Applying Small-Scale Liquefied Natural Gas Supply Chain by Fluvial Transport in the Isolated Systems: The Case Study of Amazonas, Brazil

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ABSTRACT

There are currently several studies about the necessity of increasing access to sustainable electricity for isolated communities or in remote areas using alternative energy sources. There are about 212 energy grid isolated systems in Brazil, mainly concentrated in the North of the country, especially in the state of Amazonas, largely supplied by diesel power plants. The isolated systems in Amazonas present significant logistical challenges due primarily to the dependence on fluvial transport. The small-scale liquefied natural gas by fluvial transport can be an alternative to natural gas supply to remote areas and isolated systems and the non-dependence or construction of new pipelines. Based on this context, the work aims to evaluate the small-scale liquefied natural gas economic costs by fluvial transport to replace diesel oil with natural gas in power plants in the state of Amazonas. It then also analyses whether this substitution can significantly mitigate greenhouse gas emissions of the electricity sector at the local level. As a result, the use of natural gas in just a few scenarios elaborated from the case studies can provide energy security, decrease local emissions of CO_2eq, and reduce the electricity cost to the final consumer.

Keywords:
Small-scale liquefied natural gas
Electricity sector
Economic model cost
Low-carbon economy
Fluvial transport
Isolated systems

Introduction

Rapid and deep decarbonization of the energy sector requires achieving the Paris Agreement's targets to limit global warming below 2 °C and pursuing efforts to limit it to 1.5 °C, compared to pre-industrial levels (UNFCCC, 2015). One of the main challenges and objectives for reducing Greenhouse Gas (GHG) emissions, mainly carbon dioxide (CO_2), is concentrated in the power sector's decarbonization (IRENA, 2017; Jenkins et al., 2018; Williams et al., 2012). From 1990 until 2016, electricity and heat production were the largest contributors to overall GHG emissions (Ritchie & Roser, 2020). In this context, low-carbon technologies represent an essential alternative to contribute to the sector's decarbonization (Amponsah et al., 2014; Hirth & Steckel, 2016). However, the high costs of the low-carbon technologies (Mileva et al., 2016; Wendling, 2019), the lack of a governance mechanism (Knopf et al., 2015), the intermittency of renewable energy and limitations/fluctuations in the power grid to achieve the full potential (Fattouh et al., 2019; Kim, 2019; Papadis & Tsatsaronis, 2020), availability of natural resources (Capellán-Pérez et al., 2016; Papadis & Tsatsaronis, 2020), and guarantee of energy security (Cohen et al., 2011) make the gas-fired power plants one of the alternatives for electricity supply (Wendling, 2019). Besides, the gas-fired power plants provide low-carbon emissions compared to other fossil fuels and cheap electricity, mainly if gas is abundant (Wendling, 2019).

Natural gas, coal, and nuclear energy continue to dominate electricity generation globally (Papadis & Tsatsaronis, 2020). However, natural gas's abundance and low prices can replace other fossil fuels and renewables (Gillingham & Huang, 2019) or establish a pathway to greater reliance on renewable fuel sources (Greiner et al., 2018; Jacoby et al., 2021). Besides, the shale gas revolution (Kerr, 2010), technological advancements for Liquefied Natural Gas (LNG) storage and transportation (Kim & Kil, 2016; Kumar et al., 2011), and the reducing CO_2 combining natural gas with other technologies or low-carbon fuel (e.g. carbon

Abbreviations: ANEEL, National Electricity Agency; ANP, National Agency of Petroleum, Natural Gas and Biofuels; CAPEX, Capital Expenditure; CCC, Fossil Fuels Consuming Account; CDE, Energy Development Account; CO_2, Carbon Dioxide; CO2eq, Equivalent Carbon Dioxide Emissions; GHG, Greenhouse Gas; IS, National Isolated Systems; LNG, Liquefied Natural Gas; OPEX, Operational Expenditure; PV, Photovoltaic; SDG(s), Sustainable Development Goal(s); SIN, National Interconnected System; SSLNG, Small-scale Liquefied of Natural Gas.

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capture and storage and blue hydrogen) (Babaee & Loughlin, 2020; Bui et al., 2018; Díaz-Herrera et al., 2020; Quarton & Samsatli, 2020) have contributed to the use of natural gas in the electricity sector. Natural gas can also play a role as an energy security component (Cohen et al., 2011) due to resource availability (Wigley, 2011) and as a bridge to a low-carbon economy (Hafeznia et al., 2017; Levi, 2013; Wendling, 2019). Although the meaning of decarbonization is related to eliminating fossil fuel use, the reality of remote regions/isolated systems and the availability of natural resources make the use of natural gas a possible alternative to reduce GHG emissions compared to oil and its derivatives or coal (Linton et al., 2021; Relva et al., 2021; Unruh, 2000).

Natural gas also plays an ambiguous role as a transition fuel in the electricity sector (Campos et al., 2017; García Kerdan et al., 2019; Vahl & Filho, 2015). In Brazil, hydroelectricity represented almost 65% of the electricity generation, while fossil fuels reached an average of 15% (9.7% from natural gas), and wind and solar 10%, in 2019 (EIA, 2021a, b). In 2020, the Brazilian electricity sector had 2,439 thermal power plants operating (2,198 powered by diesel oil, 166 powered by natural gas, 75 powered by fuel oil, and 13 by mineral coal) (ANEEL, 2020c). Also, Brazil has two electric systems: (i) the National Interconnected System (SIN), in which gas-fired power plants have played a strategic role (Corrêa Da Silva et al., 2016; Frota & Rocha, 2010; ONS, 2021b) and tend to be even more relevant in specific demands, such as peak loads in SIN (EPE, 2020a) and, (ii) the National Isolated Systems (IS) which consists of about 212 isolated locations, mostly concentrated in the North of the country, particularly in the Amazon region (ONS, 2021c). Although electricity consumption in the IS represents less than 1% of the total national demand, since the supply comes primarily from diesel power plants (ONS, 2021c), the GHG emissions are seven times more intense than SIN (EPE, 2020a). Some studies pointed out that replacing diesel oil with natural gas can be considered an economically viable and low-emission option for power generation (Frota et al., 2010a,b; Frota & Rocha, 2010; Isper Jr & Picanço, 2020; Kuwahara et al., 2000). Besides, the discoveries and explorations of oil and natural gas in pre-salt layers (e.g. Santos, Campos, Espírito Santo,and Pará-Maranhão Basins), onshore fields (e.g. Urucu Petroleum Province, in the state of Amazonas), and the importation of LNG have significantly expanded the national natural gas supply (EPE, 2020a). Therefore, according to the national energy planning, natural gas will be one of the main fuels for expanding electricity generation in the coming years in the country (EPE, 2020a,b).

Natural gas has already been identified as a sustainable development and energy option for the state of Amazonas (Frota et al., 2010a; Frota & Rocha, 2010; Isper Jr & Picanço, 2020; Silva et al., 2015). In the short term, the replacing of petroleum-derived liquid fuels in thermal power plants includes both economic and environmental benefits (Frota & Rocha, 2010; Silva et al., 2015). Besides, the use of natural gas for electricity generation in Amazonas has a positive effect by reducing the power cost and the emissions ($CO_2$and oxides of nitrogen) in a short period and at the local level (Silva et al., 2015). However, most of the case studies concentrate the research on converting the thermal power plants operation with natural gas instead of diesel in the state's capital city, Manaus, and neighboring cities due to the connection to the Urucu-Manaus pipeline (Frota et al., 2010b; Martinez-Bolaños et al., 2021; Silva et al., 2015). Also, the state of Amazonas is seeking alternative solutions to reduce CO_2 emissions, such as solar energy combined with natural resources available in the region as biomass and water resources (Matos et al., 2011). In addition, actions to control deforestation and preserve the biome of the Amazon have a central and global role in reducing GHG emisisons (Marcovitch & Pinsky, 2020).

Based on the panorama above mentioned, the Small-Scale LNG (SSLNG) can be considered an alternative to natural gas supply to geographically scattered populations with a cost-effectiveness challenge (Bittante et al., 2018; Budiyanto et al., 2020) and the non-dependence or construction of new pipelines (e.g. in the Amazon rainforest). Unlike other Brazilian states, Amazonas depends on fluvial transport, which affects the logistic system of fuel transportation (Frota & Rocha, 2010). Also, the state concentrates 72% of the country's diesel power plants (ANEEL, 2020a). Recognizing this, the work evaluates whether the economic cost of replacing diesel with natural gas in the electricity generation in IS using SSLNG by fluvial transport is viable, leveraging on the existing regional availability of natural gas and aiming to keep the electricity security, while, in parallel, the use of renewable energy is developed. In addition, this paper examines whether the replacement of diesel oil with natural gas can significantly contribute to mitigating CO_2eq emissions of the electricity sector at the local level. This work has a pioneering approach considering SSLNG by fluvial transport to replace diesel in thermal power plants, having the case study of the state of Amazonas. This study answers a gap related to the possibility of using the SSLNG for isolated areas' energy supply which depends on fluvial transport or can use this system. Besides, the study of SSLNG is a novel area of research that needs to be more explored, including together with fluvial transport.

State of the art at the global scale

There are currently several studies about the necessity of increasing access to electricity sustainably in remote areas in various countries by different energy sources, mainly hybrid systems using renewable sources (El-houari et al., 2020; Juanpera et al., 2021; Khamis et al., 2020; Majdi Nasab et al., 2021; Sokolnikova et al., 2020). Besides, ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030 corresponds to one of the 17 Sustainable Development Goals (SDGs), SDG 7, of the 2030 Agenda for Sustainable Development, adopted by all the United Nations Member States in 2015 (United Nations, 2021). Despite government efforts in the last decades to reduce the number of people without access to energy, the COVID-19 pandemic has aggravated this situation in some places, such as sub-Saharan Africa (EIA, 2021a,b). However, energy efficiency and policies investments continue to improve gains in the electricity sector (EIA, 2021a,b; Ponte et al., 2021).

In sum, most of the studies have validated that hybrid systems can benefit remote areas and communities. The economic feasibility (Combe et al., 2020; El-houari et al., 2020; Hernández-Fontes et al., 2020; Majdi Nasab et al., 2021; Murty & Kumar, 2020; Sokolnikova et al., 2020), the creation of local jobs (Brandão et al., 2021; Mahbaz et al., 2020) and reduction of GHG emissions (particularly CO_2) (Akinyele et al., 2020; Brandão et al., 2021; Combe et al., 2020; El-houari et al., 2020; García-Vera et al., 2020; Mahbaz et al., 2020; Minaei et al., 2021; Murty & Kumar, 2020; Niyonteze et al., 2020; Oliveira et al., 2021) are the main positive points discussed. Seasonality (Khamis et al., 2020; Murty & Kumar, 2020), high cost, and investment (Husein et al., 2020; Shrestha et al., 2021) are negative points following regional features. However, part of some isolated communities uses diesel oil as one of the main fuels for electricity generation, as in Brazil (Frota & Rocha, 2010). The

Table 1
Key points address replacing diesel with natural gas.

Key points	References
Energy security	(Murty & Kumar, 2020)
Environmental preservation	(Frota et al., 2010a)
Reduction of the costs of generated electricity	(Frota et al., 2010a; Frota & Rocha, 2010; Kuwahara et al., 2000; Silva et al., 2015)
Reduce CO_2 emissions	(Combe et al., 2020; Frota et al., 2010a; Frota & Rocha, 2010; McFarlan, 2020; Silva et al., 2015)
Regional development and benefit to the local population	(Frota et al., 2010a; Frota & Rocha, 2010)
High investment cost	(Shrestha et al., 2021)
Low reliability and low load factor	(Shrestha et al., 2021)
High reliability and high factor	(Combe et al., 2020)

Table 2
The potential of LNG in a remote area or IS.

Country	Source
Brazil	The supply of LNG to the state of Pará to generate energy for non-interconnected electrical grids (Kuwahara et al., 2000)
Canada	LNG to replace diesel in Canadian remote Northern communities (McFarlan, 2020)
Greek	LNG is one of the potential fuels to the electricity generation in an isolated Greek island, Lesvos (Strantzali et al., 2017)
	The possibility of LNG supply for sustainable electricity production in insular small-scale electricity systems (Strantzali et al., 2018)
Indonesia	The use of SSLNG to mobile power plants in the Sulawesi region Indonesia (Budiyanto et al., 2020)

replacement of this fuel with renewables sources or natural gas has been pointed out as one of the leading environmental and economic solutions. In the case of natural gas, several articles in the last decades have demonstrated the feasibility of replacing diesel oil and the advantages and disadvantages of this change (see Table 1). The results have shown more benefits and the introduction of new techniques, for example, the LNG, which can support the use of natural gas in these remote areas and IS (see Table 2).

Materials and methods

The methodology used in this paper is organized in three steps: (i) choice of the case studies focus on fluvial transport, IS, and thermal power plants moved by diesel; (ii) application of an economic model cost (i.e. costs involved in the logistics of transporting LNG by fluvial transport in small-scale) developed by Fraga (2018) and Fraga et al. (2019); and (iii) low-carbon economy analysis of diesel and natural gas (IPCC, 2006; SENAI, 2017) (see Fig. 1).

The isolated system in the state of Amazonas

The largest state of Brazil, Amazonas, is situated in the country's North region and represents 18.5% of the territory (IBGE, 2019a). The state is also part of the Amazon Basin, the world's largest river basin, and an extensive river network (Coe et al., 2016). The high potential for navigability through rivers (e.g. Negro, Amazonas, Solimões, and Madeira) becomes the state of Amazonas dependent almost exclusively on the fluvial transport of cargo and passengers (DomÌnguez, 2004). In 2020, Amazonas had about 63 ISs (61 by diesel, one by natural gas, and one by fuel oil), serving a total population of 1,657,298 inhabitants (ANEEL, 2020c; EPE, 2019a; ONS, 2021b). Diesel power plants have become the primary option for decentralized thermal power plants generation due to logistical barriers and natural obstacles (Wilke, 2015). We selected two diesel power plants for the case studies (see Fig. 2). The first case study is Borba Thermal Power Plant due to the greater distance from the Port of Coari and the Azulão field. The Coari terminal plays a significant role in the flow of oil and natural gas produced in the Urucu region, operated by Petrobras (Brazilian oil company) and; the Azulão field located 210 km east of the capital Manaus, operated by Eneva S.A. (power generation company), both in the state of Amazonas. The second case study is Itacotiara Thermal Power Plant as it is the largest states's dieseil oil consumer. It is noteworthy that there is no liquefaction plant in the Port of Coari, while in the Azulão field, there is an LNG plant in construction. Currently, the diesel oil production to supply fuel to power plants derives from the Port of Coari.

The study has considered two efficiency values for both thermal power plants: 42% and 63%. These values refer to the minimum efficiency for thermal power plants with a steam cycle and the maximum for plants with a combined cycle (Tolmasquim, 2016). Both cycles may replace the current generation model with diesel oil, which has an efficiency of 44% (EPE, 2019a). The thermal power plants infrastructure costs are not considered in this work. The research's scope focuses on calculating the SSLNG logistical costs by fluvial transport and reducing emissions by replacing diesel oil with natural gas. Both case studies (Borba and Itacotiara Thermal Power Plants) are integrated into the IS and use diesel oil as fuel. Thus, we opted to calculate the economic costs from the Port of Coari and the Azulão field using SSLNG by fluvial transport until Borba and Itacoatiara thermal power plants. The Borba and Itacoatiara thermal power plants have 6,990 kW and 29,700 kW of nominal installed capacity power (ANEEL, 2020b). The municipality of Borba is located on the right bank of the Madeira River (around 150 km south of Manaus (the capital of the state)) (Eletrobras Distribuição Amazonas, 2016). In 2020, its population was 41,748 inhabitants (IBGE, 2020a). Borba's economy depends on the primary sector, largely on fishing, agriculture, and extractive activities (Eletrobras Distribuição Amazonas, 2016). A single diesel power plant serves the municipality. The municipality of Itacoatiara is located on the Amazon River banks, in the state's central-eastern portion. Agriculture, livestock, and fishing predominate the economic

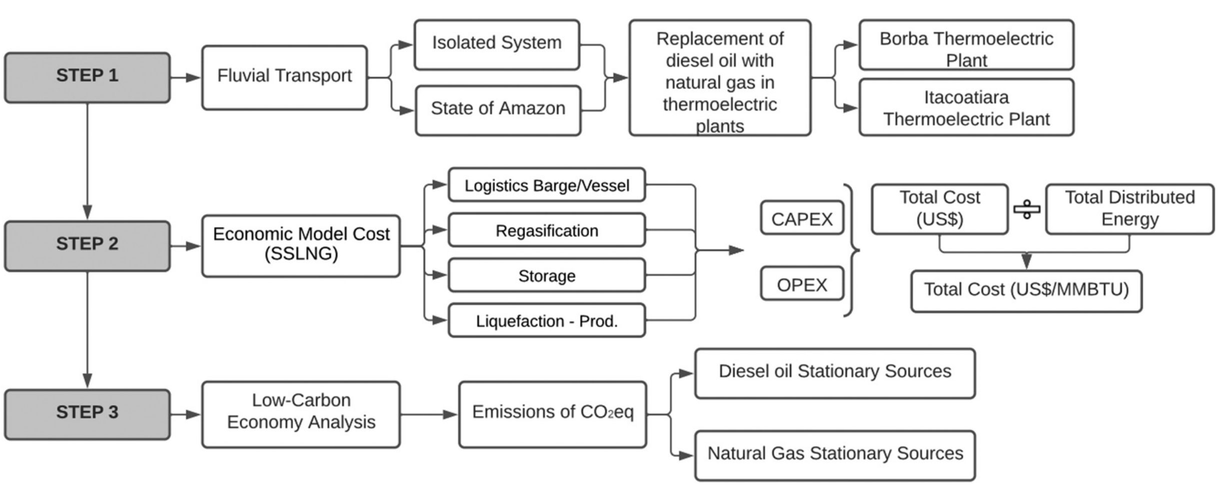

Fig. 1. Methodological procedures.
Source: Elaborated by the authors based on Fraga (2018), Fraga et al. (2019), IGU (2015), IPCC (2006), and SENAI (2017).

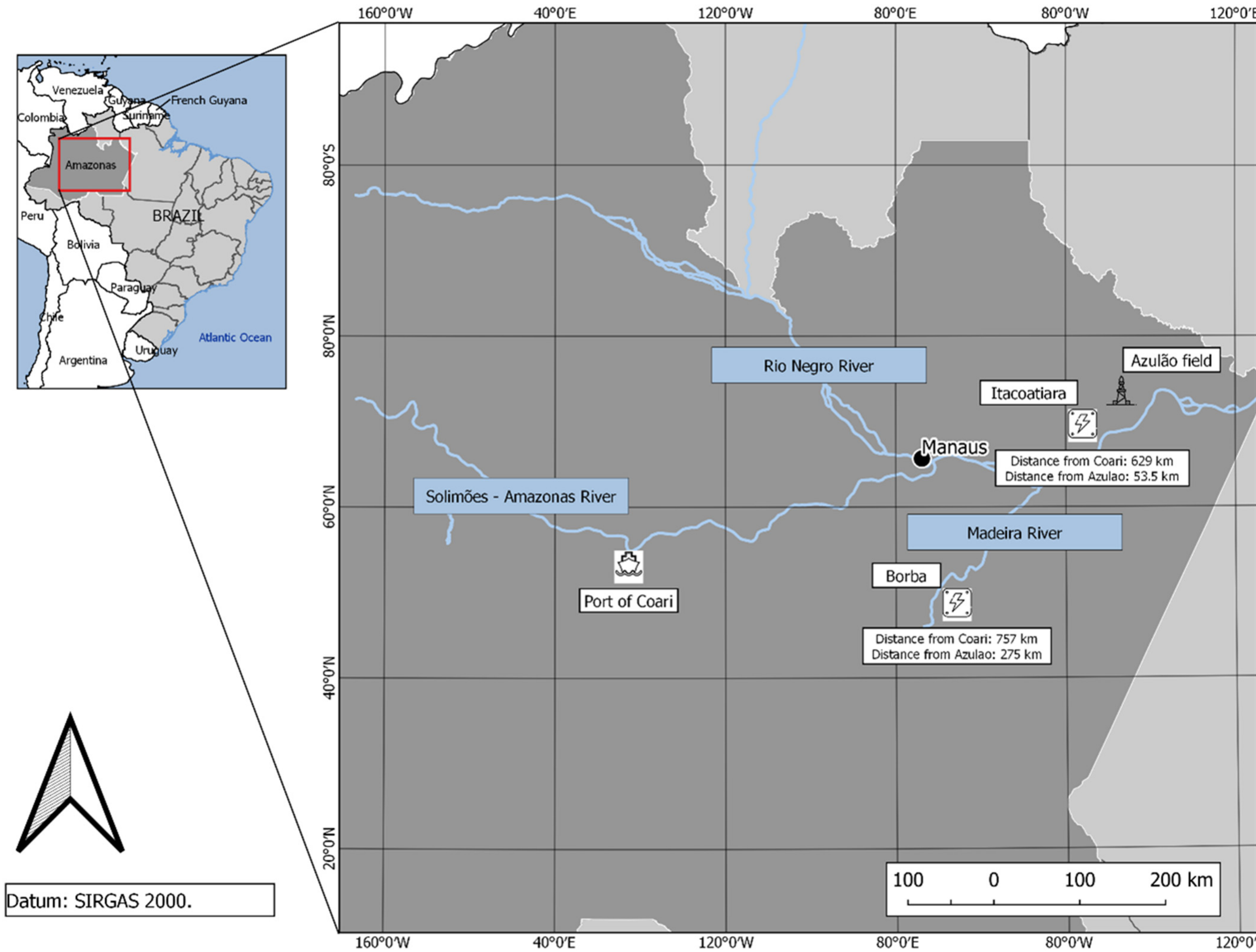

Fig. 2. Geographic location of Borba and Itacoatiara thermal power plants.
Source: Elaborated by the authors based on ANEEL (2020b), ANP (2020), and IBGE (2019b).

activities of the city. In 2020, its population was 102,701 inhabitants, the third most populous city in the state (IBGE, 2020b). Itacoatiara has a port responsible for a considerable amount of cargo transportation in Amazonas (IBGE, 2020b).

Economic model cost

This section introduces the economic model designed to solve the cost of the SSLNG value chain to supply thethermal power plants used in the case studies.

Demand for natural gas and input data

The SSLNG value chain is characterized by four steps from the natural gas source until the delivery point by fluvial transport: i) liquefaction, ii) logistics, iii) storage, and iv) regasification (Fraga, 2018; Fraga et al., 2019; IGU, 2015). The first step of the financial analysis consisted of calculating the demand for natural gas from the selected thermal power plants (see Table 3).

Following the Brazilian electricity sector regulation, a 15-years contract has estimated for the thermal power plant's concession, using the consumption, power, and percentage equal to 100% (total replacement of diesel oil with natural gas). The input data to compose the operating costs of the fluvial transport are shown in Table 4. The calculations considered the logistics from two sources of natural gas based on the distance from Coari Port (LNG flow point) to the Borba thermal power plants (757 km) and Itacoatiara (629 km) and from the Azulão field to the Borba (275 km) and Itacoatiara (53.5 km) thermal power plants.

Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs

The CAPEX and the OPEX values were calculated for each step from the input data (Araújo et al., 2014; IGU, 2015), for all the stages of the SSLNG chain, LNG transport cost in dollars per energy unit (USD/MMBtu), and a split between CAPEX and OPEX costs by the LNG amount be transported (MMBtu) (Fraga, 2018; Fraga et al., 2020). The following values were considered for calculation: the number of required liquefaction plants [O], i.e., one. It emphasizes that there is no liquefaction plant built in the scenario of outflow of natural gas from the Port of Coari. 600,000 tons per year of the capacity of the liquefaction plant [P], 981.62 USD/ton for the value of the liquefaction plant (Fraga,

Table 3
Consumption of natural gas per month.

Thermal power plants	Daily consumption of natural gas (m^3)	Monthly consumption of natural gas (m^3)	
		42% of efficiency	63% of efficiency
Borba	7196	513,973	342,648
Itacoatiara	39,100	2,792,818	1,861,878

Source: Elaborated by the authors based on Main Engines (n.d.) and ONS (2020).

Table 4
Input data to compose operating costs.

Value chain stage	Type	Description	Value input	Unit
Logistics barge/vessel	Volumetric	Vessel capacity	4000	m³ of LNG
		Fillable volume	98,50%	% of capacity
		Fuel consumption	8,4	t/d
		Boil off	0,10%	% per day
	Time	Vessel disponibility	7884	hours/year
		Max hours of working	7008	hour
		Balancing and adjusting time and connections	1	hour
		Loading/offloading time	7	hours/operation
		Preparation for departure	25	
		Anchoring and arrival	25	
		Preparation for returning	3	
	Distance	Liquefaction plant to regas	627 or 757	km
	Flow	Vessel flow rate	1000	m^3/h
	Depreciation	Vessel depreciation after 10 years	50%	% CAPEX
	Speed	Vessel speed	13,5	knt
	OPEX	Periodic maintenance	15	days
		Cost	0,06	USD/mmbtu[a]
Regasification	Capacity	Regas plant	0,5	MTPA
	CAPEX	Regas plant	104,81	USD[a]/t
Storage	Capacity	Storage per tank	757	m^3 LNG
		Storage days capacity	3	#daysstorage
	CAPEX	Storage tank	2016,5	USD/m^3[a]
Liquefaction - Prod.	Energy	Consumption liquefaction plant	471	kWh/TPA
		Energy cost	92,9	USD/kWh[a]
	Capacity	Liquefaction plant capacity	0,6	MTPA
	CAPEX	Liquefaction CAPEX	981,62	USD[a]/t

Source: Elaborated by the authors based on the economic model developed by Fraga (2018) and Fraga et al. (2019).
[a] The average of the last semester (November 2020 until April 2021) was used to convert the exchange rate (Real to USD Dollar = 5.425).

2018; Fraga et al., 2019) and, 1–15 years of the contract were considered [R]. Thus, the project's CAPEX expense will be USD 108,567,000 (sum of both thermal power plants), discounted only in year 0. Table 5 shows the OPEX cost for thermal power plants used in the case studies.

Low-carbon economy analysis

The consumption of natural gas and CO_2eq emissions was calculated based on the annual energy generation of the selected thermal power plants. Furthermore, stationary diesel oil fuel sources emit 74.35 tCO_2eq per TJ, while stationary natural gas sources emit 56.15 tCO_2eq per TJ [86]. For calculating CO_2eq emissions from stationary sources, Eq. (1) is used. The results are presented in Table 6.

$$
\begin{aligned}
CO2\ eq\ emissions_{(t/TJ)} = {} & CO2\ emissions_{(t/TJ)} \times cf\ CO2 \\
& + CH4\ emissions_{(t/TJ)} \times cf\ CH4 \\
& + N2O\ emissions_{(t/TJ)} \times cf\ N2O
\end{aligned}
\tag{1}
$$

To calculate the values of emissions from transport of LNG, it considered the round trip and diesel oil and natural gas consumption for both thermal power plants. The calculation also reflects the distance from the origin (Azulão field or Port of Coari), the volume of transportation, the density of fuels transported, and the vessel's mission factor (20gCO_2/tku) (EPL & IEMA, 2021; MME/EPE, 2021). For a holistic overview of emissions, it is interesting to understand GHG emissions throughout the chain. According to (Turconi et al., 2013), the generation of electric energy from natural gas emits, in the whole chain, about 105 to 278 CO_2eq t/TJ, while the oil power generation emits about 147 to 250 tCO_2eq per TJ. The study method used by Turconi et al. (2013) was based on the review of 167 case studies involving life cycle analysis. It is concluded that there is an equality of GHG emissions between the energy generation from the two sources. Thus, when analyzed holistically, emissions from the use of diesel oil and natural gas would be practically the same. However, this work only has analyzed direct emissions from energy generation and emissions caused by transportation of the fuels. Thus, it is concluded that the local CO_2eq emission can be lower using natural gas.

Results and discussion

Fig. 3 shows the financial analysis for the Borba and Itacoatiara thermal power plants through four scenarios for each case study. For this analysis, interest rates were considered for each scenario of natural gas output, inflation, the construction, or not, of a liquefaction plant, and population growth. A discount value range between 5% and 20% was considered to illustrate different risks and opportunity cost scenarios. The results show the costs (USD/MMBtu) of the four stages of the chain: liquefaction, logistics, storage, and regasification. The natural gas sold by the Azulão field (scenarios without the construction of a liquefaction plant) is significantly more advantageous than the scenarios with constructing a liquefaction plant, even being close to natural gas exploration fields.

The variable costs of gas-fired power plants depend on the existing infrastructure and the project design (Lawson & Pereira, 2017). Diesel power plants have a low implementation cost, a very high variable cost, high GHG emission, fast activation, and ease of transport and fuel storage (Lawson & Pereira, 2017). In comparison, the gas-fired power plants have higher implementation costs, lower variable costs, medium-level GHG emissions compared to other fossil fuels sources (Lawson & Pereira, 2017). Another decisive factor in implementing the substitution is comparing natural gas and diesel oil costs. The molecule's value was considered in the diesel oil operation costs since the entire infrastructure is already built. The conversion of diesel oil to the same unit as natural gas, considering the average value for February 2021, obtains a value of 22,416 USD/MMBtu (ANP, 2021; CEGAS, 2021). Thus, using

Table 5
OPEX estimated costs for Borba and Itacoatiara thermal power plants.

Description	Unit	Year 0		Year 1–15	
		Itacoatiara	Borba	Itacoatiara	Borba
OPEX personnel/plant	USD/liquefaction plant	2,431,894	2,431,894	2,431,894	2,431,894
Consumables - refrigerants (ethane)	USD/tonne	659,427	659,427	659,427	659,427
Consumables - refrigerants (propane)	USD/tonne	700,151	700,151	700,151	700,151
Consumables - chemicals (gas sweetening)	USD/year	1,023,955.31	1,023,955.31	1,023,955.31	1,023,955.31
Storage	USD/m^3	449	449	449	449
Regasification	USD/year	786,251	786,251	786,251	786,251
Logistics	USD/year	1,368,182	1,368,182	1,368,182	1,368,182
Energy consumption	kWh/TPY			3,909,403	719,46
Energy costs	USD/kWh			576,122.59	106,025.75

Source: Elaborated by the authors based on the economic model developed by Fraga (2018) and Fraga et al. (2019).

Table 6
Conversion to CO_2eq.

Fuel type	Type emission values (t/TJ)			Conversion factors (cf)			Total CO_2 eq (t/TJ)
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	
Diesel oil	74.100	0.003	0.0006	1	21	310	74.349
Natural gas	56.100	0.001	0.0001	1	21	310	56.152

Source: Elaborated by the authors based on IPCC (2006) and SENAI (2017).

natural gas as a fuel in the Itacoatiara and Borba (with just 5%) thermal power plants proved possible, with less cost than the Azulão field. However, when comparing the values of diesel oil and natural gas, which is sold through the port of Coari, there is a loss of profit, with diesel oil being more economically advantageous (see Fig. 3). In addition, Fig. 4 shows the cost composition through the economic model applied. Its y-axis is on a log scale, as liquefaction costs significantly outweigh the other cost compositions. In scenarios where there is no need to build a liquefaction plant, the higher cost is due to regasification (regas).

In conclusion, the use of LNG becomes an economic advantage when a liquefaction plant is available for use. Besides, this replacement is a great option due to the increased demand and expansion of the thermal power plants' capacity. In 2019, the Borba thermal power plant used 25,997 MWh of capacity (consume + supply + losses) and demanded 4717 kW. For the year 2028, Borba and Itacoatiara thermal power plants are expected to increase their capacity to 34,018 MWh (consume + supply + losses) and 234,533 MWh (consume + supply + losses) and demand of 5794 kW and 49,723 kW (EPE, 2019a). The feasibility of projects through the construction of two terminals for receiving and stocking LNG in Itacoatiara has been discussed by Amazonas Energy company (EPE, 2019b). The municipality of Itacoatiara is in a strategic geographical position and has an extensive port infrastructure. Besides, there are investments from the government and the private sector to implement a logistical system for this fuel through fluvial transport, as suggested here in this study (EPE, 2019b). With the adoption of LNG (Sovacool & Dworkin, 2015), some logistical investments are being analyzed beyond the state of Amazonas. For example, the LNG storage in a Floating Storage Unit of 180,000 m^3 of capacity, then transferred it to barges for redistribution to the potential market for natural gas along waterways in the states of Pará, Amazonas, Roraima, and Rondônia (EPE, 2019b).

Fig. 5 shows the CO_2eq emissions for the scenarios analyzed in this paper. As a result, the lowest emission was found in the Azulão field origin scenarios and 63% efficiency in the thermal power plants, i.e., it consumes a smaller volume of natural gas and has a shorter distance between the liquefaction plant and the thermal power plants. In the Borba thermal power plant, the emissions of CO_2eq can be reduced by up to 36% with the replacement of diesel oil by natural gas and, in the Itacoatiara thermal power plant by up to 38%. Due to electricity

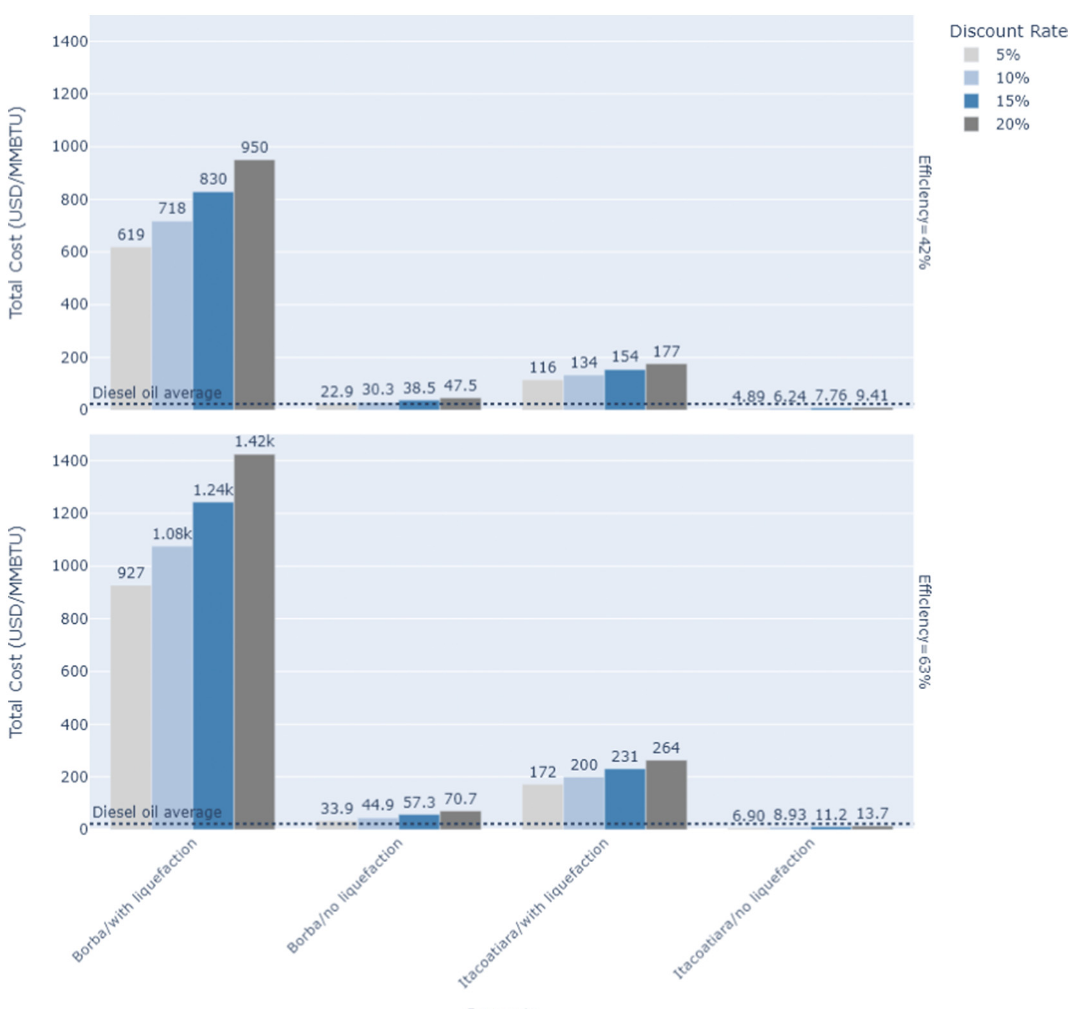

Fig. 3. Comparison between the values of diesel oil and natural gas.
Source: Elaborated by the authors based on Fraga (2018), Fraga et al. (2019), and IGU (2015).

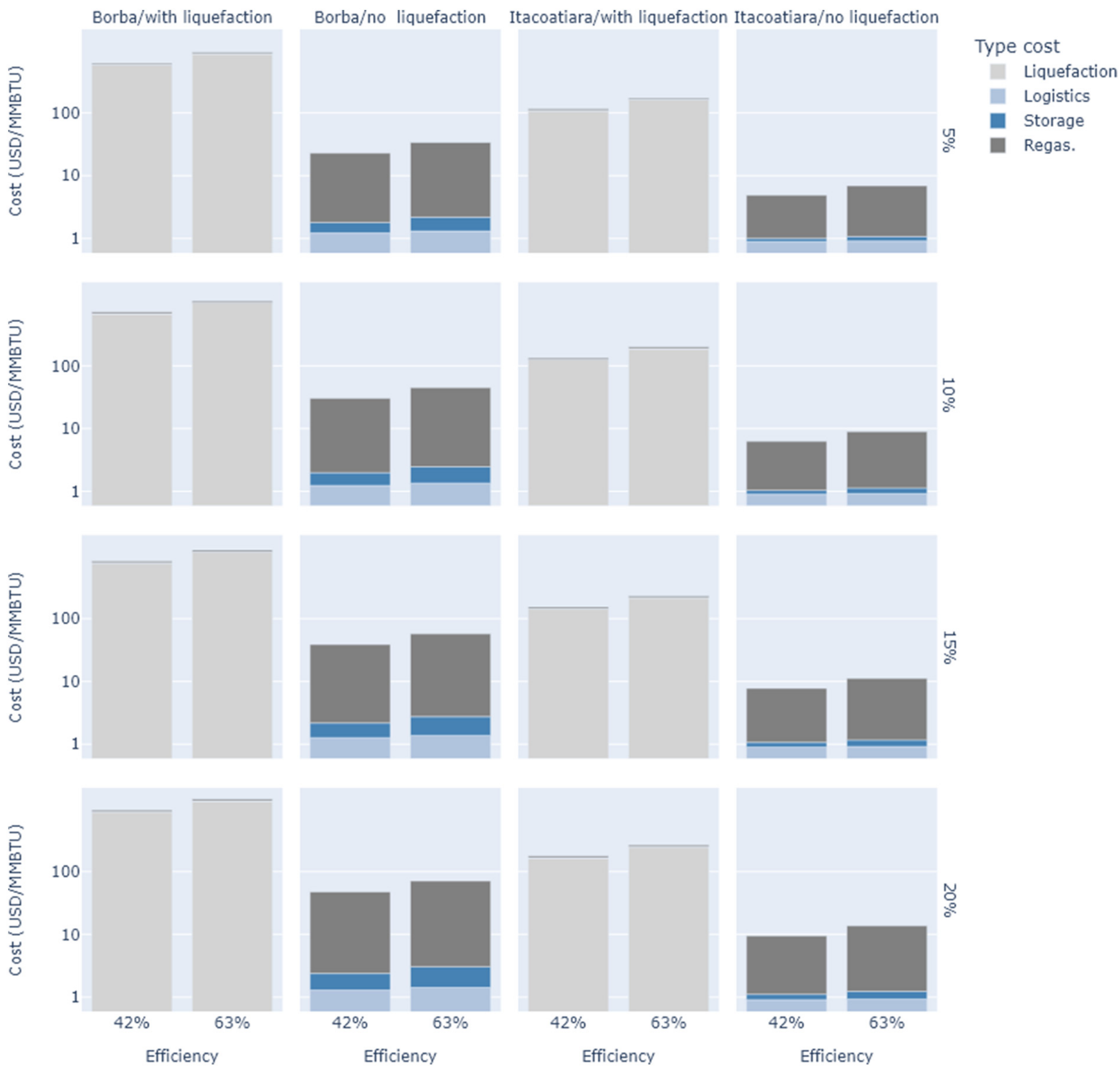

Fig. 4. Composition of costs.
Source: Elaborated by the authors based on Fraga (2018), Fraga et al. (2019), and IGU (2015).

generation and losses, the volume of emissions at the plants was significantly higher than emissions in the transport. Transport emissions were lower in the use of natural gas scenarios.

Fig. 6 shows an economic and environmental analysis of the scenarios proposed in this research. The y-axis shows the total costs of the scenarios, with each point plotting the previously projected discount value, and the x-axis shows the CO_2eq emission values for each scenario. All scenarios with 42% efficiency proved to be more environmentally advantageous, with lower emissions than diesel oil. Economically, the scenarios that showed feasibility were those that do not require the construction of a liquefaction plant. All scenarios with 63% efficiency proved to be significantly environmentally viable; however, the scenarios without building a liquefaction plant were not cost-effective. When comparing the efficiencies of both case studies, the scenarios with 42% efficiency had higher emissions; however, being more financially viable, i.e., the scenarios need a larger volume of natural gas, thus reducing their costs.

The electrification of isolated communities using conventional supply presents significant barriers such as high costs of the transmission lines, transportation of diesel oil, and the community residents' low income (Goldemberg et al., 2004). Thus, there is a social role in ensuring affordable energy prices for people living in these areas (Ponte et al., 2021). Electricity tariffs represent the energy price that the distribution companies will charge consumers for the energy consumed (Lima et al., 2017). Distribution and transmission costs constitute 25% of the energy tariff, while energy generation and subsides represent 37% and 11%, respectively (ANEEL, 2019). Currently, energy tariffs are divided into two main items: manageable and not manageable costs (Lima et al., 2017). The first one includes operational costs and capital returns from the distribution company investments. These costs go to the consumers' tariffs under an efficiency reference indicator to motivate the constant improvement of the services offered by the distribution companies. The second item represents costs such as the generation purchase and sectorial charges (subsides and political policies). These costs go automatically to the consumers' tariffs since the distribution companies are not responsible for its application (Ramos et al., 2012). The Energy Development Account (CDE) is the main source of subsiding in the energy tariff, and it englobes many items to benefit different agents. The two main dispenses in the CDE are the discounts for renewable generation and the Fossil Fuels Consuming Account (CCC) (Ministério da Economia,

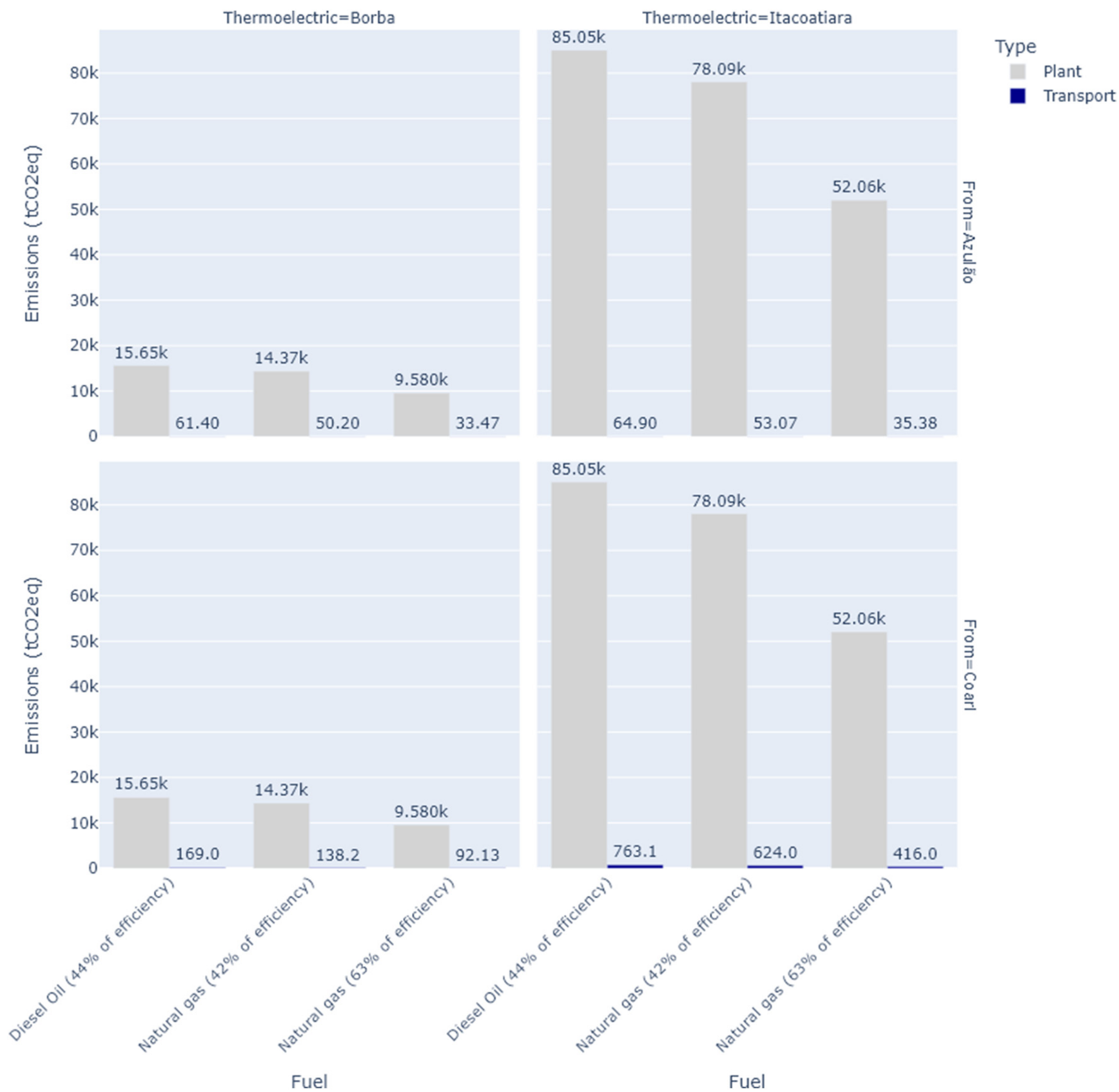

Fig. 5. Emissions (tCO_2eq) by power plants, fuel and energy efficiency.
Source: Elaborated by the authors based on IPCC (2006) and SENAI (2017).

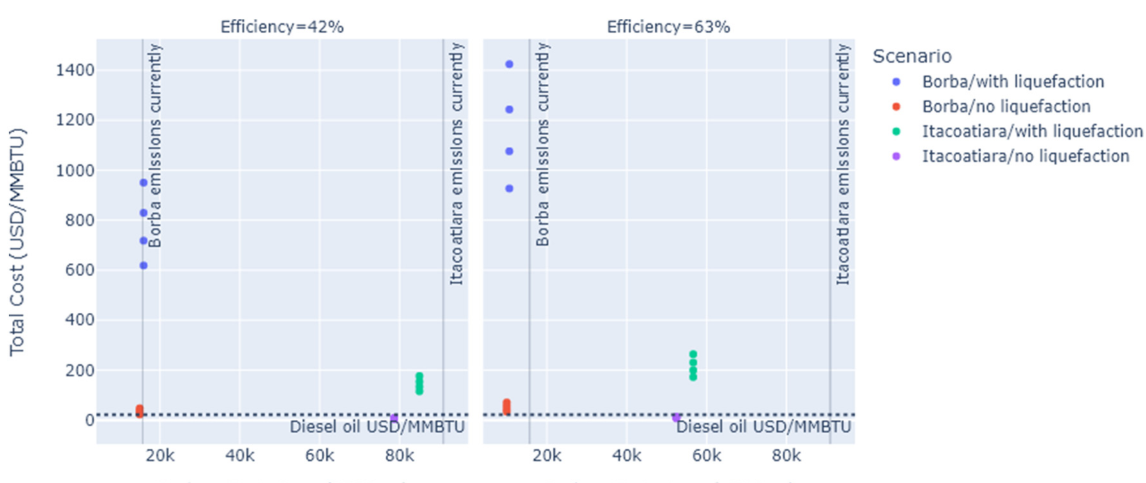

Fig. 6. Environmental and economic analysis.
Source: Elaborated by the authors based on IPCC (2006), Natural Resources Canada (2014), and SENAI (2017).

2020). The CCC is a specific fund for the IS to pay for diesel oil generation's expenses since its costs are superior to the SIN's hydropower matrix (Frota et al., 2010a). The electricity tariff of all consumers in the country contains a fee used for supplying the CCC fund. Thus, con-sumers in the IS pay only the average cost of generating the national regulated market (ACRmed). The CCC subsidizes the difference between the total cost of IS generation and the ACRmed (Ponte et al., 2021). In 2020, USD 1,34 billion were spent to power the IS (Câmara de Comercialização de Energia Elétrica, 2021) and sustained by the elec-tricity bill of all consumers. In 2021, the ACRmed is expected to reach USD 47,00/MWh, while the energy price in isolated systems is up to USD 368,66/MWh due to diesel oil generation (ONS, 2021a). As a result, considering the scenarios, without building a liquefaction plant, the generation cost would vary from 22.90–47.50 (Borba power plant with 42% efficiency) and 4.89–9.41 (Itacoatiara power plant with 42%efficiency) USD/MMBtu, switching to 63% efficiency from 33.90–70.7 (Borba power plant) and 6.90–13.70 USD/MMBtu (Itacoatiara power plant). Thus, when comparing with the value of 22,416 USD/MMBtu of diesel oil, Itacoatiara thermal power plant presents the most significant reduction to the system for both efficiency conditions. Moreover, the high values regarding diesel oil generation in IS, the CCC subside brings inefficiencies that may result in even higher energy tariffs. The payment for energy generators on IS comprises two major parts: paying invest-ment costs and operational expenditures, including fuel price. The first term is corrected every year by a national inflation index, while the fuel is monthly updated, considering the price published by National Agency of Petroleum, Natural Gas and Biofuels (ANP) (Ponte et al., 2021). To access the CCC fund, power plants managed by the electricity distribution companies in the IS must accomplish regulated fuel con-sumption limits imposed by the National Electricity Agency (ANEEL). However, as the major cost of generation is subsidized, fuel cost is not an essential issue for distribution companies since the subsidies cover the difference between the total cost of local generation and the average cost of power generation in the national grid (Ponte et al., 2021). Since natural gas is less expensive than diesel oil, the substitution proposed in this study is a relevant measure to reduce the electricity tariff of con-sumers.

As a result, this work has indicated that the replacement of diesel power plants in the Amazon state with natural gas can be one of the solutions to contribute to the decrease local carbon emissions in the energy sector. In addition to the environmental benefit and low cost to the consumer, the concept of energy justice is present, with a possibility for energy planners and consumers in making more informed energy choices (Sovacool & Dworkin, 2015). The energy security of remote areas (e.g. IS) becomes a challenge even for the Brazilian government's compliance with the right of access to energy for all by 2030 (SDGs - Goal 7) (Munro et al., 2017). Therefore, the local community's guarantee of electricity made us look for specific solutions for these locations. Besides, the state of Amazonas already has some locations supplied by natural gas (e.g. Anamã, Anori, Caapiranga, and Codajás), presenting experiences with the local use of this fuel.

Conclusions

When dealing with decarbonization, electricity access, and particularly the reality of IS, the work has sought to find economical, environmental, and logistics solutions, besides offering the community energy security and reducing the electricity cost significantly to the final consumer. Besides, the use of SSLNG becomes another advantage for fluvial transport. Concerning the logistical, seasonality, resource availability, and environmental aspects of the isolated system in Amazonas, the sub-stitution of diesel oil by natural gas using SSLNG can significantly con-tribute to levels on different scales as local (e.g. healthy benefits, creation of jobs, regional development), national and international (e.g. SDGs, Paris Agreement).

It should be noted that the article is not supported the idea of promoting the use of fossil fuels. The discussion is also based on the abundance of resources locally, regional particularities, available technologies, consumer costs, and carbon emissions decrease. This study presented a real possibility to promote economic and health benefits to the local community. Besides, the implications of this work for broader remote area electrification can be useful. Also, local transitions to a low-carbon economy are necessary to achieve climate change mitigation. Furthermore, there is a concern with the increase in demand that needs to be incorporated into energy planning for the coming years. For the subsequent study, the suggestion is to replace the fuel (e.g. diesel oil) of vessels with other fuels and the role of the public policies in these processes.

CRediT authorship contribution statement

Drielli Peyerl: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Celso da Silveira Cachola:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Victor Harano Alves:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Marcella Mondagron:** Conceptualization, Methodology, Writing – original draft. **Sabrina Fernandes Macedo:** Writing – review & editing. **Xavier Guichet:** Writing – review & editing. **Edmilson Moutinho dos Santos:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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