for environmental damage in the analysis and are divided into fossil fuel storage, transportation, and electricity generation.

The total impact in the GWP category was 1,209.38 and 678.73 kg CO₂ eq. per MWh for Lábrea and Manicoré, respectively. The power plant stage alone contributed 590 kg CO₂ eq., within the expected range of 530 to 900 kg CO₂ eq., according to TURCONI; BOLDRIN; ASTRUP, (2013). Among the transportation modes, trucks were found to be the most carbon-intensive, with a GWP of 532.73 kg CO₂ eq. Literature values report 632.068 kg CO₂ eq. per km for diesel-powered heavy trucks (RIAL; PÉREZ, 2021). However, the 14% biodiesel blend currently used in Brazilian diesel may explain the difference between the emissions.

For Manicoré, the transportation stage accounted for only 2.09 kg CO₂ eq. of GWP impact. At first glance, this might seem misleading; however, the result can be explained by the functional unit adopted in this study. To generate 1 MWh of electricity, approximately 202 kg of diesel is required. This amount was entered as the payload for transportation via inland ship, with a maximum capacity of 1,100 tons. Consequently, the calculated emissions are proportional to these 202 kg of cargo out of the ship's total capacity, resulting in a lower impact

than truck transportation. Trucks, with a load capacity of 20 tons – about 55 times smaller than the inland ship – assign a much higher share of emissions to the same 202 kg of diesel transported. Thus, directly comparing the net GWP emissions of the different transportation modes used in this study could lead to analytical errors, as their load capacities differ significantly. Furthermore, due to software limitations, the ship’s 1,100-ton capacity was the smallest option available in LCA-Sphera software.

Three parameters were considered to accurately compare the transportation impacts: fuel consumption, the percentage of load relative to total capacity, and distance. As expected, the inland ship demonstrated the lowest rate of $(kg\ of\ diesel)/(kg\ of\ cargo) \times (distance)$ compared to trucks, aligning with findings reported by (FAN et al., 2021). This result highlights the inland ship as the most environmentally favorable modal choice, reinforcing the study’s core argument: infrastructure planning in the Amazon should prioritize forest-based socio-biodiversity solutions that minimize environmental impacts rather than defaulting to pre-existing, generalized solutions.

Table 6. LCIA results for the fossil fuel (Diesel) chain for 1MWh.

	Lábrea Power System	Manicoré Power System
Global Warming Potential (GWP kg CO₂ eq.)		
Transportation	5.33E+02	2.09E+00
Power Plant	5.90E+02	5.90E+02
Human Toxicity Potential (HTP kg DCB eq.)		
Storage	2.52E+02	2.52E+02
Transportation	1.90E+01	1.05E-01
Power Plant	2.56E+01	2.56E+01
Acidification Potential (AP) (kg SO₂ eq.)		
Transportation	5.51E-01	1.39E-02
Power Plant Emissions	3.75E+01	3.75E+01
Abiotic Depletion from fossil fuels (ADP fossil) (MJ)		
Transportation	7.15E+03	2.78E+01
Power Plant Chemicals	2.57E+01	2.57E+01
Power Plant Emissions	9.28E+03	9.28E+03
Eutrophication Potential (EP) (kg Phosphate eq.)		
Transportation	2.17E-01	3.87E-02
Power Plant Emissions	8.38E+00	8.38E+00

However, the financial burden of current logistics, which relies heavily on long-distance diesel transport by ship, remains significant. Electricity generated in isolated systems is currently more expensive than electricity provided by the SIN. Additionally, in September 2024, the Madeira River underwent its worst drought, disrupting transportation and plant

access. This event caused fuel prices to rise by USD 0.025 per liter, further emphasizing the economic vulnerabilities of the existing logistics model.

The acidification potential (AP) from the power plant stage for both cities reached 37.55 kg SO₂, considerably higher than the 4.33 kg SO₂ reported in the literature (SANTOYO-CASTELAZO; GUJBA; AZAPAGIC, 2011). At the same time, the eutrophication potential (EP) was 8.41 kg Phosphate equivalents, exceeding values noted in (OZTURK; DINCER, 2019). This elevated EP value is largely attributed to significant atmospheric nitrogen monoxide emissions, along with nitrite and nitrogen oxides released into freshwater. These high AP and EP values can be linked to the engines employed by Amazonas Energia, which emit more nitrogen monoxide and sulfur dioxide than other engine types, such as steam and gas turbines.

Accounting for the power plant stage and the chemicals products, the abiotic depletion (ADP_{fossil}) totaled 9,280.05 MJ for both cities due to the use of HFO, lubricant oil and coal during the production of ammonium chloride, sodium nitrite and monoethanolamine. The results emphasize the requirement to decarbonize the *hard-to-abate* sectors, such as industry, specifically to avoid emissions from Scope 3, known as indirect emissions in the Greenhouse Gas (GHG) Protocol methodology.

Finally, the human toxicity potential (HTP) revealed a significant impact of 252.35 kg DCB for fuel storage, primarily due to airborne emissions of hydrocarbon compounds present in fossil fuels, such as benzene, toluene, o-xylene, and m-xylene. These results support the findings of HAMPL, (2024), emphasizing that the current choice of energy solutions for isolated systems entails a high carbon and ecological footprint, especially when relying on fossil fuel sources. This highlights the importance of placing citizens at the center of infrastructure decisions through the services they will benefit from and their active participation in shaping energy infrastructure to ensure sustainable and locally tailored solutions (ABRAMOVAY, 2022).

5.2 Life Cycle Impact Assessment: Bioenergy Chain

The same impact categories were analyzed for the bioenergy chain, as shown in Table 7. To assess the bioenergy results, one form of defining biogenic carbon, carbon derived from organic material that is part of the natural carbon cycle, were considered. As this is a sensitive topic in the literature involving considerations of the “territorial basis” (LIU et al., 2018) a conservative approach was adopted. The “Biogenic Carbon” is a parameter to represent the neutrality of carbon uptake from combustion phase.

For the GWP, a total of 117.39 kg CO₂ eq was calculated, including Carbon Uptake. The primary emissions originate from the decomposition process during storage and the bioenergy power plant. Biomass storage accounted for 58 kg CO₂ eq., mainly due to methane emissions. An LCA study on wood pellets from pine for electricity generation conducted by RÖDER; WHITTAKER; THORNLEY, (2014), reported net emissions higher than those observed in the present study. This discrepancy can be attributed to differences in system boundaries, as this study did not account for the management stage or the use of different wood species. Nevertheless, the contribution of biomass storage to GWP observed here aligns with the findings of that study, reinforcing the relevance of storage emissions in the overall environmental impact. The bioenergy production stage (at the power plant) resulted in 37.84 kg CO₂ eq.

Table 7. LCIA results for the bioenergy chain for 1 MWh.

Bioenergy System	
Global Warming Potential (GWP) (kg CO₂ eq.)	
Biomass Storage	5.80E+01
Transportation	2.12E+01
Power Plant	3.79E+01
Human Toxicity Potential (HTP) (kg DCB eq.)	
Biomass Storage	0.00E+00
Transportation	7.56E-01
Power Plant	3.67E+00
Acidification Potential (AP) (kg SO₂ eq.)	
Transportation	2.18E-02
Power Plant	3.03E+01
Eutrophication Potential (EP) (kg Phosphate eq.)	
Biomass Storage	0.00E+00
Transportation	8.65E-03
Power Plant	5.88E-01
Abiotic Depletion from fossil fuels (ADP fossil) (MJ)	
Transportation	2.85E+02
Power Plant	0.00E+00
Chemicals	1.00E-01

Furthermore, when comparing the GWP results of this study with findings on Amazonian biogas produced from agricultural residues, bioenergy from SFM appears to have a greater environmental impact. (MIRANDA; KULAY, 2023). The results reported by MIRANDA; KULAY, (2023) for agricultural biogas was for some cases, approximately to 300 kg, about one-third of the values observed for SFM-based systems. However, it is important to note that the referenced study does not account for the environmental burden associated with

corn, cattle manure, and rice straw, which could undermine key results and distort the data. It is also important to emphasize that agriculture in the Brazilian North poses significant challenges to forest and biodiversity preservation, particularly due to extensive livestock farming and monoculture of commodities (DE AREA LEÃO PEREIRA et al., 2019). These challenges are especially evident in Pará, where forest fires reached national records in 2024, totaling 540.52 occurrences, according to the National Institute for Space Research (INPE).

The Acidification Potential (AP) category resulted in 30.30 kg SO₂ eq. for the bioenergy power plant, primarily due to sulfur dioxide emissions. Literature values for AP vary significantly, ranging from 5.16 kg SO₂ eq. MWh⁻¹ for torrefied pellets derived from forest residues to 105 kg SO₂ eq. MWh⁻¹ for Canadian forestry materials (KADIYALA; KOMMALAPATI; HUQUE, 2016). This variation can be attributed to the specific biomass species' sulfur content.

Additionally, electricity generation from wood biomass appears to produce higher AP values than natural gas, as corroborated by the findings of CHO; STREZOV, (2020) and further supported by data from DE ALMEIDA et al., (2017). The EP showed a lower overall impact, with most contributions stemming from the presence of nitrogen compounds during the bioenergy plant stage. These impacts are likely linked to ammonia and sodium hydroxide, chemicals used in bioenergy facilities (CORONA et al., 2020).

Regarding the ADP for fossil resources, Table 7 shows that the primary impacts stem from the transportation stage using diesel trucks. This result suggests that transportation distance significantly contributes to higher emissions (CHO; STREZOV, 2020). The impacts associated with chemicals can be attributed to the energy sources utilized to produce chemical products and lubricants (COCCO et al., 2014).

Finally, HTP revealed a total impact of 4.55 kg DCB eq., primarily due to sulfur dioxide emissions and particulate matter released into the air. Other studies have identified particulate emissions during biomass combustion as a major source of respiratory health impacts (SADAGHIANI; MAFAKHERI; CHEN, 2023). As noted earlier, the higher sulfur content in some Amazonian biomass species used in this study may explain the small but relevant contribution to HTP. Notably, biomass storage showed no impact in this category.

5.3 Comparison of Operation Modes

Figure 4(a) illustrates the total environmental results within the scope of this LCA, focusing on the power plant, storage and transport processes. Overall, Lábrea exhibits higher

impacts in the ADP fossil, HTP, EP, AP and GWP categories, suggesting that this isolated system has a greater potential for decarbonization. Consequently, it should be prioritized in the Annual Plan for Energy Operation of Isolated Systems (PEN SISOL) by EPE and the More Light for All Program.

A considerable impact is observed in the bioenergy scenario Figure 4(a) for the ADP fossil and AP categories. In contrast, the lowest impacts occur in the GWP (including CO₂ uptake), EP and HTP categories. For the latter category, the energy transition in isolated systems shows benefits that extend primarily to human health impacts. A prior study MARTÍN-GAMBOA et al., (2021) conducted a comparative S-LCA of Portugal's bioenergy system and fossil fuel chain. The findings indicated that the fossil fuel chain could exacerbate issues such as the gender gap, increased health expenditures, and forced labor. On the other hand, the development of bioenergy infrastructure has the potential to drive economic growth and generate significant added value.

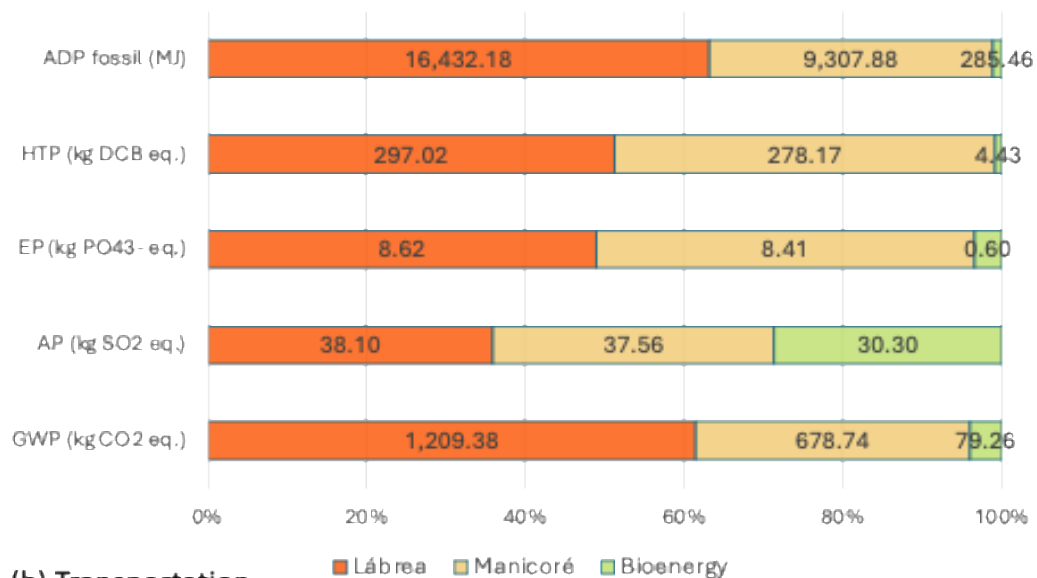
Finally, the total GWP for the bioenergy chain is lower than the value presented by the Lábrea and Manicoré systems. The lower values for bioenergy are similar to those reported in the literature (CHO; STREZOV, 2020). However, the values presented here can differ as this study adopts a holistic perspective, including direct and indirect emissions (e.g., resource extraction, downstream residue management, and logistics). This comprehensive approach could increase GHG emissions by up to 25% for fossil fuel systems and even higher percentages for renewable technologies (TURCONI; BOLDRIN; ASTRUP, 2013).

According to Figure 4(b), Manicoré and Lábrea exhibit different results in the GWP category for the transport stage, primarily due to the choice of transportation modes. Inland ships are less carbon-intensive because they can carry larger loads per route, resulting in lower fuel consumption per kilometer per cargo unit. When comparing the findings for bioenergy systems with the Lábrea scenario, the results align with the main literature (COCCO et al., 2014).

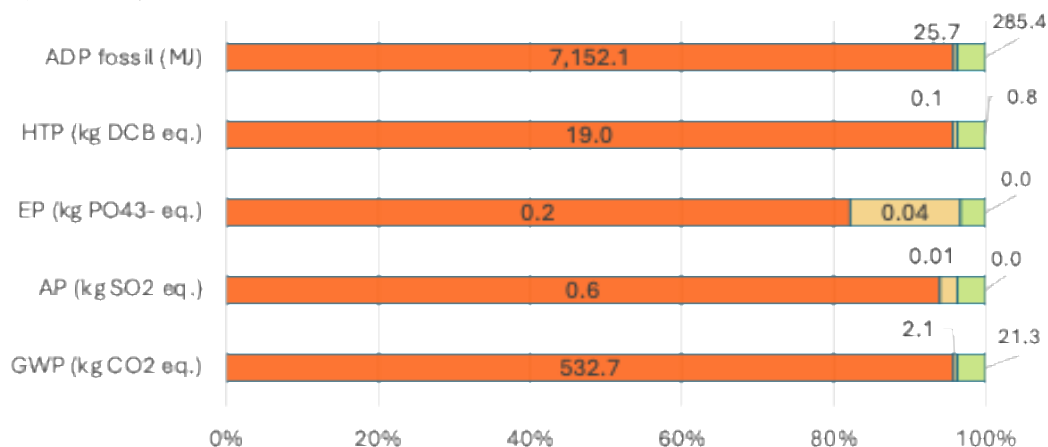
Additionally, the comparison between Manicoré and the bioenergy scenario reaffirms that waterways represent the optimal solution for fuel logistics in isolated systems. Furthermore, leveraging rivers for transportation in the Amazon aligns with the first requirement of the B-cube paradigm (biodiversity-biomass-biotechnology). This approach emphasizes the use of biodiversity not just for cataloging species and genes but also for utilizing ecosystems and landscapes as a resource for a modern biomass-based civilization that respects and integrates its diversity (SACHS, 2009).

Building upon this perspective, decarbonizing isolated systems using forest residues from areas under SFM could be a possible solution for coupled carbon market developments with electricity. A parallel can be drawn with Colombia, which has successfully combined REDD+ tropical forest projects with new initiatives in the aviation sector, demonstrating steady progress in assigning tangible value to the carbon stored in forests (LOZANO-BAEZ et al., 2024). This approach holds relevance since the Brazilian government approved Law 15.402 to implement the regulated carbon market in Brazil, the Brazilian Emissions Trading System (SBCE), in 2024, which can help improve forestry projects' credibility (ATMADJA et al., 2022).

(a) Total impact assessment results for 1 MWh



(b) Transportation



(c) Power plants

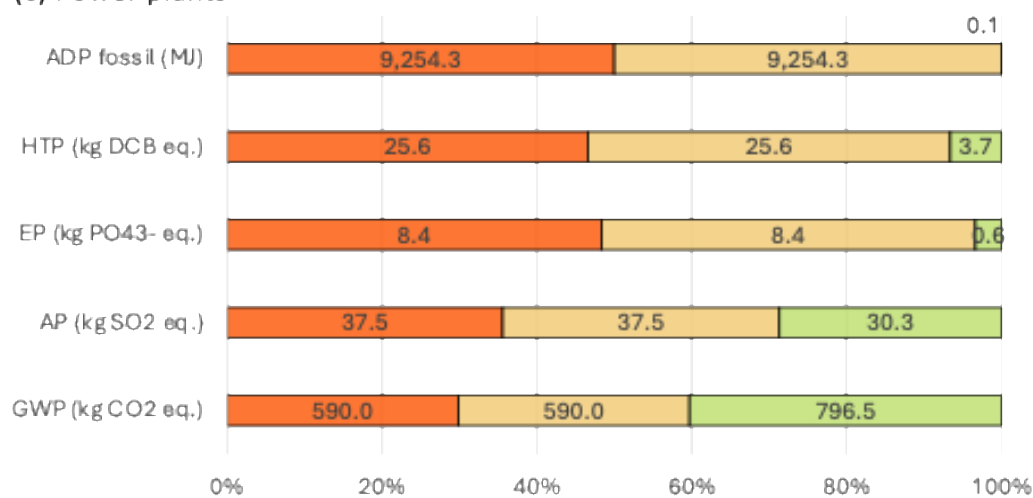


Figure 4. LCA results for (a) total, (b) transport and (c) power plants assessments.

Regarding the impact results specifically for the power plant stage (Figure 4(c)), Manicoré and Lábrea present identical values, as both systems share the same LCI. These systems yielded lower GWP emissions compared to bioenergy in this stage. SÁ et al., (2024) evaluated and compared the CO₂ and CH₄ emission factors, expressed in energy terms, for wood residues derived from Amazon forest biomass and diesel combustion used for energy production. The study revealed that CO₂ emissions were relatively similar between raw biomass combustion (69.773 tons MJ⁻¹) and diesel combustion (73.830 tons MJ⁻¹). However, depending on the combustion technology used, CH₄ emissions from the inefficient combustion of biomass could be significantly higher for forest residues (0.138 tons MJ⁻¹) than those from diesel combustion (0.007 tons MJ⁻¹), resulting in a greater overall GWP of biomass than diesel.

As illustrated in Figure 4(a), when accounting for carbon neutrality and performing a complete gate-to-grave analysis, the GWP of the bioenergy system is considerably lower than those of the fossil fuel chain. It is important to note that the stage of wood processing in the forest was excluded from this study due to a lack of available literature and primary data. Nevertheless, even if this stage were integrated within the limits of the LCA, the overall GWP results would still be significantly less intensive for biomass than those of the fossil fuel chain, as indicated by the order of magnitude obtained in this analysis.

In addition, the bioenergy scenario stands out due to its favorable AP, EP, HTP and ADP fossil results. Furthermore, bioenergy performance could be enhanced by implementing carbon capture and storage (CCS) technologies (LIU et al., 2024) and physical or thermochemical pre-treatments of the biomass, such as pelletization (SÁ et al., 2024) and torrefaction (SILVEIRA et al., 2025), and more intensive thermochemical treatments such as pyrolysis (SANTOS et al., 2025). These advancements would directly affect AP, HTP, and GWP results. It is important to note that this study does not consider any biomass treatment or advanced technological applications.

Finally, for diesel and biomass storage, the results are the opposite. While diesel presents a high score for HTP, the GWP impact of this stage is null. On the other hand, biomass storage shows considerable value for GWP due to methane and nitrous oxide emissions and a null impact for HTP. These results align with the findings presented by REPO; TUOMI; LISKI, (2011) Without any treatment or management, the bioenergy production from forest harvest residues produces emissions comparable to fossil fuel emissions over the first few years and decades. After 50 years, the bioenergy scenario decreases average emissions by 20% up to 60% compared to natural gas's entire fuel cycle emissions. However, this scenario could change with a pre-treatment process, such as torrefaction (SILVEIRA et al., 2025) and pelletization (SÁ et

al., 2024), which could increase energy density, decrease moisture content and fungal attacks, and minimize the impact of GWP on storage.

Figure 5 overviews the air, soil, and water emissions during the gate-to-gate analysis. The data indicate that Lábrea exhibits higher air emissions (1573.97 kg) than those from the Manicoré system (938.02 kg), primarily driven by CO₂ and CO emissions during transportation. The bioenergy system provides significantly lower air emissions (154.354 kg) compared to both scenarios.

Manicoré recorded the highest levels of water emissions (18.27 kg), attributed to the extended distances involved in inland ship transportation, significantly contributing to the HTP impact on freshwater. Meanwhile, soil emissions were 0.12 kg for the bioenergy system, whereas Lábrea displayed a lower impact (0.01 kg). This effect is specifically linked to agricultural emissions, likely resulting from the current mandatory biodiesel blending in diesel-based fuel enforced in Brazil.

According to PASI, (2024), the total energy generation in Lábrea was 48,067.09 MWh, while in Manicoré, it was 45,381.90 MWh in 2023. Based on the findings of this LCA, the total GWP emissions for 2023 for Manicoré and Lábrea were 32,624.57 t CO₂ and 54,883.96 t CO₂, respectively. However, the PASI data for Lábrea reported only 36,627.12 t CO₂, representing 66% of the total emissions identified in this study. This discrepancy can be attributed to including the transport stage in this LCA, which is not accounted for in the government's calculations. This highlights the importance of incorporating LCA methodologies into government planning to support more comprehensive and informed decision-making.

The results presented for the diesel-based systems in Manicoré and Lábrea underscore the urgent need to accelerate the transition away from fossil fuels, particularly when comparing the current emission factor of the SIN with the values identified in this study. In 2023, Brazil's National Emissions Registration System (SIRENE) reported an average emission factor of 38.5 kg CO₂ eq per MWh for the SIN (MCTI, 2024).

In contrast, Lábrea and Manicoré exhibit an emission factor of approximately 32 and 18 times higher than those from the SIN. This significant disparity is particularly striking given that Brazil has a renewability of the electrical matrix close to 87%, mainly through hydropower, biomass, wind and solar sources (EXECUTIVO et al., 2024).

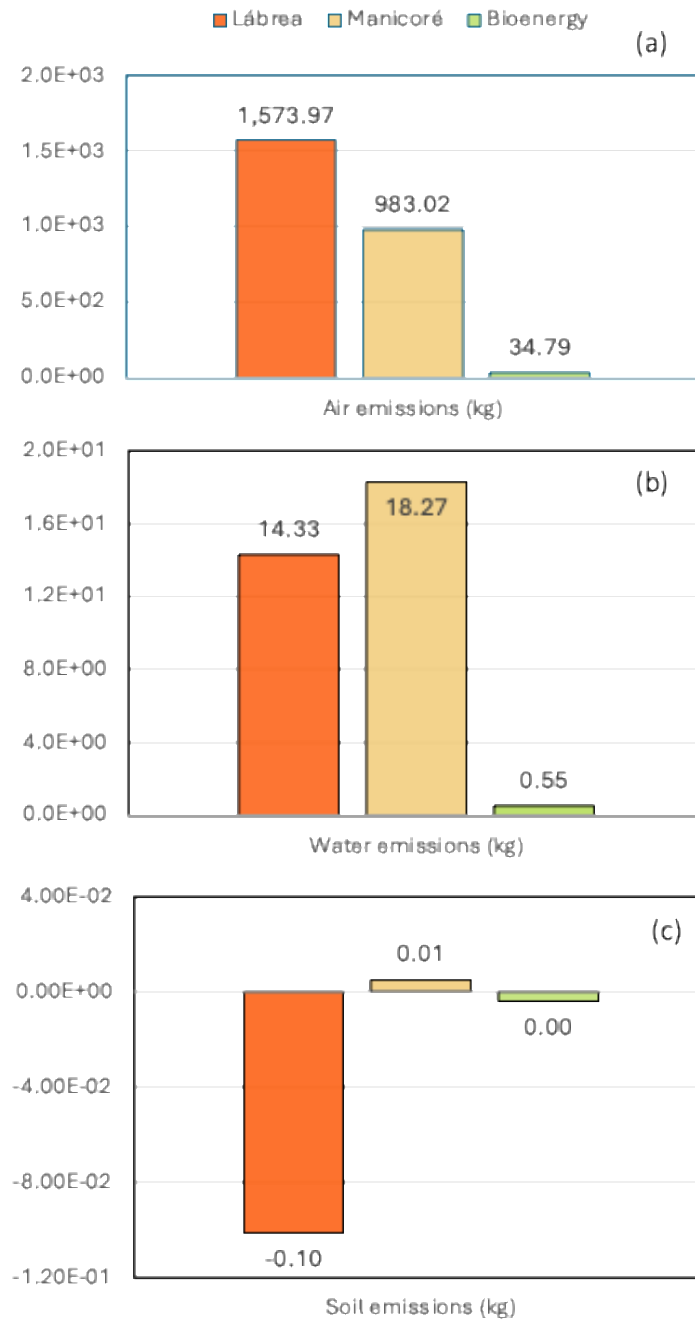


Figure 5. Total emissions to air (a), soil (b), and water (c) per 1 MWh of electricity produced for the fossil fuel chain (Lábrea and Manicoré) and bioenergy systems.

At the same time, Mexico's National Electric System (SEN) relies heavily on fossil fuels, which account for 79% of its total primary energy supply, resulting in an emission factor of 573.3 kg CO₂ eq. MWh⁻¹, as reported in the LCA conducted by SANTOYO-CASTELAZO; GUJBA; AZAPAGIC, (2011). Even though the emission factor value is lower for Mexico, compared to Manicoré and Lábrea, due to the 30% of renewables in the Mexican electricity matrix, Manicoré has an emission factor of 1.18 times higher. This disparity poses a significant

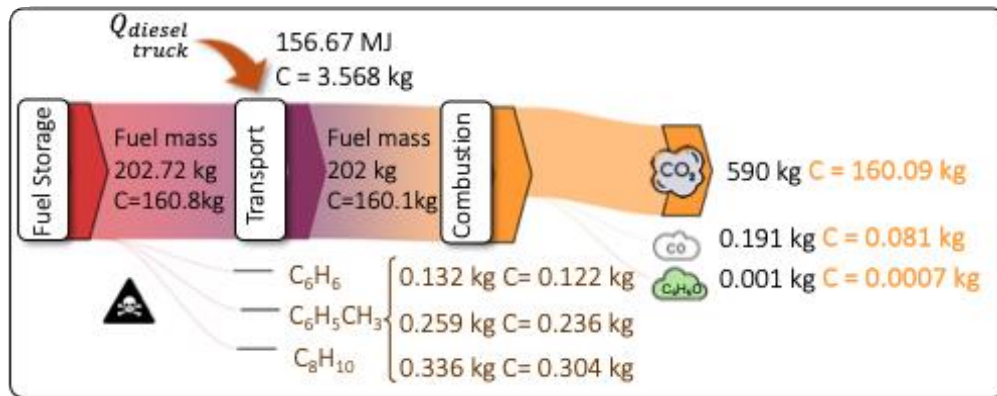
challenge to the climate change agenda, especially considering that Manicoré is a small city with a relatively low electricity demand compared to Mexico. Moreover, the energy profiles of Manicoré and Lábrea bear striking similarities to those of some Caribbean islands, where fossil fuels account for 97% of the total final energy consumption (IRENA, 2024). For islands such as Turks and Caicos, Saint Lucia, Saint Vincent and the Grenadines, and Saint Kitts and Nevis, the energy consumption pattern mirrors that of Manicoré and Lábrea, with 100% of energy consumption derived from fossil fuels (IRENA, 2024).

5.4 Carbon Balance

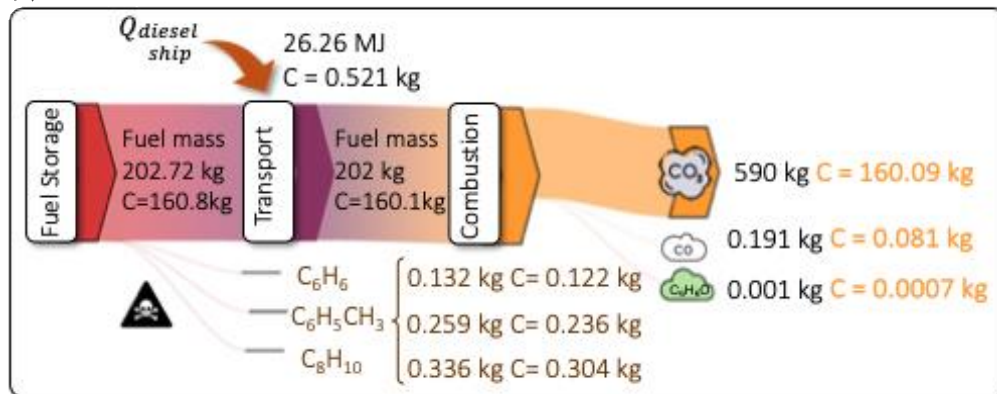
Figure 6 presents the carbon balance results for bioenergy and diesel systems. In Figures 6(a) and (b), it is evident that most of the carbon emissions in the diesel system occur during the combustion phase, with minimal hydrocarbon emissions during storage; however, emissions from storage are carcinogenic. Additionally, the carbon balance highlights the benefits of waterway transportation, which emerges as the optimal solution from an energy perspective and in terms of minimizing carbon injected into the system.

Figure 6(c) reveals a carbon neutrality of 758.611 kg CO₂, a value derived from biogenic carbon captured by photosynthesis. This value is relatively conservative; since it is under the assumption of biomass combustion carbon neutrality. Conversely, total CO₂ emissions from bioenergy could potentially be higher if more stringent accounting approaches were applied, as CO₂ emitted during biomass combustion is released as a one-time pulse but persists in the atmosphere for several years (GUEST; CHERUBINI; STRØMMAN, 2013). In the work performed by LIU et al., (2017), for a 20-year rotation in SFM, there is a 35% decay of CO₂ in the atmosphere, which implies a carbon removal of 517.66 kg CO₂ and a residual unaccounted value of 278.74 kg CO₂. Extending the rotation period to 30 years could further enhance carbon removal, potentially neutralizing nearly all combustion emissions, considering the one-time pulse effect.

(a) Lábrea Carbon Balance for FU of 1 MWh



(b) Manicoré Carbon Balance for FU of 1 MWh



(c) Bioenergy Carbon Balance for FU of 1 MWh

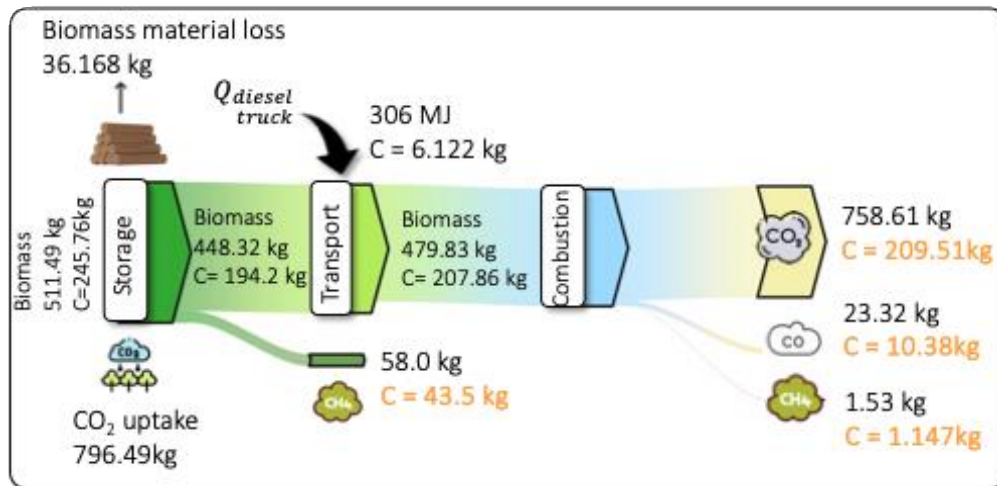


Figure 6. Carbon balance for 1MWh in (a) Lábrea, (b) Manicoré, and (c) Bioenergy energy systems.

5.5 Carbon Market

The combination of avoided CO₂ eq. emissions and financial gains derived from carbon credits and CBIO values demonstrate the economic and environmental viability of transitioning to bioenergy models. This analysis underscores the critical role of bioenergy systems in

reducing greenhouse gas emissions while encouraging financial sustainability through increasing carbon credit values. Figure 7(a) shows the GWP impact of the biomass valorization route, considering key sources such as storage, transportation, power plant emissions, and the carbon uptake by biomass.

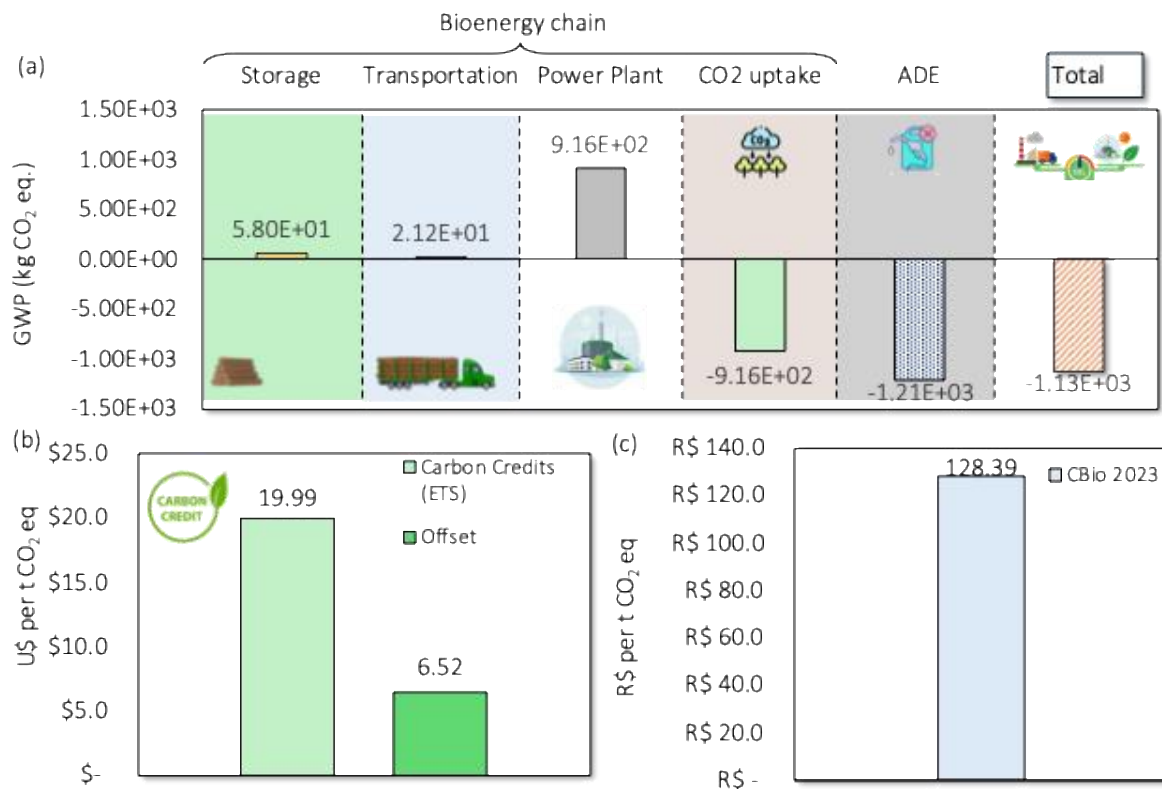


Figure 7. Global warming potential (GWP) assessment of the biomass valorization route, detailing contributions from storage, transportation, power plant emissions, CO₂ uptake, and avoided diesel emissions (ADE). Financial analysis (b) of carbon credits (in USD) and (c) CBIOs values (in BRL).

Notably, the CO₂ neutrality by the biomass (-7.58E+02 kg CO₂ eq.) and avoided diesel emissions (ADE, -1,209.38 kg CO₂ eq.) contributed significantly to offsetting emissions from storage (5.80E+01 kg CO₂ eq.), transportation (2.12E+01 kg CO₂ eq.), and power plant operations (3.79E+01 kg CO₂ eq.). This outcome highlights the substantial environmental benefits of substituting fossil fuel-based systems with biomass-based energy production, aligning with the targets to reduce greenhouse gas emissions and promote sustainable practices.

Figures 7(b) and (c) present the carbon credits and CBIOs prospects for the project (detailed calculation is available in Annex 5). From an economic perspective, integrating carbon credits and CBIOs assessment highlights the economic viability of transitioning to bioenergy systems. In a regulatory market scenario, the value of carbon credits was estimated at \$19.32

per t CO₂ eq. in 2024, reflecting a promising trajectory for market-driven incentives. The credit price could reach US\$6.30 per t CO₂ eq in offset markets. Additionally, CBIOs in Brazil were valued at R\$124.09 per t CO₂ eq. in 2023. These values emphasize the financial benefits realized through carbon trading mechanisms, enhancing the economic attractiveness of biomass power plants and incentivizing broader adoption of renewable energy models.

Furthermore, CBIOs serve not only as a valuable tool for engaging investors and fostering interest in energy transition but also as a strategic instrument for policymakers to manage the risks associated with energy prices, a critical issue in isolated systems where volatile diesel costs largely influence electricity prices (PALAZZI et al., 2024).

6. LIMITATIONS AND PROSPECTS

This study faced limitations inherent to its nature as the first attributional LCA conducted in this field and due to certain assumptions made during the analysis. To evaluate the proposition presented by MARTINEZ-HERNANDEZ et al., (2022) the bioenergy system was modeled using the simplest technology available. Consequently, the bioenergy GWP, excluding carbon uptake, reached levels higher than those observed in the fossil fuel (diesel-based) scenario. While simple systems may offer social benefits, they fail to mitigate environmental risks adequately. Incorporating pre-treatment processes and advanced technologies, such as carbon capture and storage, could reduce environmental impacts.

Additionally, the transportation technology for biomass and diesel may not accurately reflect the logistical realities of the region. Euro VI trucks were selected for this analysis due to their superior environmental performance. However, Brazil is equipped with an old fleet of heavy-duty vehicles (MINISTÉRIO DO TRANSPORTE, 2024), particularly in the northern regions, which are characterized by lower gross domestic product (GDP) and weaker economic indicators (NOBRE et al., 2023).

Another critical aspect relates to carbon uptake. This study adopted the standard approach for bioenergy, which consists in biomass carbon neutrality. However, this does not align with the advanced literature for SFM (LIU et al., 2018), which often incorporates the capture of CO₂ in the atmosphere and *in situ* decomposition rates.

To address these gaps, future research should be carried out on a cradle-to-grave LCA for bioenergy, encompassing pre-treatment processes, grinding, wood biodegradation, biomass processing and natural drying at the forest stage. A more accurate methodology for accounting for CO₂ uptake, such as those employed in (GUEST; CHERUBINI; STRØMMAN, 2013; LIU

et al., 2017), should be adopted. Future studies should also integrate social and economic life cycle assessments into bioenergy systems analysis, such as employability, socio-environmental issues and tax collection, as these points are particularly critical for isolated systems. In addition, the data presented here for the bioenergy life cycle inventory could present improvements, since some numbers are results of averages and data with unknown reliability index.

7. CONCLUSIONS

This study analyzed the environmental impacts of electricity generation in isolated systems through an LCA, comparing diesel-powered thermal power plants with bioenergy derived from wood residues produced by SFM. The results indicated that Lábrea exhibits the highest environmental footprint compared to Manicoré's city, highlighting the need to prioritize this municipality in future PEN SISOL plans. The fossil fuel-based system demonstrated higher impacts across most environmental indicators, including human toxicity potential (HTP), abiotic depletion potential for fossil resources (ADP-fossil), acidification potential (AP), and eutrophication potential (EP), than the bioenergy alternative. Bioenergy exhibited lower emissions for global warming potential (GWP) than those from Lábrea and Manicoré, assuming carbon uptake is factored into the analysis. However, given the ongoing debate in the literature regarding biogenic carbon, GWP results may vary, potentially making bioenergy appear less environmentally favorable.

Nevertheless, this discrepancy should not be interpreted as a justification for maintaining the status quo or continuing reliance on fossil fuels. Instead, this study compares a well-established fossil fuel technology and a simpler and less sophisticated bioenergy alternative. The results indicate that bioenergy from Amazonian residues holds promise, as the power plant stage of the bioenergy system resulted in lower GWP.

Bioenergy thus emerges as a viable solution for decarbonizing isolated systems while contributing to several Sustainable Development Goals (SDGs), including SDG1 (No Poverty), SDG7 (Affordable and Clean Energy), SDG8 (Decent Work and Economic Growth), and SDG10 (Reduced Inequalities). The social benefits of transitioning to bioenergy extend beyond SDGs 7 and 8. In Global South countries, this transition could enable infrastructure development for basic sanitation services, such as water pumping, purification, and sewage treatment (SDG6). In the specific cases of Manicoré and Lábrea, bioenergy could positively

impact approximately 1,547 families by increasing their income and enabling the production of more complex, low-carbon goods for external markets.

Finally, given the Amazon biome's ecological and cultural heterogeneity, this study does not propose bioenergy from SFM residues as a one-size-fits-all solution. A universal approach would fail to address the unique challenges at the micro-regional level. Instead, this work aligns with Sachs' B-cube concept, which promotes a holistic and multidisciplinary framework combining natural and social sciences to utilize biodiversity resources sustainably.

REFERENCES

ABDEL AZIZ, O. et al. **Plano de Manejo da Reserva de Desenvolvimento Sustentável do Rio Amapá**. Manaus: [s.n.].

ABNT. **Armazenagem de líquidos inflamáveis e combustíveis Parte 1: Armazenagem em tanques estacionários**. [s.l.: s.n.]. Disponível em: <www.abnt.org.br>.

ABRAMOVAY, R. **Infraestrutura para o desenvolvimento sustentável da Amazônia**. São Paulo: Editora Elefante, 2022.

AMARAL, S. S. et al. Comparative study for hardwood and softwood forest biomass: Chemical characterization, combustion phases and gas and particulate matter emissions. **Bioresource Technology**, v. 164, p. 55–63, 2014.

AMORIM, E. B. et al. Influence of specimen size, tray inclination and air flow rate on the emission of gases from biomass combustion. **Atmospheric Environment**, v. 74, p. 52–59, ago. 2013.

ANP. **Painel Dinâmico da Tancagem do Abastecimento Nacional de Combustíveis**. Disponível em: <<https://app.powerbi.com/view?r=eyJrIjoiaWJlY00MzgzLThjNWUtMzUxMjg1ZGYwY2FhIiwidCI6IjQ0OTlmNGZmLTl0YTYtNGI0Mi1iN2VmLTExNGFmY2FkYzkxMyJ9>>. Acesso em: 11 jun. 2024.

ARAUJO, R. O. et al. **Renewable Energy from Biomass: an Overview of the Amazon Region**. **Bioenergy Research** Springer, , 1 jun. 2022.

ARCOS–AVILES, D. et al. Model predictive control-based energy management system for an isolated electro-thermal microgrid in the Amazon region of Ecuador. **Energy Conversion and Management**, v. 310, 15 jun. 2024.

ATMADJA, S. S. et al. How do REDD+ projects contribute to the goals of the Paris Agreement? **Environmental Research Letters**, v. 17, n. 4, 1 abr. 2022.

BARROS, D. DE S. et al. Does the Segregation of Wood Waste from Amazonia Improve the Quality of Charcoal Produced in Brick Kilns? **Bioenergy Research**, v. 16, n. 3, p. 1604–1617, 1 set. 2023.

BLANTON, A. et al. **The status of forest carbon markets in Latin America**. **Journal of Environmental Management** Academic Press, , 1 fev. 2024.

BOUZAROVSKI, S.; PETROVA, S. A global perspective on domestic energy deprivation: Overcoming the energy poverty-fuel poverty binary. **Energy Research and Social Science**, v. 10, p. 31–40, 11 jul. 2015.

BRADSHAW, A.; DE MARTINO JANNUZZI, G. Governing energy transitions and regional economic development: Evidence from three Brazilian states. **Energy Policy**, v. 126, p. 1–11, 1 mar. 2019.

CALDEIRA-PIRES, A. et al. Implications of removing straw from soil for bioenergy: An LCA of ethanol production using total sugarcane biomass. **Journal of Cleaner Production**, v. 181, p. 249–259, 20 abr. 2018.

CCEE. **Conta de consumo de combustíveis - ccc**. Disponível em: <<https://www.ccee.org.br/mercado/contas-setoriais/conta-consumo-de-combustiveis-ccc>>. Acesso em: 28 jan. 2025a.

CCEE. **Estudo da CCEE aponta crescimento de 6,8% no consumo de energia no primeiro semestre de 2024**. Disponível em: <<https://www.ccee.org.br/pt/web/guest/-/estudo-da-ccee-aponta-crescimento-de-6-8-no-consumo-de-energia-brasileiro-no-primeiro-semester-de-2024>>. Acesso em: 21 jan. 2025b.

CHO, H. H.; STREZOV, V. **A Comparative Review on the Environmental Impacts of Combustion-Based Electricity Generation Technologies**. **Energy and Fuels**American Chemical Society, , 17 set. 2020.

COCCO, D. et al. LCA study of oleaginous bioenergy chains in a Mediterranean environment. **Energies**, v. 7, n. 10, p. 6258–6281, 2014.

CONDÉ, T. M. et al. Effects of sustainable forest management on tree diversity, timber volumes, and carbon stocks in an ecotone forest in the northern Brazilian Amazon. **Land Use Policy**, v. 119, p. 106145, ago. 2022.

CORDEIRO, D. DE F. DE J. **Avaliação de Resíduos de Exploração Florestal de Impacto Reduzido da Fazenda Rio Capom-Cikel Brasil Verde Madeira Ltda no Município de Paragominas - PA**. Dissertation—Belém : Universidade Federal Rural da Amazônia, 2006.

CORONA, B. et al. Consequential Life Cycle Assessment of energy generation from waste wood and forest residues: The effect of resource-efficient additives. **Journal of Cleaner Production**, v. 259, 20 jun. 2020.

DE ALMEIDA, C. F. et al. Environmental assessment of a bi-fuel thermal power plant in an isolated power system in the Brazilian Amazon region. **Journal of Cleaner Production**, v. 154, p. 41–50, 15 jun. 2017.

DE AREA LEÃO PEREIRA, E. J. et al. Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest. **Environmental Science and Policy**, v. 100, p. 8–12, 1 out. 2019.

DE OLIVEIRA, D. C. et al. Small steam turbine operating at low pressure for generating electricity in the Amazon. **Revista Materia**, v. 28, n. 2, 2023.

DEUTSCH, L. et al. Life cycle and risk assessment of vinasse storage dams: A Brazilian sugar-energy refinery analysis. **Sustainable Futures**, v. 4, p. 100083, 1 jan. 2022.

ECOSYSTEM MARKETPLACE. **Global Carbon Markets Hub**. Disponível em: <<https://hub.ecosystemmarketplace.com/landing>>. Acesso em: 4 jan. 2025.

EGBAELU, P.; BELLO, E. I.; AYODEJI, O. Z. Performance and Evaluation of the Heating Value of Wood Biomass for Use in Steam Thermal Power Plant. **International Research Journal of Innovations in Engineering and Technology**, v. 05, n. 12, p. 73–83, 2021.

EMPRESA DE PESQUISA ENERGÉTICA. **Balanco Energético Nacional 2024: Ano base 2023**. Rio de Janeiro: [s.n.]. Disponível em: <<http://www.epe.gov.br>>.

ENBPAR. **Programa de Incentivo às Fontes Alternativas de Energia Elétrica**. Disponível em: <<https://enbpar.gov.br/areas-de-atuacao/programas-setorias/proinfra/>>. Acesso em: 24 jan. 2025.

EPE. **Planejamento do Atendimento aos Sistemas Isolados Horizonte 2023-2027 Ciclo 2022**. [s.l: s.n.]. Disponível em: <www.epe.gov.br>.

EPE. **Informativo Técnico n.011/2022**. Rio de Janeiro: [s.n.]. Disponível em: <https://www.epe.gov.br/sites-pt/areas-de-atuacao/estudos-socioambientais/SiteAssets/Paginas/Emissoes-de-Gases-de-Efeito-Estufa/Informativo%20Tecnico_11-2022_fatores%20de%20emissaoSMA.pdf>. Acesso em: 19 set. 2024b.

EXECUTIVO, S. et al. **Plano de Expansão Decenal de Energia 2034: Caderno de Consolidação de Resultados**. [s.l: s.n.]. Disponível em: <[https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-804/topico-709/PDE%202034_Consolidacao%20de%20Resultados_20241106%20\(1\).pdf](https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-804/topico-709/PDE%202034_Consolidacao%20de%20Resultados_20241106%20(1).pdf)>. Acesso em: 1 jan. 2025.

FAN, A. et al. Decarbonising inland ship power system: Alternative solution and assessment method. **Energy**, v. 226, 1 jul. 2021.

FERREIRA, G. et al. Wood Waste Pellets as an Alternative for Energy Generation in the Amazon Region. **Bioenergy Research**, v. 16, n. 1, p. 472–483, 1 mar. 2023.

FINNVEDEN, G. et al. **Recent developments in Life Cycle Assessment**. **Journal of Environmental Management** Academic Press, , 2009.

FRANÇA, L. C. DE J. et al. Towards renewable energy projects under sustainable watersheds principles for forest biomass supply. **Biomass and Bioenergy**, v. 176, 1 set. 2023.

GOOGLE. **GoogleMaps: Lábrea and Manicoré**. Disponível em: <<https://www.google.com/maps>>. Acesso em: 10 dez. 2024.

GUEST, G.; CHERUBINI, F.; STRØMMAN, A. H. The role of forest residues in the accounting for the global warming potential of bioenergy. **GCB Bioenergy**, v. 5, n. 4, p. 459–466, 2013.

HAMPL, N. **Energy systems for Brazil's Amazon: Could renewable energy improve Indigenous livelihoods and save forest ecosystems?** **Energy Research and Social Science** Elsevier Ltd, , 1 jun. 2024.

HENRIQUE DA COSTA OLIVEIRA, C. et al. Evaluation of the hydraulic potential with hydrokinetic turbines for isolated systems in locations of the Amazon region. **Sustainable Energy Technologies and Assessments**, v. 45, 1 jun. 2021.

IBGE. **Produção da Extração Vegetal e Silvicultura**. [s.l: s.n.]. Disponível em: <<http://comexstat.mdic.gov.br/pt/comex-vis>>.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. Em: **Climate Change 2021 – The Physical Science Basis**. [s.l.] Cambridge University Press, 2023. p. 923–1054.

IRENA. **Renewable energy for remote communities: A guidebook for off-grid projects**. Abu Dhabi: International Renewable Energy Agency, 1 nov. 2023. Disponível em: <<https://www.irena.org/Publications/2023/Nov/Renewable-energy-for-remote-communities-A-guidebook-for-off-grid-projects>>. Acesso em: 31 mar. 2024.

IRENA. **Sustainable bioenergy potential in Caribbean small island developing states**. Abu Dhabi: [s.n.]. Disponível em: <<https://www.irena.org/Publications/2024/Feb/Sustainable-bioenergy-potential-in-Caribbean-small-island-developing-states>>. Acesso em: 19 set. 2024.

JENKINS, K. et al. **Energy justice: A conceptual review**. *Energy Research and Social Science* Elsevier Ltd, , 1 jan. 2016.

KADIYALA, A.; KOMMALAPATI, R.; HUQUE, Z. Evaluation of the life cycle greenhouse gas emissions from different biomass feedstock electricity generation systems. **Sustainability (Switzerland)**, v. 8, n. 11, 16 nov. 2016.

KUMARI, P. et al. Measurement of benzene and other volatile organic compounds: implications for its inhalation health risk associated with the workers at a fuel station in Delhi. **Asian Journal of Atmospheric Environment**, v. 17, n. 1, 1 dez. 2023.

LIMA, M. D. R. et al. Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation. **Biomass and Bioenergy**, v. 166, 1 nov. 2022.

LIU, C. et al. Ammonia-based post-combustion CO₂ and SO₂ integrating capture using multi-stage solvent circulation process. **Separation and Purification Technology**, v. 339, 2 jul. 2024.

LIU, W. et al. Analysis of the Global Warming Potential of Biogenic CO₂ Emission in Life Cycle Assessments. **Scientific Reports**, v. 7, 3 jan. 2017.

LIU, W. et al. **A critical analysis of the carbon neutrality assumption in life cycle assessment of forest bioenergy systems**. *Environmental Reviews* Canadian Science Publishing, , 2018.

LOZANO-BAEZ, S. E. et al. **Attention needed in forest carbon projects: An analysis of initiatives in Colombia**. *Forest Ecology and Management* Elsevier B.V., , 15 dez. 2024.

LUIZ, A.; DE ANDRADE, M. **Plano de Manejo da Reserva de Desenvolvimento Sustentável Rio Madeira**. Manaus: [s.n.].

LUIZ, A.; DE ANDRADE, M. **Plano de Manejo da Reserva de Desenvolvimento Sustentável Igapó-Açú**. Manaus: [s.n.].

MACHADO, V. DE F. **A PRODUÇÃO DO DISCURSO DO DESENVOLVIMENTO SUSTENTÁVEL: DE ESTOCOLMO À RIO-92**. Brasília: Universidade de Brasília, Centro de Desenvolvimento Sustentável, ago. 2005.

MAJ, G. Emission factors and energy properties of agro and forest biomass in aspect of sustainability of energy sector. **Energies**, v. 11, n. 6, 1 jun. 2018.

MARTINEZ-HERNANDEZ, E. et al. Modelling to analyse the process and sustainability performance of forestry-based bioenergy systems. **Clean Technologies and Environmental Policy**, v. 24, n. 6, p. 1709–1725, 1 ago. 2022.

MARTÍN-GAMBOA, M. et al. Comparative social life cycle assessment of two biomass-to-electricity systems. **International Journal of Environmental Research and Public Health**, v. 18, n. 9, 1 maio 2021.

MCTI. **Fator médio - Inventários corporativos**. Disponível em: <<https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/dados-e-ferramentas/fatores-de-emissao>>. Acesso em: 30 dez. 2024.

MINISTÉRIO DE MINAS E ENERGIA. **Programa Luz para Todos**. Disponível em: <<https://www.gov.br/mme/pt-br/destaques/Programa%20Luz%20para%20Todos/sobre-o-programa>>. Acesso em: 21 jan. 2025.

MINISTÉRIO DO TRANSPORTE. **Frota de Veículos - 2024**. Disponível em: <<https://www.gov.br/transportes/pt-br/assuntos/transito/conteudo-Senatran/frota-de-veiculos-2024>>. Acesso em: 1 jan. 2025.

MIRANDA, D. S.; KULAY, L. A prospective study on the environmental feasibility of supplying electricity to the Brazilian Amazon through biogas power generation. **Sustainable Energy Technologies and Assessments**, v. 55, 1 fev. 2023.

MMA. **Instrução normativa Número 5. Ministério do Meio Ambiente**. https://snif.florestal.gov.br/images/pdf/legislacao/normativas/in_mma_04_2006.pdf, 11 dez. 2006.

NEWELL, P.; PHILLIPS, J. Neoliberal energy transitions in the South: Kenyan experiences. **Geoforum**, v. 74, p. 39–48, 1 ago. 2016.

NOBRE, C. A. et al. New Economy for the Brazilian Amazon. **World Resources Institute**, jul. 2023.

OZTURK, M.; DINCER, I. Comparative environmental impact assessment of various fuels and solar heat for a combined cycle. **International Journal of Hydrogen Energy**, v. 44, n. 10, p. 5043–5053, 22 fev. 2019.

PALAZZI, R. B. et al. Exploring the potential of the carbon credit program for hedging energy prices in Brazil. **Environmental Science and Pollution Research**, v. 31, n. 13, p. 20678–20688, 1 mar. 2024.

PASI. **Portal de Acompanhamento e Informação dos Sistemas Isolados**. Disponível em: <<https://pasi.epe.gov.br>>. Acesso em: 14 jun. 2024.

PENA-VEGA, A. **Os sete saberes necessários a educação sobre as mudanças climáticas**. São Paulo: Cortez Editora, 2023.

PEREIRA, A. A. et al. Grouping of wood residues from sustainable forest management aiming at bioenergy generation. **Scientia Forestalis/Forest Sciences**, v. 48, n. 127, 2020.

PRETO, F. **Plano de Gestão do Mosaico de Unidades de Conservação do Apuí**. [s.l: s.n.].

REPO, A.; TUOMI, M.; LISKI, J. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. **GCB Bioenergy**, v. 3, n. 2, p. 107–115, 2011.

RIAL, M.; PÉREZ, J. Environmental performance of four different heavy-duty propulsion technologies using Life Cycle Assessment. **Transportation Research Interdisciplinary Perspectives**, v. 11, 1 set. 2021.

RÖDER, M.; WHITTAKER, C.; THORNLEY, P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. **Biomass and Bioenergy**, v. 79, p. 50–63, 26 jun. 2014.

SÁ, I. A. et al. Evaluating the quality of wood waste pellets and environmental impact mitigation for decentralized energy recovery in the Amazon. **Renewable Energy**, v. 231, 1 set. 2024.

SACHS, I. **Caminhos para o desenvolvimento sustentável**. Rio de Janeiro: Garamond, 2009.

SADAGHIANI, S.; MAFAKHERI, F.; CHEN, Z. Life Cycle Assessment of Bioenergy Production Using Wood Pellets: A Case Study of Remote Communities in Canada. **Energies**, v. 16, n. 15, 1 ago. 2023.

SÁNCHEZ, M. DE LA C. Pobreza y vulnerabilidad energética en México: caracterización a partir de los usos locales de la energía. **Espiral estudios sobre Estado y sociedad**, v. 31, n. 91, 2 set. 2024.

SANTOS, P. L. DOS et al. Exploring the effects of slow pyrolysis temperature and species on the quality of charcoal from Amazonian woody wastes. **Renewable Energy**, p. 122257, dez. 2025.

SANTOYO-CASTELAZO, E.; GUJBA, H.; AZAPAGIC, A. Life cycle assessment of electricity generation in Mexico. **Energy**, v. 36, n. 3, p. 1488–1499, 2011.

SEMA (SECRETARIA DE ESTADO DO MEIO AMBIENTE DO AMAZONAS). **Informações Gerais das Unidades de Conservação estaduais do Amazonas**. Disponível

em: <https://www.sema.am.gov.br/wp-content/uploads/2024/03/Planilha_Infor-UC-atualizada-2021.pdf>. Acesso em: 11 jun. 2024.

SILVA, D. A. L. et al. **A systematic review and life cycle assessment of biomass pellets and briquettes production in Latin America. Renewable and Sustainable Energy Reviews** Elsevier Ltd, , 1 abr. 2022.

SILVEIRA, E. A. et al. Mass and energy allocation method analysis for an oil refinery characterization using multi-scale modeling. **The International Journal of Life Cycle Assessment**, v. 22, n. 11, p. 1815–1822, nov. 2017.

SILVEIRA, E. A. et al. Effect of torrefaction severity on the energy recovery from amazonian wood residues for decentralized energy conversion systems. **Biomass and Bioenergy**, v. 193, p. 107515, fev. 2025.

SINGH, P.; SINGH, N. Political economy of bioenergy transitions in developing countries: A case study of Punjab, India. **World Development**, v. 124, 1 dez. 2019.

SOARES NETO, T. G. et al. Laboratory evaluation of Amazon forest biomass burning emissions. **Atmospheric Environment**, v. 45, n. 39, p. 7455–7461, dez. 2011.

SOLIANO PERREIRA, O.; REIS, T. M.; RÜTHER, R. Amazon energy transition: The need to accelerate emission reduction by the extensive adoption of solar photovoltaics and storage in Brazil. **Energy for Sustainable Development**, v. 80, 1 jun. 2024.

S&P GLOBAL. **Interactive: Platts Carbon Price Explorer**. Disponível em: <<https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/090624-interactive-platts-carbon-price-explorer>>. Acesso em: 6 jan. 2025.

TOLMASQUIM, M. T. et al. Electricity market design and renewable energy auctions: The case of Brazil. **Energy Policy**, v. 158, 1 nov. 2021.

TURCONI, R.; BOLDRIN, A.; ASTRUP, T. **Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews** Elsevier Ltd, , 2013.

VOIVODIC, M. et al. **Perfil socioeconômico e ambiental do sul do estado do Amazonas: Subsídios para Análise da Paisagem**. [s.l: s.n.].

WERNER, D.; LAZARO, L. L. B. The policy dimension of energy transition: The Brazilian case in promoting renewable energies (2000–2022). **Energy Policy**, v. 175, 1 abr. 2023.

WIHERSAARI, M. Evaluation of greenhouse gas emission risks from storage of wood residue. **Biomass and Bioenergy**, v. 28, n. 5, p. 444–453, maio 2005.

WORLD BANK. **State and Trends of Carbon Pricing Dashboard**. Disponível em: <<https://carbonpricingdashboard.worldbank.org>>. Acesso em: 4 jan. 2025.

WORLD RESOURCES INSTITUTE. **Climate Watch Historical GHG Emissions**.
Disponível em: <<https://www.climatewatchdata.org/ghg-emissions>>. Acesso em: 28 jan. 2025.

APPENDIX

APPENDIX 1

The total amount of biomass residues produced in Lábrea and Manicoré were calculated by data provided by the Plant Extraction and Forestry Production (PEVS), a sawmill coefficient of 1.70 presented by (CORDEIRO, 2006), and a management coefficient of 0.65. The result was the Equation S1 for estimating residues production, where R_{PEVS} corresponds to the wood production in m³.

$$R_{production} = (R_{PEVS} \cdot 1.7) + (R_{PEVS} \cdot 0.65) \quad (S1)$$

Subsequently, the total available energy was estimated using an average calorific value of 21.32 MJ/kg and a mean basic density of 662.11 kg/m³. The result is presented in Equation S2, where $E_{available}$ represents the total energy availability in MWh.

$$E_{available} = \frac{662.11 \cdot 21.32}{3600} \cdot R_{PEVS} \quad (S2)$$

APPENDIX 2

Table A 1. Information sources for the inventory.

Source	Information	Ref.
CCEE (The Electricity Trading Chamber)	Annual consumption of diesel	(CCEE, 2024a)
EPE (Energy Research Company)	Energy demand and losses	(EPE, 2022a)
ANP (National Oil and Gas Agency)	Tankage information (location and volume)	(ANP, 2023)
PASI (Monitoring and Information Portal for Isolated Systems)	Energy consumption profile per sector and activity	(PASI, 2024)
IBGE (Brazilian Institute of Geography and Statistics)	PEVS (Quantity of Roundwood produced and the value of production for extraction of wood	(IBGE, 2022)
SEMA (Amazonas State Secretariat for the Environment)	Sustainable forest plans, management data, type of species per conservation units	(SEMA (SECRETÁRIA DE ESTADO DO MEIO AMBIENTE DO AMAZONAS), 2021)
WWF (Worldwide Fund for Nature)	Socioeconomic and environmental profile of Amazonas state	(VOIVODIC et al., 2017)

APPENDIX 3

The inventory for the fossil fuel chain mainly comprises the upstream production, storage, transport and conversion of diesel stages.

Regarding the diesel storage, the National Petroleum and Gas Agency (ANP) provides a Power BI for platform for tanking and national fuel supply. For Manicoré and Lábrea cities, the company responsible for fuel supply is Atem (Manaus, Brazil), which operates a total of 15 tanks with varying sizes and a combined capacity of 77,105 m³. Table A2 presents the different sizes of the tanks located in Manaus.

Table A 2. Size of the tanks of Atem company in Manaus.

Tank TAG	Type of Unit	Size (m³)
TQ01	Tank	1,379
TQ03	Tank	1,383
TQ02	Tank	1,377
TQ04	Tank	1,381
TQ05	Tank	521
TQ06	Tank	1.382
TQ07	Tank	521
TQ10	Tank	2,657
TQ09	Tank	2,652
TQ12	Tank	10,639
TQ13	Tank	10,644
TQ14	Tank	10,645
TQ15	Tank	10,643
TQ15	Tank	10,641
TQ17	Tank	10,640

According to the Brazilian Association of Technical Standards NBR 7505-1 (ABNT, 2000), a tank has to be situated at least 1/6 of the sum of the diameters of adjacent tanks, or minimum 1 m away. Additionally, the distance between the tanks and the wall should be 1.5 m. This results in a total empty volume of 1,185 m³. This article assumes that the average height of the tanks is 34 m.

APPENDIX 4

Units of conservation (UCs) classified as Sustainable Development Reserve and State Forest in Manicoré and Lábrea were selected for the bioenergy chain. State natural parks were not considered in this work, as they are fully protected by Brazilian law. The UCs analyzed in this article include the Amapá River Sustainable Development Reserve, Igapó-Açú Sustainable Development Reserve, Rio Madeira Sustainable Development Reserve, and Manicoré State Forest.

The next stage involved collecting the Conservation Units' Sustainable Management Plan (SMP). According to the CONAMA 406 resolution, the SMP must include a characterization of the fauna and flora present in the area. The SMP typically provide a list with scientific names and the number of individuals per area for wood species. For this research, an average of 10 species with the highest frequency was selected per UC, totaling 37 species.

Out of the 37 species collected from the Sustainable Forest Management Plans of the Amapá River Sustainable Development Reserve, Igapó-Açú Sustainable Development Reserve, Rio Madeira Sustainable Development Reserve, and Manicoré State Forest, 23 are listed in Table A3. The remaining species were excluded due to a lack of available literature or databases providing their physical and chemical characterizations. Moreover, some species lack comprehensive characterization, as existing studies often focus either on chemical or physical properties, with few offering a full description of the biomass.

Table A 3. Summary of the wood species and their physical and chemical characterization.

Scientific name	Common name	C%	H%	N%	O%	S%	Ashes %	HHV (MJ/kg)	Density (g/cm ³)
<i>Pouteria durlandii</i> (Standl.) Baehni	Abiurana	50.29	-	-	-	0.01	2.80	-	-
<i>Protium divaricatum</i> Engl.	Casca Fina	-	-	-	-	-	0.30	-	-
<i>Cecropia</i> sp.	Breu Branco	-	-	-	-	-	-	-	-
<i>Licaria martiniana</i> (Mez) Kosterm	Embaubarana	-	-	-	-	0.1	1.41	20.05	-
<i>Chrysobalanus venezuelanus</i> Prance	Louro Preto	-	-	-	-	-	-	-	0.46
<i>Eschweilera wachenheimii</i> (Benoist) Sandwith	Macucu	-	-	-	-	-	-	-	0.83
<i>Naucleopsis caloneura</i> (Huber) Ducke	chiador	-	-	-	-	-	-	-	0.79
<i>Hymenolobum sericeum</i> Ducke	Matamata amarelo	-	-	-	-	-	-	-	0.79
<i>Mezilaurus itauba</i>	Muiratinga	-	-	-	-	-	-	-	0.57
<i>Cedrela fissilis</i>	Angelim	-	-	-	-	-	1.41	17.51	0.28
<i>Manilkara elata</i>	Itaúba	-	-	-	-	-	0.62	18.54	0.68
<i>Erisma Uncinatum</i>	Cedro	50.10	6.34	0.37	42.37	0.82	0.86	19.83	0.43
<i>Bowdichia nitida</i>	Maçaranduba	50.95	3.58	1.23	13.58	0.01	0.20	20.10	0.90
<i>Pouteria</i> sp.	Cedrinho	-	-	-	-	0.13	0.83	20.25	0.46
<i>Minquartia guianensis</i> Aubl.	Sucupira	-	-	-	-	-	1.69	20.18	0.77
<i>Dipteryx odorata</i>	Abiurona	50.06	3.36	1.58	10.01	0.02	1.21	29.10	0.76
<i>Goupia glabra</i>	Acariquara	-	-	-	-	0.02	49.94	-	-
<i>Calophyllum brasiliense</i>	Cumarú	-	-	-	-	0.08	0.07	20.13	0.91
<i>Simarouba amara</i>	Cupiúba	-	3.56	1.05	14.65	0.0	0.36	19.37	0.76
<i>Tabebuia serratifolia</i>	Jacareúba	-	-	-	-	-	-	-	0.54
<i>Hymenaea parvifolia</i>	Marupá	48.53	6.28	0.41	44.05	0.73	0.20	19.66	0.37
<i>Peltogyne</i> sp.	Ipê	-	-	-	-	-	0.65	33.082	0.89
<i>Aspidosperma macrocarpon</i>	Jatobá	-	5.77	0.50	42.89	0.67	0.37	20.32	0.90
	Roxinho	-	-	-	-	0.09	0.35	20.37	0.64
	Peroba	-	-	-	-	-	0.93	-	0.65

ANNEX 5

The price of carbon credits depends on various factors, including the type of project implemented. In this study, the project is associated with three types of carbon credits: forestry/land use, renewable energy, and fuel-switching projects. To account for these three categories, an average price was calculated using data from the Ecosystem Marketplace platform for the year 2023 (ECOSYSTEM MARKETPLACE, 2023), where the respective prices for each type were \$9.74, \$3.92, and \$3.65 per t CO₂. The price of carbon credits depends on various factors, including the type of project implemented. In this study, the project is associated with three types of carbon credits: forestry/land use, renewable energy, and fuel-switching projects. To account for these three categories, an average price was calculated using data from the Ecosystem Marketplace platform for the year 2023 (ECOSYSTEM MARKETPLACE, 2023), where the respective prices for each type were \$9.74, \$3.92, and \$3.65 per t CO₂.

After considered the average prices for voluntary market, carbon taxes and CBIOs in 2023 and 2024, this article performed a series of calculations to obtain the values for CBio₂₀₂₃, Offset₂₀₂₃ and ETM₂₀₂₄. The analysis used the life cycle inventory (LCI) information of 202 kg of diesel, the results of the total global warming potential for bioenergy (GWP_{bio}) and for diesel chain (GWP_{diesel}) of -32.0589 kg CO₂ eq and 1,209.38 kg CO₂ eq., respectively. Subsequently, the efficiency grade (EG) of the fuel-switching process was calculated using Equation S3, resulting in 1,241.45 kg CO₂ eq.

$$EG = GWP_{diesel} - GWP_{bio} \quad (S3)$$

The next step was the calculation of the Equation S4 for CBio₂₀₂₃, considering the average CBIO credit price of \$113.61 per t CO₂ eq. in 2023:

$$CBO_{2023} = 113.61 * \frac{EG}{1000} \quad (S4)$$

Following this, the value for $Offset_{2023}$ was calculated in the same way using Equation S5, based on the average voluntary credit price for 2023 of \$5.77 per t CO₂ eq. (ECOSYSTEM MARKETPLACE, 2023).

$$Offset_{2023} = 5.77 * \frac{EG}{1000} \quad (S5)$$

Finally, for carbon taxes in Emissions Trade Systems (ETS), the average price was obtained from World Bank data for Yucatan, Mexico in 2024, amounting to \$17.69 per t CO₂ eq. (WORLD BANK, 2024).

$$ETM_{2024} = 17.69 * \frac{EG}{1000} \quad (S6)$$

ANNEX 6

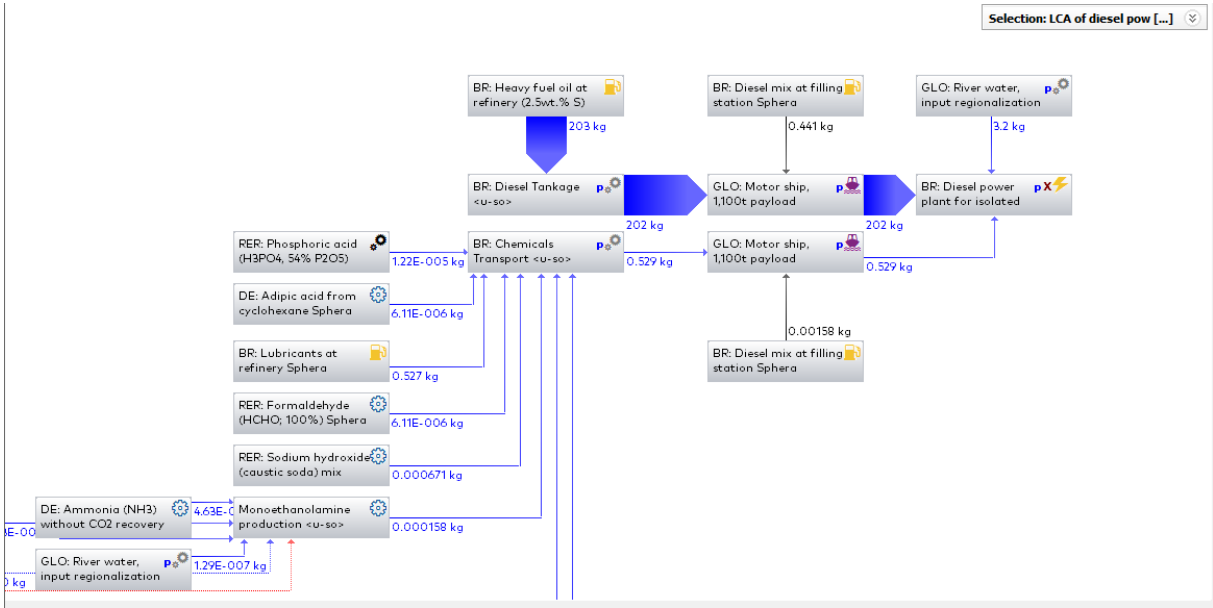


Figure A 1. Model for Manicoré system at GaBi

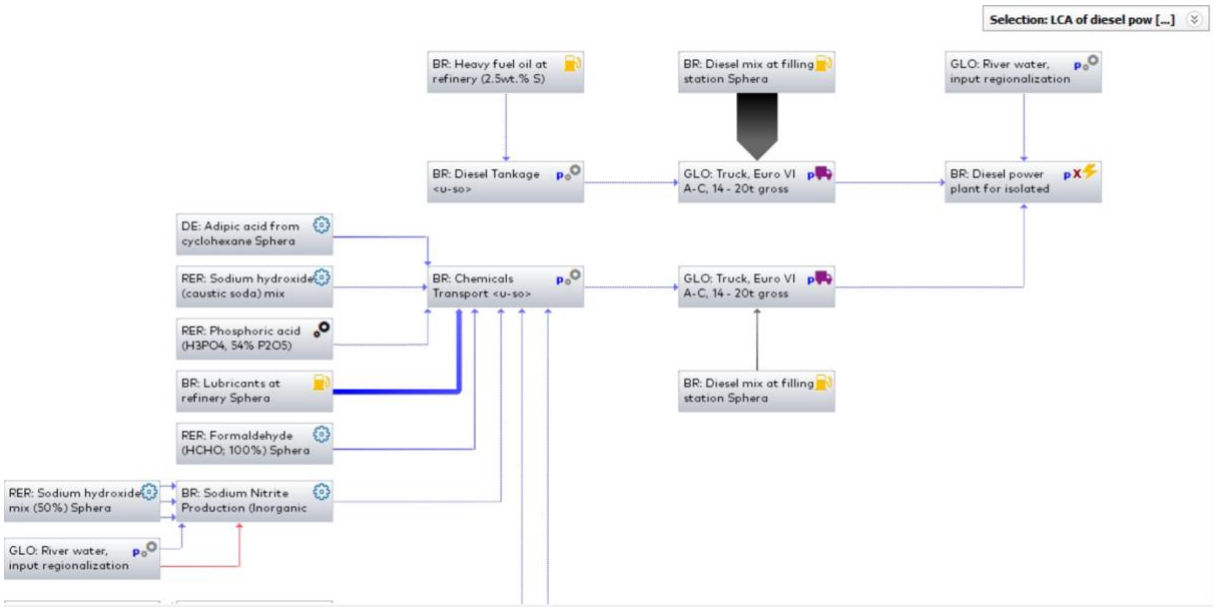


Figure A 2. Model for Lábrea system at GaBi

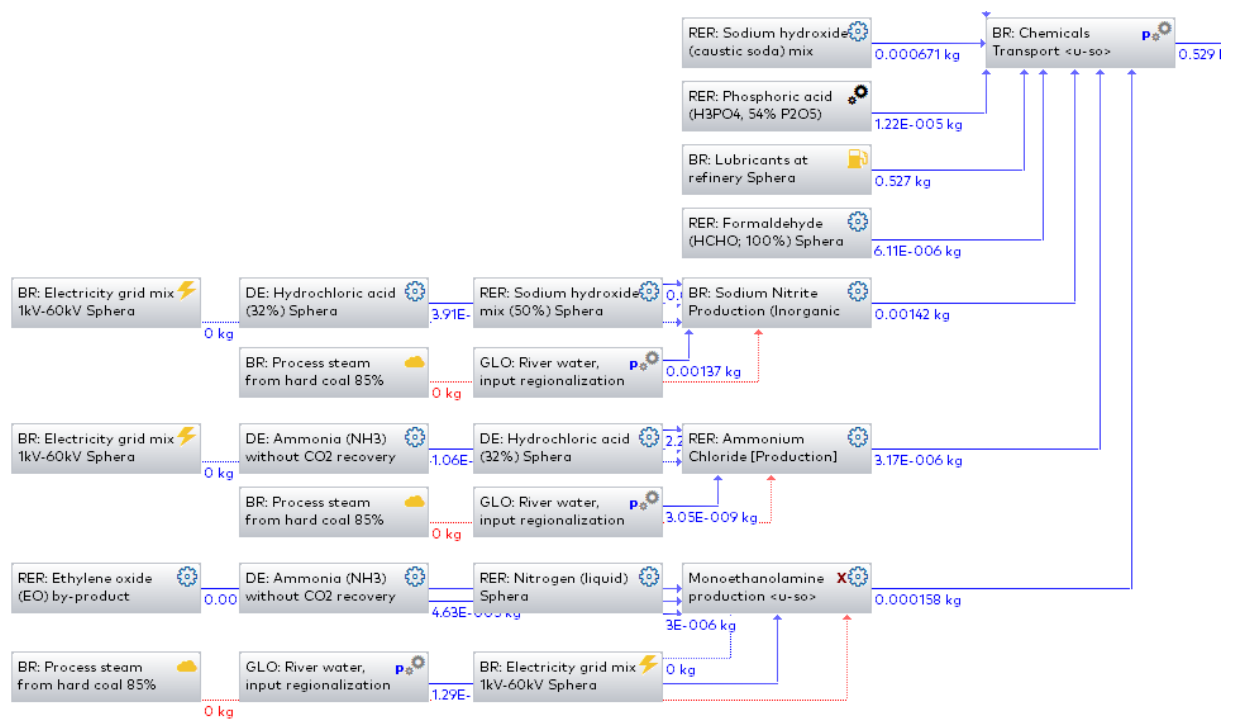


Figure A 3. Model for chemicals in diesel power plants at GaBi

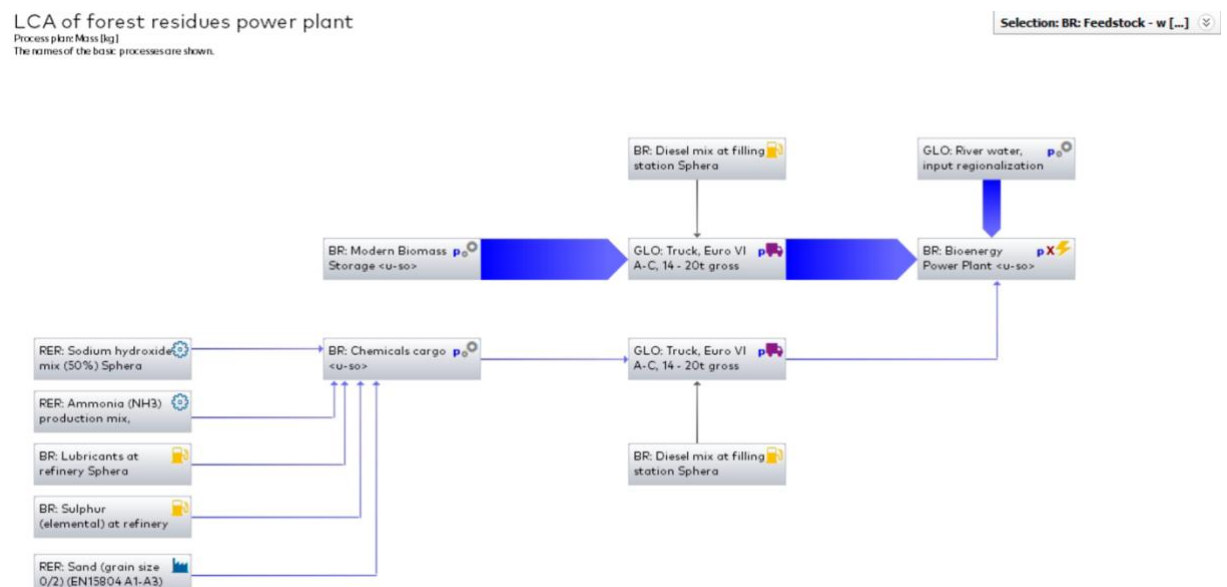


Figure A 4. Model for bioenergy system at GaBi

ANNEX 7

Table A 4. Results for each impact category described in detail in subcategories

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
1) Abiotic Depletion Potential (ADP fossil)								
Total	1.64E+04	0.00E+00	7.15E+03	9.28E+03	9.31E+03	0.00E+00	2.78E+01	9.28E+03
1.1 Resources	1.64E+04	0.00E+00	7.15E+03	9.28E+03	9.31E+03	0.00E+00	2.78E+01	9.28E+03
1.1.1 Energy Resources	1.64E+04	0.00E+00	7.15E+03	9.28E+03	9.31E+03	0.00E+00	2.78E+01	9.28E+03
1.1.1.1 Non renewable energy resources	1.64E+04	0.00E+00	7.15E+03	9.28E+03	9.31E+03	0.00E+00	2.78E+01	9.28E+03
Crude oil (resource)	1.51E+04	0.00E+00	6.43E+03	8.72E+03	8.75E+03	0.00E+00	2.50E+01	8.72E+03
Crude oil (in MJ)	1.51E+04	0.00E+00	6.43E+03	8.72E+03	8.75E+03	0.00E+00	2.50E+01	8.72E+03
Natural gas (resource)	1.25E+03	0.00E+00	7.02E+02	5.53E+02	5.55E+02	0.00E+00	2.73E+00	5.53E+02
Natural gas (in MJ)	1.05E+03	0.00E+00	5.16E+02	5.34E+02	5.36E+02	0.00E+00	2.01E+00	5.34E+02
Tight gas (in MJ)	1.67E+02	0.00E+00	1.51E+02	1.53E+01	1.59E+01	0.00E+00	5.89E-01	1.53E+01
Shale gas (in MJ)	3.52E+01	0.00E+00	3.22E+01	2.99E+00	3.12E+00	0.00E+00	1.25E-01	2.99E+00
Hard coal (resource)	2.43E+01	0.00E+00	1.97E+01	4.66E+00	4.74E+00	0.00E+00	7.65E-02	4.66E+00
Hard coal (in MJ)	2.43E+01	0.00E+00	1.97E+01	4.66E+00	4.74E+00	0.00E+00	7.65E-02	4.66E+00
Lignite (resource)	6.22E+00	0.00E+00	4.58E+00	1.64E+00	1.65E+00	0.00E+00	1.78E-02	1.64E+00
Lignite (in MJ)	6.22E+00	0.00E+00	4.58E+00	1.64E+00	1.65E+00	0.00E+00	1.78E-02	1.64E+00
Coalbed methane (in MJ)	1.75E+00	0.00E+00	1.65E+00	1.02E-01	1.09E-01	0.00E+00	6.41E-03	1.02E-01
Pit Methane (in MJ)	2.33E-01	0.00E+00	1.95E-01	3.85E-02	3.92E-02	0.00E+00	7.58E-04	3.85E-02
Oil sand (10% bitumen) (in MJ)	6.93E-02	0.00E+00	5.22E-02	1.70E-02	1.72E-02	0.00E+00	2.03E-04	1.70E-02
Oil sand (100% bitumen) (in MJ)	5.63E-02	0.00E+00	4.24E-02	1.38E-02	1.40E-02	0.00E+00	1.65E-04	1.38E-02
Peat (resource)	1.16E-02	0.00E+00	9.60E-03	2.01E-03	2.04E-03	0.00E+00	3.73E-05	2.01E-03

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
Peat (in MJ)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E-03	0.00E+00	3.73E-05	2.01E-03
Pit gas (in MJ)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.11E-12	0.00E+00	7.81E-14	8.04E-12
2) Acidification Potential (AP)								
Total	3.81E+01	0.00E+00	5.51E-01	3.76E+01	3.76E+01	0.00E+00	1.40E-02	3.76E+01
2.1 Emissions to air	3.81E+01	0.00E+00	5.51E-01	3.76E+01	3.76E+01	0.00E+00	1.40E-02	3.76E+01
2.1.1 Inorganic emissions to air	3.81E+01	0.00E+00	5.51E-01	3.76E+01	3.76E+01	0.00E+00	1.40E-02	3.76E+01
Nitrogen monoxide	3.19E+01	0.00E+00	2.38E-01	3.16E+01	3.16E+01	0.00E+00	7.02E-05	3.16E+01
Sulphur dioxide	5.95E+00	0.00E+00	8.44E-02	5.86E+00	5.86E+00	0.00E+00	3.86E-04	5.86E+00
Nitrogen oxide	2.06E-01	0.00E+00	1.37E-01	6.88E-02	8.22E-02	0.00E+00	1.34E-02	6.88E-02
Nitrogen dioxide	5.72E-02	0.00E+00	5.69E-02	2.51E-04	2.54E-04	0.00E+00	3.03E-06	2.51E-04
Ammonia	3.26E-02	0.00E+00	3.19E-02	7.23E-04	7.93E-04	0.00E+00	7.07E-05	7.23E-04
Hydrogen sulphide	2.86E-03	0.00E+00	1.58E-03	1.28E-03	1.28E-03	0.00E+00	6.15E-06	1.28E-03
Hydrogen chloride	2.06E-03	0.00E+00	1.23E-03	8.31E-04	8.36E-04	0.00E+00	4.78E-06	8.31E-04
Hydrogen fluoride	9.98E-05	0.00E+00	8.07E-05	1.91E-05	1.94E-05	0.00E+00	3.14E-07	1.91E-05
Sulphur trioxide	6.86E-05	0.00E+00	6.82E-05	3.71E-07	6.36E-07	0.00E+00	2.65E-07	3.71E-07
Sulphur oxides	9.00E-06	0.00E+00	6.34E-06	2.66E-06	2.68E-06	0.00E+00	2.47E-08	2.66E-06
Ammonium nitrate	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-2.90E-18	0.00E+00	-2.01E-20	-2.88E-18
Sulphuric acid	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-7.22E-06	0.00E+00	-6.51E-08	-7.16E-06
2.1.1 Urban air close to ground	9.73E-07	0.00E+00	0.00E+00	9.73E-07	9.73E-07	0.00E+00	9.73E-07	9.73E-07
Nitrogen oxides	8.25E-07	0.00E+00	0.00E+00	8.25E-07	8.25E-07	0.00E+00	8.25E-07	8.25E-07
Ammonia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.48E-07	0.00E+00	0.00E+00	1.48E-07
2.2 Emissions to fresh water	5.23E-07	0.00E+00	4.20E-07	1.03E-07	1.05E-07	0.00E+00	1.63E-09	1.03E-07

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
2.2.1 Inorganic emissions to fresh water							1.63E-09	1.03E-07
	5.23E-07	0.00E+00	4.20E-07	1.03E-07	1.05E-07	0.00E+00		
Sulphuric acid	2.93E-07	0.00E+00	2.28E-07	6.52E-08	6.61E-08	0.00E+00	8.87E-10	6.52E-08
Ammonia	1.48E-07	0.00E+00	0.00E+00	1.48E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ammonium	1.26E-07	0.00E+00	8.40E-08	4.25E-08	0.00E+00	0.00E+00	0.00E+00	3.29E-08
Hydrogen chloride	1.20E-07	0.00E+00	8.72E-08	3.29E-08	3.33E-08	0.00E+00	3.39E-10	3.29E-08
Hydrogen fluoride (hydrofluoric acid)	1.09E-07	0.00E+00	1.05E-07	4.79E-09	5.20E-09	0.00E+00	4.07E-10	4.79E-09
Hydrogen bromide (hydrobromic acid)	1.68E-08	0.00E+00	1.34E-08	3.41E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitric acid	2.39E-09	0.00E+00	1.82E-09	5.77E-10	-3.74E-19	0.00E+00	1.70E-21	-3.76E-19
Hydrogen sulphide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.97E-18	0.00E+00	1.26E-19	9.84E-18
2.3 Emissions to industrial soil	9.37E-14	0.00E+00	3.83E-13	-2.89E-13	-2.88E-13	0.00E+00	1.49E-15	-2.89E-13
2.3.1 Inorganic emissions to industrial soil							1.49E-15	-2.89E-13
	9.37E-14	0.00E+00	3.83E-13	-2.89E-13	-2.88E-13	0.00E+00		
Nitric acid	9.37E-14	0.00E+00	3.83E-13	-2.89E-13	-2.88E-13	0.00E+00	1.49E-15	-2.89E-13
Hydrogen sulphide	4.23E-17	0.00E+00	3.25E-17	9.84E-18	0.00E+00	0.00E+00	0.00E+00	
2.4 Emissions to agricultural soil	2.25E-27	0.00E+00	2.25E-27	3.40E-33	8.77E-30	0.00E+00	8.77E-30	3.40E-33
2.4.1 Inorganic emissions to agricultural soil							8.77E-30	3.40E-33
	2.25E-27	0.00E+00	2.25E-27	3.40E-33	8.77E-30	0.00E+00		

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
Sulphuric acid	2.25E-27	0.00E+00	2.25E-27	3.40E-33	8.77E-30	0.00E+00	8.77E-30	3.40E-33
Ammonium nitrate	-8.06E-18	0.00E+00	-5.18E-18	-2.88E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3) Eutrophication Potential (EP)								
Total	8.62E+00	0.00E+00	2.18E-01	8.41E+00	8.41E+00	0.00E+00	3.87E-03	8.41E+00
3.1 Emissions to air	8.47E+00	0.00E+00	1.30E-01	8.34E+00	8.34E+00	0.00E+00	3.53E-03	8.34E+00
3.1.1 Inorganic emissions to air	8.47E+00	0.00E+00	1.31E-01	8.34E+00	8.34E+00	0.00E+00	3.53E-03	8.34E+00
Nitrogen monoxide	3.54E-04	0.00E+00	6.25E-02	8.32E+00	8.32E+00	0.00E+00	1.85E-05	8.32E+00
Nitrogen dioxide	1.49E-02	0.00E+00	0.014598	6.53E-05	6.70E-05	0.00E+00	7.88E-07	6.53E-05
Nitrous oxide (laughing gas)	1.04E-02	0.00E+00	8.28E-03	-6.03E-04	2.14E-02	0.00E+00	3.49E-03	1.79E-02
Ammonia	7.14E-03	0.00E+00	3.01E-03	1.58E-04	1.74E-04	0.00E+00	1.55E-05	1.58E-04
Nitrogen (N-compounds)	1.26E-06	0.00E+00	2.39E-10	1.26E-06	1.26E-06	0.00E+00	8.40E-13	1.26E-06
3.1.2 Urban air close to ground	2.47E-07	0.00E+00	2.39E-10	2.47E-07	2.47E-07	0.00E+00	0.00E+00	2.47E-07
Nitrogen oxides	2.15E-07	0.00E+00	2.39E-10	2.15E-07	2.15E-07	0.00E+00	0.00E+00	2.15E-07
Ammonia	3.25E-08	0.00E+00	2.39E-10	3.25E-08	3.25E-08	0.00E+00	0.00E+00	3.25E-08
Ammonium	1.30E-08	0.00E+00	2.40E-10	4.38E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitric acid	5.51E-10	0.00E+00	2.39E-10	1.33E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Phosphorus	8.69E-11	0.00E+00	2.39E-10	2.76E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Phosphate	3.36E-15	0.00E+00	2.39E-10	9.88E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrate	1.59E-18	0.00E+00	2.39E-10	3.57E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ammonium nitrate	-1.70E-18	0.00E+00	2.39E-10	-6.06E-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.2 Emissions to fresh water	1.55E-01	0.00E+00	8.58E-02	6.89E-02	6.93E-02	0.00E+00	3.34E-04	6.89E-02

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
3.2.1 Inorganic emissions to fresh water	1.13E-01	0.00E+00	8.31E-02	3.01E-02	3.04E-02	0.00E+00	3.23E-04	3.01E-02
3.2.2 Ecoinvent	200E-02	0.00E+00	2.39E-10	2.00E-02	2.00E-02	0.00E+00	0.00E+00	2.00E-02
3.2.3 Analytical measures to fresh water	1.84E-02	0.00E+00	1.45E-07	1.69E-02	1.69E-02	0.00E+00	5.63E-06	1.69E-02
3.2.4 Organic emissions to fresh water	3.14E-03	0.00E+00	1.24E-07	1.90E-03	1.91E-03	0.00E+00	4.82E-06	1.90E-03
3.3 Emissions to sea water	1.12E-03	0.00E+00	4.99E-08	6.20E-04	6.22E-04	0.00E+00	1.93E-06	6.20E-04
3.3.1 Organic emissions to sea water	5.60E-04	0.00E+00	2.38E-08	3.24E-04	3.25E-04	0.00E+00	9.16E-07	3.24E-04
3.3.2 Analytical measures to sea water	5.28E-04	0.00E+00	2.51E-08	2.78E-04	2.79E-04	0.00E+00	9.69E-07	2.78E-04
3.3.3 Inorganic emissions to sea water	3.00E-05	0.00E+00	1.5E-09	1.74E-05	1.74E-05	0.00E+00	4.93E-08	1.74E-05
Nitrate	3.00E-05	0.00E+00	1.50E-09	1.74E-05	1.74E-05	0.00E+00	4.92E-08	1.74E-05
Phosphate	6.24E-11	0.00E+00	2.39E-10	1.40E-11	1.42E-11	0.00E+00	1.88E-13	1.40E-11
3.4 Emissions to industrial soil	4.52E-04	0.00E+00	4.38E-08	1.66E-05	1.83E-05	0.00E+00	1.70E-06	1.66E-05
3.4.1 Inorganic emissions to industrial soil	4.52E-04	0.00E+00	4.38E-08	1.66E-05	1.83E-05	0.00E+00	1.70E-06	1.66E-05
3.5 Emissions to agricultural soil	2.44E-12	0.00E+00	2.39E-10	5.82E-13	5.89E-13	0.00E+00	7.23E-15	5.82E-13
3.5.1 Inorganic emissions to agricultural soil	2.44E-12	0.00E+00	2.39E-10	5.82E-13	5.89E-13	0.00E+00	7.23E-15	5.82E-13
4) Global Warming Potential (GWP)								

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
Total	2.86E+00	0.00E+00	5.33E+02	6.77E+02	6.79E+02	0.00E+00	2.09E+00	6.77E+02
4.1 Resources	-5.72E-01	0.00E+00	-5.46E+01	-7.95E-01	-1.01E+00	0.00E+00	-2.12E-01	0.00E+00
4.1.1 Material resources	-5.72E-01	0.00E+00	-5.46E+01	-7.95E-01	-1.01E+00	0.00E+00	-2.12E-01	0.00E+00
Renewable resources	-5.72E-01	0.00E+00	-5.46E+01	-7.95E-01	-1.01E+00	0.00E+00	-2.12E-01	0.00E+00
Carbon dioxide	-5.53E+01	0.00E+00	-5.46E+01	-7.95E-01	-1.01E+00	0.00E+00	-2.12E-01	0.00E+00
4.2 Emissions to air	1.26E+03	0.00E+00	5.87E+02	6.77E+02	4.29E+00	0.00E+00	2.30E+00	6.77E+02
4.2.1 Inorganic emissions to air	6.14E+02	0.00E+00	5.60E+02	5.45E+01	5.67E+01	0.00E+00	2.19E+00	5.45E+01
Carbon dioxide	5.78E+02	0.00E+00	5.23E+02	5.44E+01	5.65E+01	0.00E+00	2.08E+00	5.44E+01
Carbon dioxide (biotic)	2.66E+01	0.00E+00	2.59E+01	7.06E-01	8.09E-01	0.00E+00	1.03E-01	7.06E-01
Nitrous oxide (laughing gas)	1.02E+01	0.00E+00	1.08E+01	-5.92E-01	-5.82E-01	0.00E+00	1.03E-02	-5.92E-01
Sulphur hexafluoride	1.26E-04	0.00E+00	8.77E-05	3.83E-05	3.86E-05	0.00E+00	3.41E-07	3.83E-05
Carbon dioxide (aviation)	5.12E-06	0.00E+00	3.61E-06	1.50E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrogentriflouride	7.29E-07	0.00E+00	5.51E-07	1.78E-07	1.80E-07	0.00E+00	2.14E-09	1.78E-07
4.2.2 Ecoinvent long-term to air	5.90E+02	0.00E+00	0.00E+00	5.90E+02	5.90E+02	0.00E+00	0.00E+00	5.90E+02
Carbon dioxide, fossil	5.90E+02	0.00E+00	0.00E+00	5.90E+02	5.90E+02	0.00E+00	0.00E+00	5.90E+02
4.2.3 Organic emissions to air (group VOC)	6.03E+01	0.00E+00	2.73E+01	3.30E+01	3.31E+01	0.00E+00	1.09E-01	3.30E+01
5) Human Toxicity Potential (HTP)								
Total	2.97E+02	2.52E+02	1.90E+01	2.57E+01	2.78E+02	2.52E+02	1.05E-01	2.57E+01
5.1 Emissions to air	2.63E+02	2.52E+02	5.36E+00	4.96E+00	2.57E+02	2.52E+02	5.17E-02	4.96E+00
5.1.1 Ecoinvent long-term to air	2.55E+02	2.52E+02	0.00E+00	2.80E+00	2.55E+02	2.52E+02	0.00E+00	2.80E+00

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
5.1.2 Organic emissions to air (group VOC)	4.59E+00	0.00E+00	3.77E+00	8.21E-01	8.34E-01	0.00E+00	1.31E-02	8.21E-01
5.1.3 Heavy metals to air	1.57E+00	0.00E+00	9.22E-01	6.52E-01	6.56E-01	0.00E+00	3.59E-03	6.52E-01
5.1.4 Inorganic emissions to air	1.33E+00	0.00E+00	6.52E-01	6.79E-01	7.12E-01	0.00E+00	3.29E-02	6.79E-01
5.1.5 Particles to air	2.35E-02	0.00E+00	1.80E-02	5.47E-03	7.56E-03	0.00E+00	2.09E-03	5.47E-03
5.1.6 Urban air close to ground	3.38E-03	0.00E+00	0.00E+00	3.38E-03	3.38E-03	0.00E+00	0.00E+00	3.38E-03
5.1.7 Pesticides to air	5.45E-05	0.00E+00	5.44E-05	1.13E-07	3.24E-07	0.00E+00	2.11E-07	1.13E-07
5.2 Emissions to fresh water	3.00E+01	0.00E+00	1.18E+01	1.82E+01	1.82E+01	0.00E+00	4.60E-02	1.82E+01
5.2.1 Organic emissions to fresh water	1.42E+01	0.00E+00	5.56E+00	8.61E+00	8.63E+00	0.00E+00	2.16E-02	8.61E+00
5.2.2 Inorganic emissions to fresh water	1.29E+01	0.00E+00	5.08E+00	7.87E+00	7.89E+00	0.00E+00	1.98E-02	7.87E+00
5.2.3 Ecoinvent long-term to fresh water	4.92E-05	4.92E-05	0.00E+00	4.92E-05	4.92E-05	0.00E+00	0.00E+00	4.92E-05
5.2.4 Other emissions to fresh water	3.69E-05	0.00E+00	3.67E-05	1.80E-07	3.22E-07	0.00E+00	1.43E-07	1.80E-07
5.3 Emissions to sea water	4.47E+00	0.00E+00	1.88E+00	2.59E+00	2.60E+00	0.00E+00	7.31E-03	2.59E+00
5.3.1 Inorganic emissions to sea water	2.95E+00	0.00E+00	1.24E+00	1.71E+00	1.72E+00	0.00E+00	4.83E-03	1.71E+00

Scenario	Manicoré system				Lábrea system			
Impact category	Total	Storage	Transport	Power plant	Total	Storage	Transport	Power plant
5.3.2 Heavy metals to sea water	1.23E+00	0.00E+00	5.18E-01	7.11E-01	7.13E-01	0.00E+00	2.01E-03	7.11E-01
5.3.3 Organic emissions to sea water	2.89E-01	0.00E+00	1.21E-01	1.68E-01	1.68E-01	0.00E+00	4.73E-04	1.68E-01
5.3.4 Other emissions to sea water	6.42E-19	4.54E-23	4.55E-19	1.88E-19	1.89E-19	0.00E+00	1.77E-21	1.88E-19
5.4 Emissions to industrial soil	5.17E-06	0.00E+00	4.09E-06	1.08E-06	1.09E-06	0.00E+00	1.59E-08	1.08E-06
5.4.1 Heavy metals to industrial soil	4.53E-06	0.00E+00	3.65E-06	8.85E-07	8.99E-07	0.00E+00	1.42E-08	8.85E-07
5.4.2 Organic emissions to industrial soil	6.32E-07	0.00E+00	4.42E-07	1.91E-07	1.92E-07	0.00E+00	1.72E-09	1.91E-07
5.4.3 Inorganic emissions to industrial soil	1.21E-12	0.00E+00	8.60E-13	3.52E-13	3.55E-13	0.00E+00	3.35E-15	3.52E-13
5.4.4 Other emissions to industrial soil	9.12E-24	0.00E+00	6.45E-24	2.66E-24	2.69E-24	0.00E+00	2.51E-26	2.66E-24
5.5 Emissions to agricultural soil	-1.01E-01	0.00E+00	-1.07E-01	5.57E-03	5.16E-03	0.00E+00	-4.15E-04	5.57E-03
5.5.1 Heavy metals to agricultural soil	-1.01E-01	0.00E+00	-1.07E-01	5.57E-03	5.16E-03	0.00E+00	-4.15E-04	5.57E-03
5.5.2 Inorganic emissions to agricultural soil	1.99E-20	0.00E+00	1.41E-20	5.81E-21	5.87E-21	0.00E+00	5.48E-23	5.81E-21
5.5.3 Other emissions to agricultural soil	1.81E-13	0.00E+00	2.96E-17	1.81E-13	1.81E-13	0.00E+00	1.15E-19	1.81E-13

Scenario	Bioenergy			
Impact category	Total	Storage	Transport	Power plant
1) Abiotic Depletion Potential (ADP fossil)				
Total	2.85E+02	0.00E+00	2.85E+02	1.00E-01
1.1 Resources	2.85E+02	0.00E+00	2.85E+02	1.00E-01
1.1.1 Energy Resources	2.85E+02	0.00E+00	2.85E+02	1.00E-01
1.1.1.1 Nonrenewable energy resources	2.85E+02	0.00E+00	2.85E+02	1.00E-01
Crude oil (resource)	2.56E+02	0.00E+00	2.56E+02	8.30E-03
Crude oil (in MJ)	2.56E+02	0.00E+00	2.56E+02	8.29E-03
Natural gas (resource)	2.88E+01	0.00E+00	2.80E+01	8.86E-02
Natural gas (in MJ)	2.06E+01	0.00E+00	2.06E+01	8.61E-02
Tight gas (in MJ)	6.04E+00	0.00E+00	6.90E+00	6.04E-04
Shale gas (in MJ)	1.28E+00	0.00E+00	1.47E+00	7.78E-03
Hard coal (resource)	7.86E-01	0.00E+00	7.85E-01	1.84E-03
Hard coal (in MJ)	7.86E-01	0.00E+00	7.85E-01	1.84E-03
Lignite (resource)	1.84E-01	0.00E+00	1.83E-01	1.34E-03
Lignite (in MJ)	1.84E-01	0.00E+00	1.83E-01	1.34E-03
Coalbed methane (in MJ)	6.57E-02	0.00E+00	7.50E-02	6.67E-05
Pit Methane (in MJ)	7.80E-03	0.00E+00	8.88E-03	2.38E-05
Oil sand (10% bitumen) (in MJ)	2.08E-03	0.00E+00	2.38E-03	3.68E-07
Oil sand (100% bitumen) (in MJ)	1.69E-03	0.00E+00	1.93E-03	3.00E-07
Peat (resource)	3.95E-04	0.00E+00	3.83E-04	1.18E-05
Pit gas (in MJ)	8.13E-13	0.00E+00	8.01E-13	1.22E-14
Scenario	Bioenergy			
Impact category	Total	Storage	Transport	Power plant
2) Acidification Potential (AP)				
Total	3.46E+01	0.00E+00	2.19E-02	3.46E+01

2.1 Emissions to air	3.46E+01	0.00E+00	2.19E-02	3.46E+01
2.1.1 Inorganic emissions to air	3.46E+01	0.00E+00	2.19E-02	3.46E+01
2.2 Emissions to fresh water	1.68E-08	0.00E+00	1.67E-08	2.66E-12
2.2.1 Inorganic emissions to fresh water	1.68E-08	0.00E+00	1.67E-08	2.66E-12
2.3 Emissions to industrial soil	1.71E-14	0.00E+00	1.75E-14	-4.00E-16
2.3.1 Inorganic emissions to industrial soil	1.71E-14	0.00E+00	1.75E-14	-4.00E-16
2.4 Emissions to agricultural soil	8.99E-29	0.00E+00	8.99E-29	4.45E-32
2.4.1 Inorganic emissions to agricultural soil	8.99E-29	0.00E+00	8.99E-29	4.45E-32
Scenario	Bioenergy			
Impact category	Total	Storage	Transport	Power plant
3) Eutrophication Potential (EP)				
Total	6.81E-01	0.00E+00	8.65E-03	6.81E-01
3.1 Emissions to air	6.77E-01	0.00E+00	5.93E-03	6.81E-01
3.1.1 Inorganic emissions to air	6.77E-01	0.00E+00	5.93E-03	6.72E-01
3.2 Emissions to fresh water	3.43E-03	0.00E+00	3.42E-03	1.52E-06
3.2.1 Inorganic emissions to fresh water	3.79E-03	0.00E+00	3.23E-03	1.36E-06
3.2.2 Analytical measures to fresh water	6.60E-05	0.00E+00	5.77E-05	1.96E-08
3.2.3 Organic emissions to fresh water	5.66E-05	0.00E+00	4.94E-05	1.41E-07
3.3 Emissions to sea water	1.98E-05	0.00E+00	1.98E-05	1.16E-09
3.3.1 Analytical measures to sea water	9.94E-06	0.00E+00	9.94E-06	5.97E-10
3.3.2 Organic emissions to sea water	9.39E-06	0.00E+00	9.39E-06	3.05E-10
3.3.3 Inorganic emissions to sea water	5.05E-07	0.00E+00	5.05E-07	2.56E-10
3.3 Emissions to industrial soil	1.74E-05	0.00E+00	1.73E-05	5.18E-09
3.3.1 Inorganic emissions to industrial soil	1.74E-05	0.00E+00	1.73E-05	5.18E-09
3.4 Emissions to agricultural soil	7.84E-14	0.00E+00	7.41E-14	5.92E-16

3.4.1 Inorganic emissions to agricultural soil	8.53E-14	0.00E+00	7.41E-14	5.92E-16
Scenario	Bioenergy			
Impact category	Total	Storage	Transport	Power plant
4) Global Warming Potential (GWP)				
Total	9.95E+02	5.80E+01	2.13E+01	7.18E-03
4.1 Resources	-2.49E+00	0.00E+00	-2.18E+00	-2.51E-04
4.1.1 Material Resources	-2.49E+00	0.00E+00	-2.18E+00	-2.51E-04
Renewable energy resources	-2.49E+00	0.00E+00	-2.18E+00	-2.51E-04
Carbon dioxide	-2.49E+00	0.00E+00	-2.18E+00	-2.51E-04
4.2 Emissions to air	9.97E+02	5.80E+01	2.34E+01	9.16E+02
4.2.1 Inorganic emissions to air	8.03E+01	5.80E+01	2.23E+01	6.91E-03
4.2.2 Organic emissions to air (group VOC)	5.02E+01	0.00E+00	1.09E+00	4.91E+01
4.2.3 Ecoinvent long-term to air	8.66E+02	0.00E+00	0.00E+00	8.66E+02
5) Human Toxicity Potential (HTP)				
Total	4.95E+00	0.00E+00	7.56E-01	4.20E+00
5.1 Emissions to air	4.41E+00	0.00E+00	2.14E-01	4.20E+00
5.2.1 Inorganic emissions to air	2.79E+00	0.00E+00	3.68E-02	1.12E-05
5.2.2 Ecoinvent long-term to air	1.43E+00	0.00E+00	0.00E+00	0.00E+00
5.2.3 Organic emissions to air (group VOC)	1.50E-01	0.00E+00	2.60E-02	2.77E+00
5.2.4 Heavy metals to air	3.68E-02	0.00E+00	0.00E+00	1.43E+00
5.2.5 Particles to air	8.18E-04	0.00E+00	8.18E-04	1.36E-07
5.2.6 Pesticides to air	2.48E-06	0.00E+00	2.48E-06	2.97E-11
5.2 Emissions to fresh water	4.72E-01	0.00E+00	4.72E-01	1.96E-05
5.2.1 Organic emissions to fresh water	2.03E-01	0.00E+00	2.22E-01	7.57E-06
5.2.2 Inorganic emissions to fresh water	2.22E-01	0.00E+00	2.03E-01	6.81E-06
5.2.3 Other emissions to fresh water	1.46E-06	0.00E+00	1.46E-06	6.34E-11
5.3 Emissions to sea water	7.50E-02	0.00E+00	7.50E-02	2.43E-06
5.3.1 Inorganic emissions to sea	5.65E-02	0.00E+00	4.95E-02	1.59E-06

5.3.2 Heavy metals to sea water	2.07E-02	0.00E+00	2.07E-02	6.83E-07
5.3.3 Organic emissions to sea water	4.85E-03	0.00E+00	4.85E-03	1.56E-07
5.3.4 Other emissions to sea water	1.82E-20	0.00E+00	1.81E-20	1.11E-23
5.4 Emissions to industrial soil	-4.26E-03	0.00E+00	-4.26E-03	5.26E-07
5.4.1 Heavy metals to industrial soil	-4.26E-03	0.00E+00	-4.26E-03	5.26E-07
5.4.3 Inorganic emissions to industrial soil	5.62E-22	0.00E+00	5.62E-22	3.43E-25
5.4.4 Other emissions to industrial soil	-6.84E-14	0.00E+00	1.18E-18	-6.84E-14
5.5 Emissions to agricultural soil	-4.87E-03	0.00E+00	-4.87E-03	5.26E-07
5.5.1 Inorganic emissions to agricultural soil		0.00E+00	6.42E-22	3.43E-25
5.5.2 Heavy metals to agricultural soil	-4.87E-03		-4.87E-03	5.26E-07
		0.00E+00		
5.5.3 Other emissions to agricultural soil	-6.84E-14	0.00E+00	1.35E-18	-6.84E-14
