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The economic and environmental benefits of adopting natural gas in isolated systems of Amazonas state, Brazil

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ABSTRACT

The Amazonas state in Brazil faces unique challenges regarding energy planning for its 95 isolated systems, which are remote areas not connected to the national power grid and primarily rely on diesel to generate electricity. These challenges include dense forests, low population density, low overall energy demands, and restrictions on transporting oil derivatives via waterways. However, the discovery of onshore reserves of natural gas in the state and investments in infrastructure, such as the construction of gas pipelines, have provided an opportunity to replace diesel with this cleaner and more cost-effective energy source. This study aims to assess the feasibility of completely replacing diesel-powered generators with natural gas in 14 isolated systems located near the Urucu-Manaus gas pipeline, as well as the Azulão and Japiim production fields. The methodology employed in this study aims to provide a comprehensive assessment of the economic and environmental impact of transitioning from diesel to natural gas in isolated systems. This assessment focuses on two key topics: fuel costs and CO_2 emissions resulting from electricity generation. The analysis results indicate that transitioning from diesel to natural gas can bring significant economic and environmental benefits. The switch to natural gas would reduce fuel costs by more than 40% and decrease CO_2 emissions from combustion (in one case, 39.6% and in other cities, between 16.75% and 27.10%), promoting savings for additional investments in efficiency and sustainability. Implementing these changes makes it possible to achieve a better quality of life for citizens in isolated communities by providing access to a more reliable and sustainable energy source.

1. Introduction

Universal access to modern energy services is a key global goal for achieving the Sustainable Development Goals (SDGs). It includes ensuring reliable, affordable and sustainable energy services with low greenhouse gas (GHG) emissions, providing health, education, lighting, cooking, communication, and productive uses (AGECC, 2010). Many international institutions and authors argue that access to energy should go beyond meeting basic needs demand (Coelho and Goldemberg, 2013; Mazzone, 2019, 2020; Zhong et al., 2020). Access to sufficient energy for productive activities is also crucial for regional socio-economic development and reducing energy inequality, particularly in developing countries. Besides, a direct correlation exists between electricity affordability and an improved

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Abbreviations

ANEEL	Brazilian Electricity Regulatory Agency
ANP	National Agency for Petroleum, Natural Gas and Biofuels
CNPE	National Energy Policy Council
CO_2	Carbon Dioxide
EPE	Energy Research Office
GHG	Greenhouse Gases
HDI	Human Development Index
IBGE	Brazilian Institute of Geography and Statistics
IS(s)	Isolated System(s)
LNG	Liquefied Natural Gas
LPT	Light for All Program
MLA	Most Light for the Amazon Program
MME	Ministry of Mines and Energy
ONS	National Electric System
PCH	Small Hydroelectric Power Plants
PIM	Industrial Pole of Manaus
R$	Brazilian Real
SDGs	Sustainable Development Goals
SIN	National Interconnected System

Human Development Index (HDI) (Gómez and Silveira, 2010; Yumashev et al., 2020). Moreover, the lack of electricity access, especially in rural and remote areas, can adversely affect HDI values (Frota et al., 2010).

In Brazil, efforts to establish universal access to electricity as a public service began in 2002 with Law 10.438 (Brasil, 2002). In 2003, the Ministry of Mines and Energy (MME) initiated the "Light for All" Program (LPT) as an immediate action to eliminate electricity exclusion in rural and remote areas (MME, 2018, 2017). By 2019, the country had achieved a high access rate to electricity of 99.8% (IBGE, 2019a). However, some northern states of the country still have relatively low access proportions, such as Acre (97.4%), Amazonas (98.5%) and Pará (98.7%) (IBGE, 2019a). To address this, the MME published the "Manual for Service to Remote Regions of Isolated Systems" in 2015 through an MME Ordinance (MME, 2015), which outlines viable technological options such as hydro, biofuels, natural gas, photovoltaic and wind sources, or hybrid systems to complement the actions of LPT (MME, 2017). However, specific solutions tailored to isolated areas in the Brazilian Amazon, where conventional grid expansion faces barriers, were needed approach (Andrade et al., 2011; Gómez and Silveira, 2012). In early 2020, the "Most Light for the Amazonas" Program (MLA) was launched to target remote areas of the Amazonas region (Brasil, 2020).

The isolated systems (ISs) in the North region present unique challenges compared to the rest of the country. First, the ISs are not connected to the National Interconnected System (SIN) due to the high costs of capital and challenging environmental conditions, such as precipitation, altitude, and dense vegetation (EPE, 2020a; Marengo, 2006; Michael T. Coe et al., 2016). Transmission and distribution grids are potential environmental impact sources due to the low consumption per unit, lack of economies of scale, and a dense tropical forest (Hyde et al., 2018). Moreover, the ISs require significant initial investments, have more extended recovery periods, and consumers cannot afford high tariffs (Zerriffi, 2011). As a result, decentralization of the energy supply and utilization of diesel-powered thermoelectric plants have been considered plausible solutions for some regions in Brazil in recent years (Goldemberg et al., 2004; ONS, 2019).

The management of ISs faces challenges in terms of accessibility, as well as the need for environmental, economic and sustainable alternatives from local sources (EPE, 2020a) as biomass (Brandão et al., 2021; Duarte et al., 2010; Macedo et al., 2016), hydro (Blanco et al., 2008), hybrid system (da Ponte et al., 2021; Fuso Nerini et al., 2014; Silva et al., 2010), and natural gas (Frota et al., 2010; Frota and Rocha, 2010). One promising energy alternative implemented in the state involves combining solar energy with the abundant natural resources available in the region, such as biomass and water resources (Matos et al., 2011). Several studies have demonstrated that implementing hybrid systems that utilize diesel, solar photovoltaics, and batteries can lead to a significant reduction in fuel consumption by up to 26% (Ponte et al., 2021; EPE, 2016). These systems have also been found to lower energy prices by an average of 6.5% (Ponte et al., 2021; EPE, 2016). On the other hand, the rainforest coverage limits the photovoltaic and wind sources in the region, with the most suitable sites for wind turbines, for example, concentrated in coastal areas (Sánchez et al., 2015).

In 2019, the Amazonas state had 95 ISs largely dependent on diesel thermoelectric power plants (EPE, 2020a; ONS, 2019). Furthermore, the logistic system of fuel transportation in Amazonas has been adversely affected due to the high reliance on fluvial transport due to the seasonality (Frota and Rocha, 2010). Law No. 8631 (1993) consolidated the subsidy that exclusively covers the fossil fuel costs of generating electricity for ISs, known as CCC-ISOL (Fossil Fuel Account). The subsidy is necessary to reduce regional inequalities in the country, but a more comprehensive analysis of the cost-benefit is needed to encourage more efficient energy use, both in generation and consumption (Magalhães & Tiryaki, 2008). Some punctual actions have demonstrated the government's role in planning and investing to integrate the ISs into the SIN or replace diesel with natural gas or biomass as energy sources.

Diesel replacement with an alternative energy source in the ISs has been a major challenge for the Brazilian government. The discovery of Brazil's largest proven onshore reserves of oil and natural gas in the municipality of Coari in the Amazon and new technologies such as the transport of Liquefied Natural Gas (LNG) have made natural gas one of the primary replacement sources for diesel (Peyerl et al., 2022; Almeida and Souza, 2008). In addition, natural gas emits less GHG than other fossil fuels, making it an environmentally-friendly option (Feng et al., 2016). This paper aims to analyze the environmental and economic impacts of replacing diesel with natural gas in Amazonas for electricity generation for 14 ISs, which localize closer to the potential supply infrastructure. The study focuses on emissions and costs, which are critical factors in operators' gross revenue, particularly in the rural areas of Amazonas (Frota and Rocha, 2010). The analysis is based on the production potential, natural gas infrastructure, and the planned and existing fields that can supply the total load of ISs. Besides, this study focuses on electricity generation. While this research does not approach the Life Cycle Analysis (LCA) due to the difficulty of accessing the region's oil and natural gas data, it provides valuable insights into the benefits of replacing diesel with natural gas (Turconi et al., 2013).

This paper is organized as follows: Sections 2 and 3 briefly introduce ISs and their role in regional development. Section 3 delves into the benefits of utilizing natural gas in thermal power plants and its significance. Section 4 outlines the methodology and data collection process, while Section 5 presents the findings of the case studies, including the cost savings and CO_2 emissions reduction values. Lastly, Section 6 presents the study's conclusions.

2. The isolated system in Brazil

The Brazilian electricity sector faced significant regulatory challenges in the 1990s, stemming from its complex historical development. To organize and address these issues, the Brazilian government established three institutions/agencies to structure the sector as follows: i) the National Electric Agency (ANEEL) was created in 1996 by Law 9427 to regulate and supervise the production, transmission, and commercialization of electric energy; ii) the National Energy Policy Council (CNPE) was created in 1997 by Law 9478 with a focus on formulating energy policies and guidelines and; iii) the National Electric System Operator (ONS) was created in 1998 by Law 9648 to oversee the operation of electricity generation and transmission from the SIN and ISs.

The SIN offers many advantages, including exchanging electricity between subsystems, utilizing diverse hydrographic basins and

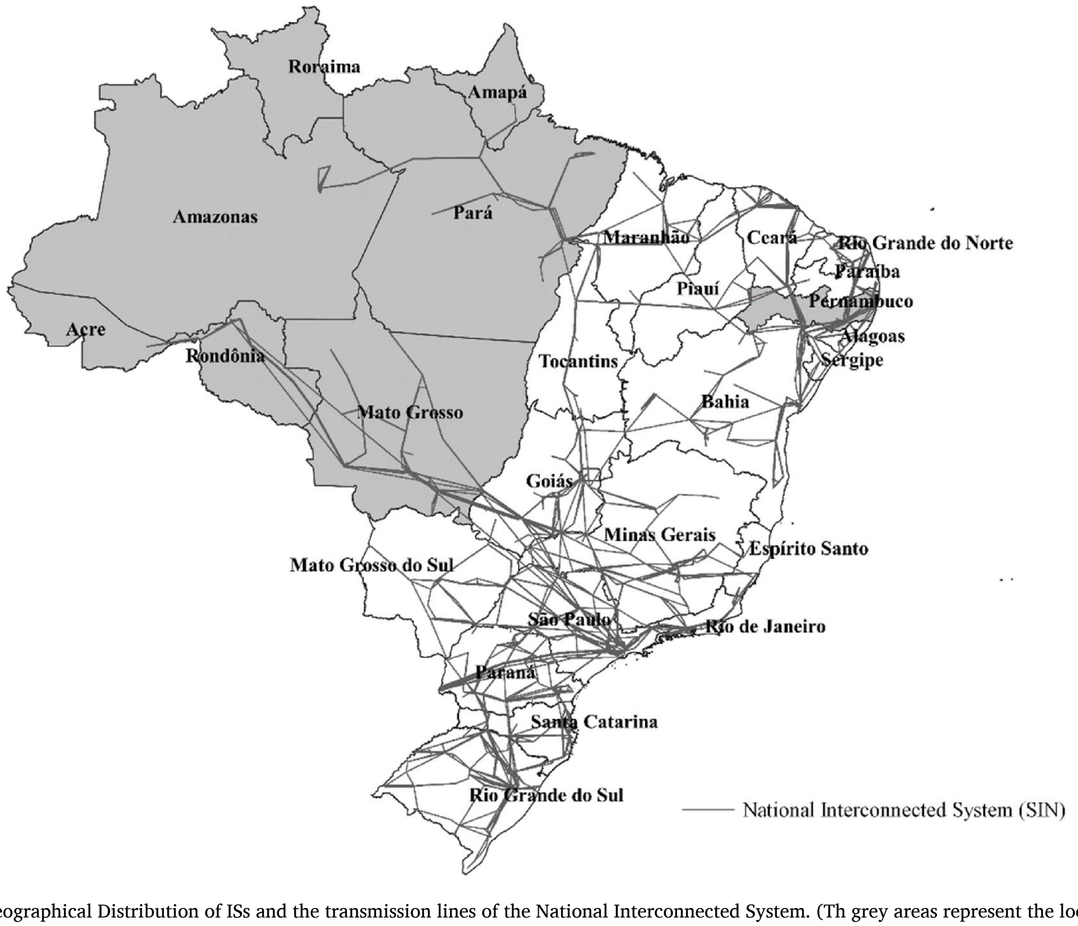

Fig. 1. Geographical Distribution of ISs and the transmission lines of the National Interconnected System. (Th grey areas represent the locations of ISs, while the grey lines represent the transmission lines that configure SIN). Source: Elaborated by the authors based on (EPE, 2020a; IBGE, 2019b; SIGEL, 2019).

non-dispatchable sources such as solar and wind power, and providing safe and cost-effective consumer services (ONS, 2020a). However, ISs remain disconnected from the SIN due to technical or economic constraints. As a result, ANEEL and energy distributors should explore independent production options that prioritize energy and economic efficiency, reduce environmental impacts, and leverage local energy sources (Brasil, 2010a). As of 2019, the ISs served a population of over 3 million inhabitants, accounting for approximately 1.6% of the Brazilian population without access to electricity and 0.7% of its total load (consumption, supply and losses) (EPE, 2020a). There are currently 212 ISs in Brazil, localized in 8 states, primarily in the northern region (ONS, 2020b) (See Fig. 1).

Moreover, due to the small total load of each IS, even a slight change in supply or demand can have significant impacts. Therefore, effective energy planning ensures quality system management (EPE, 2020a). The responsibility of executing annual load forecasting and operation planning for ISs lies with the ONS, as mandated by Law nº13360/2016 (Brasil, 2016). The ONS works closely with electrical service distributors in each area, who provide information and proposals to EPE for assessing the need for new energy contracts (Brasil, 2010b; ONS, 2020b). Additionally, ISs face higher costs for electricity generation and higher CO_2 emission factors than SIN. This is primarily due to the power generation mix in ISs, which is dominated by thermal power plants using oil derivatives such as diesel and fuel oil (94%) (MME, 2020a; ONS, 2020b), resulting in increased operating costs. In contrast, hydroelectricity constitutes the largest share of power generation in SIN (EPE, 2019a). Furthermore, the unique characteristics of the Amazon region, such as the dependence on fluvial transport and precipitation, add complexity to energy forecasting issues in this area.

3. The state of Amazonas and the natural gas

Natural gas plays a vital role as a raw material to petrochemical industries in the Industrial Pole of Manaus (PIM), but also in other sectors such as electric, residential, commercial and transport (EPE, 2020a; Frota et al., 2010). The Amazonas state boasts abundant energy resources (Matos et al., 2011), including natural gas reserves in geological basins such as Solimões and Amazon (ANP, 2020). The Urucu Pole in the Solimões basin is the country's highest onshore producer, accounting for approximately 71% of the national production with 13.8 million cubic meters per day in the first semester of 2020 (MME, 2020b). The Urucu Oil Province was discovered in the late 1980s (Almeida and Souza, 2008), and the Urucu I Processing unit commenced operations in 1993, initially transporting through the Urucu River. However, in 1998, a gas pipeline spanning 280.0 km was constructed to connect the Urucu I Processing unit to the Terminal of Solimões, where the natural gas was transported via waterway to reach final consumers (Melo, 2011; Silva Junior and Santos, 2014). In 2009, following the completion of extensive permits and construction phases, the pipelines connecting Urucu-Coari-Manaus were successfully commissioned, enabling a transport capacity of 5.5 million cubic meters per day. (Bonfim, 2008; Melo, 2011). Nevertheless, the construction and operation of these pipelines have had environmental impacts on the region (de Almeida et al., 2017; Silva Junior and Santos, 2014). The natural gas transport infrastructure also provides fuel for electricity generation in five cities not connected to the SIN: Coari, Codajás, Anori, Anamã and Caapiranga. The Azulãao field is located in the heart of the Amazon Basin, 210 km east of the Amazonas state capital, Manaus. Gas production in the region commenced in 2021, and it has rapidly gained recognition as a significant energy source in the area.. Eneva, the concessionaire responsible for operating the exploration contract, has reported that the field boasts a certified reserve of approximately 6.3 billion cubic meters.

The operation of bi-fuel plants (natural gas + diesel) results in significantly lower environmental impact than diesel, both locally and regionally. However, it should be noted that the production and transport of natural gas also have environmental consequences (de Almeida et al., 2017). The total or almost total replacement of petroleum products with natural gas in the Manaus thermal power plants resulted in substantial reductions in emissions of carbon monoxide (CO), nitrogen oxides (NOx) (Medeiros et al., 2017) and CO_2 (Rocha et al., 2015). It suggests that ambitious efforts to replace petroleum products can reduce regional environmental impacts (Medeiros et al., 2017; Rocha et al., 2015). In 2018, the average cost for power generation was R$ 213.00/MWh, while in the ISs in Amazonas, this cost was R$ 679.00/MWh (ANEEL, 2019)[1]. The estimated total CO_2eq emissions from ISs in 2019 accounted for approximately 5.5% of total emissions in the electricity generation sector (EPE, 2019b; SEEG, n.d.). The high cost of generation is one of the main reasons for the increased attention to the financial-economic performance of ISs companies in Amazon (Frota, 2004). In 2020, it was estimated that the ISs emitted a total of 0.637 tCO_2eq/MWh, a slight decrease compared to the previous year (0.674tCO_2eq/MWh) due to contributions from natural gas-powered thermal power plants and small hydroelectric power plants (EPE, 2020a). It is important to highlight that the emission factor of the SIN for the same year stands at 0.0617.

4. Materials and methods

The methodology of this paper is structured in three steps: (i) ISs selection according to the criteria of proximity (to understand definition criteria, see Fig. 2) to the natural gas transport and production infrastructure; (ii) definition and application of the methods to evaluate environmental and economic impacts, according to the fuel used for the operation of thermal power plants (diesel and natural gas) and; (iii) data collection for the processing of the method defined in item 2 (see Fig. 3).

[1] In 2018, average US$ 1.00 was equivalent to R$ 3.87. Thereby the average cost for power generation in SIN was approximately US$ 55.04/MWh, while in the ISs in the state of Amazonas was US$ 175.45/MWh, considering the currency exchange.

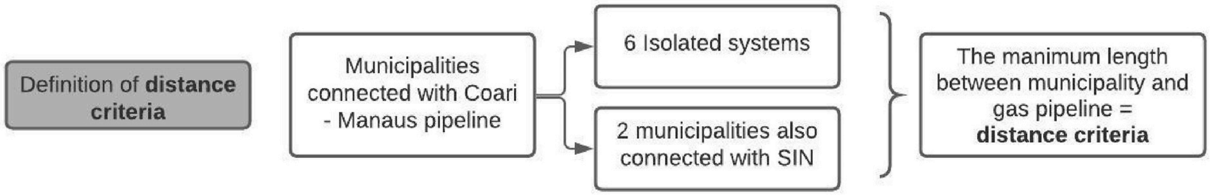

Fig. 2. Procedures to define the distance criteria. Source: Elaborated by the authors.

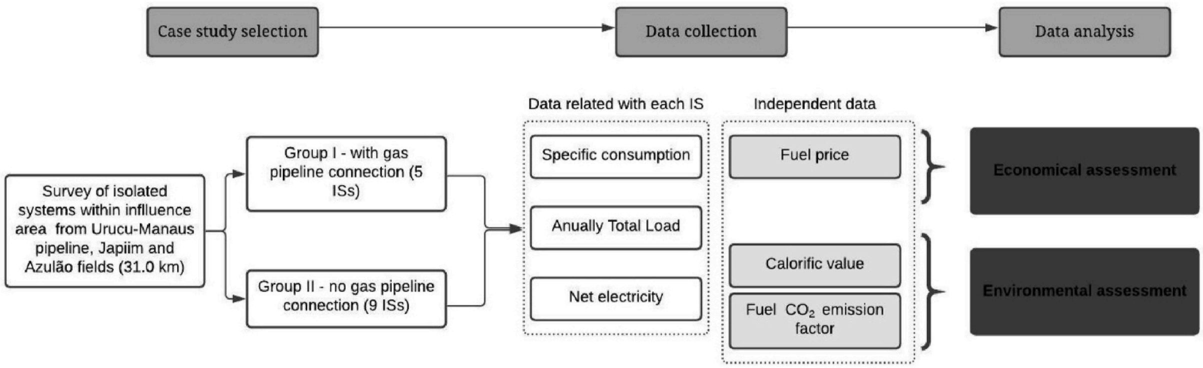

Fig. 3. Methodologic procedures. Source: Elaborated by the authors.

4.1. *The case studies of the state of Amazonas*

The Urucu-Coari and Coari-Manaus pipelines present some connections between them to a few ISs, and the other two municipalities (Iranduba and Manacapuru) recently connected to SIN. Thereby, Iranduba and Manacapuru are no longer characterized as ISs. Table 1 presents the connection distances between the thermal power plants and the central axis (Urucu-Coari and Coari-Manaus gas pipelines). The maximum observed length of these connections is 31.0 km.

This value is the distance limit to define the study area from the natural gas transport and infrastructure assets to the ISs that still use oil-derivate products for electricity generation. It includes the production of natural gas in the Azulão Field (with a scheduled date for production start in 2021) and the Japiim Field (no production start date) and the other municipalities closer but without the supply of natural gas pipeline (in operation since 2009). The survey was carried out on the thermal plants within a radius of 31.0 km from the center in the production fields and natural gas pipeline. The Azulão Field will also have a liquefied plant.

4.2. *Methods*

The economic evaluation to compare diesel oil and natural gas use in ISs' thermoelectric generators is based on fuel costs. The investments in capital goods do not enter into the calculations of the applied methodology. The analysis takes into account the total loads estimated for each municipality annually (TL) and the specific consumption (MM^3/MWh in the case of natural gas or m^3/MWh in the case of diesel) (SC), resulting in the consumption of fuels (C_{fuel}) annually (see Equation (1)). The total load includes the losses, consumption and eventual supplies of the ISs.

$$C_{fuel}\left[MM^3 ou\ m^3\right] = TL\ [MWh] \times SC\left[\frac{MM^3}{MWh} or \frac{m^3}{MWh}\right] \quad (1)$$

Thereby, the annual cost of fuels (AC_{fuel}) results from multiplying the amount consumed (MM^3 or m^3) by each fuel price (see Equation (2)).

Table 1
Municipalities connected with Coari - Manaus transport pipeline. Source(EPE, 2020a):

Municipalities	Extension of the connection originating from the Urucu-Coari or Coari-Manaus natural gas pipeline (kilometres)	Not connected with the SIN
Coari	21,5	Isolated system
Codajás	25,0	Isolated system
Anori	31,0	Isolated system
Anamã	26,5	Isolated system

$$AC_{fuel}\ [\mathrm{R\$}] = C_{fuel}\ [\mathrm{MM^3 ou\ m^3}] * \mathrm{price}\ \left[\frac{\mathrm{R\$}}{\mathrm{MM^3}}\ \mathrm{or} \frac{\mathrm{R\$}}{\mathrm{m^3}}\right] \tag{2}$$

The assessment of environmental impacts focuses on CO_2 emissions from electricity production. The adapted method calculates the emission factor based on the Guidelines for National Greenhouse Gas Inventories (Method "Simple OM" option A1) (UNFCCC, 2018) that is also mentioned in (Frota and Rocha, 2010; Rocha et al., 2015). The calculation for each fuel type follows Equation (3):

$$EF_{EG,CO2}\left[\frac{\mathrm{tCO_2}}{\mathrm{MWh}}\right] = \frac{\left(C_{fuel}\left[\mathrm{MM^3 or\ m^3}\right] \times CV\ \left[\frac{\mathrm{GJ}}{\mathrm{MM^3}} \mathrm{or} \frac{\mathrm{GJ}}{\mathrm{m^3}}\right] \times EF_{fuel,CO2}\ \left[\frac{\mathrm{tCO_2}}{\mathrm{GJ}}\right]\right)}{Elec_{net}} \tag{3}$$

Where ($EF_{EG,\ CO2}$) is the CO_2 emission factor for annual electricity generation (tCO_2/MWh). C_{fuel} is the yearly fuel consumption for the generation (diesel or natural gas) (MM^3 or m^3). CV is the calorific value of each fuel (GJ/MM^3 or GJ/m^3), $EF_{fuel,CO2}$ is the fuel emission factor (tCO_2/GJ). $Elec_{net}$ is the net amount of electricity generated and delivered to the consumer (MWh). In this case, $Elec_{net}$ deducts the loss rate and corresponds only to supply and consumption.

5. Results and discussions

5.1. Costs and environmental impacts

Fig. 4 shows the pipelines connecting the Urucu field to Manaus and its branches, and the green points represent the 14 selected municipalities for the study. The polygons represent the region that sweeps infrastructure over 31 km, as mentioned in section 4.1.

The municipalities were divided into two groups of ISs. The first group has the systems with natural gas thermal plants and supply from the Coari-Manaus gas pipeline: Coari, Codajás, Anori, Anamã and Caapiranga. The other ISs group localized in the area of influence of the gas pipelines and the production fields of Japiim and Azulão but do not present natural gas thermal power plants are: Murituba, Arara, Sacambu, Campinas, Caviana, Careiro, Santana do Uatumã, São Sebastião do Uatumã and Urucará.

According to the user variables (Table 2) and the results (Table 3, Fig. 5), the first group of ISs, i.e., those that already generate electricity from natural gas, obtained a saving in fuel purchase of more than US$ 19 million (R$ 77 million) in 2019. The greatest highlight is Coari (61% of the total economy), which has the largest consumer market among the five municipalities but started the

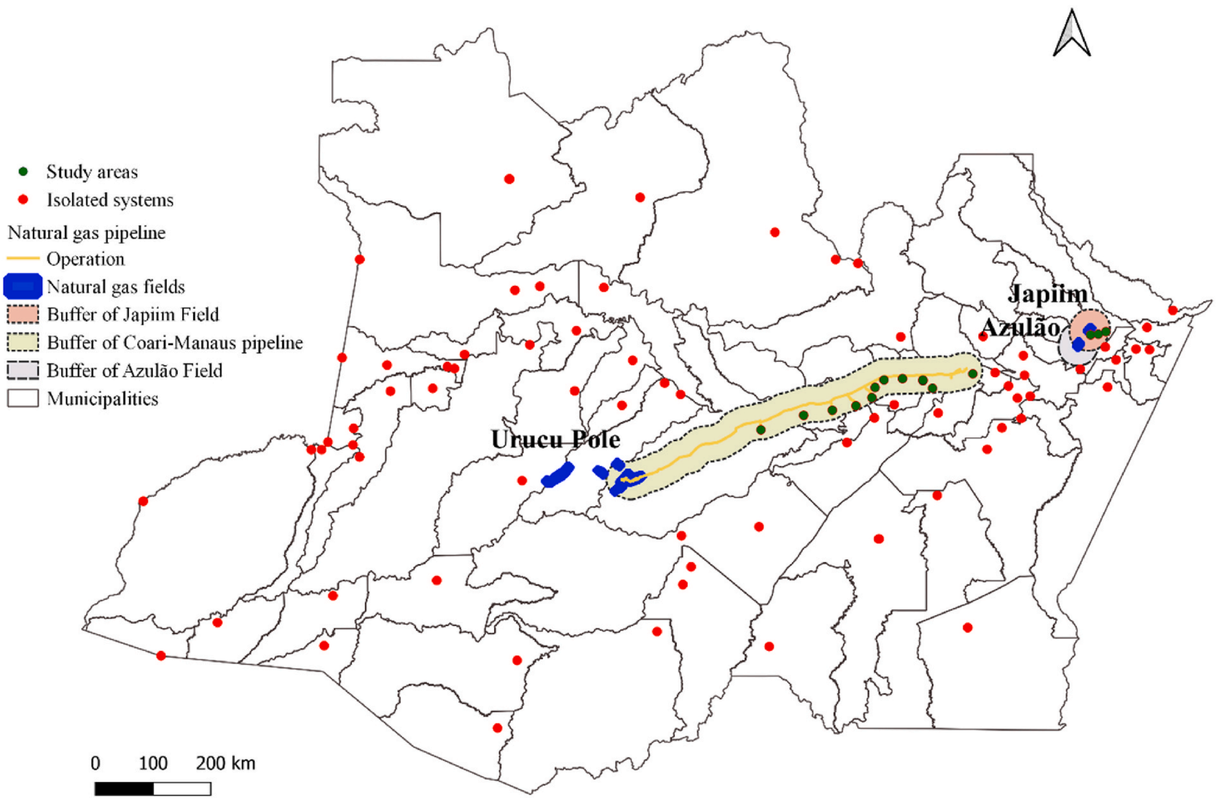

Fig. 4. Map of ISs in the state of Amazonas. In blue are the natural gas fields, emphasizing the fields of the Urucu River, Japiim and Azulão. Besides, green, blue, and pink areas influence natural gas production and transport infrastructure. Source: Elaborated by the authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Variables for economic evaluation for each isolated system compounding groups I and II. The average exchange rate was US$ 1.00 equaled R$3.94 in 2019. Source: Elaborated by authors based on (Bonfim, 2008; EPE, 2020b, 2020a; ONS, 2019) and (Cigas, 2020).

	Isolated System	Specific consumption of natural gas (MMm^3/MWh)	Specific diesel consumption (l/MWh)	Natural gas price (US $/m^3)	Diesel price (US $/l)
Group I	Coari	0,300	260	0.45	0.98
	Codajás	0,238	260		
	Anori	0,330	260		
	Anamã	0,289	260		
	Caapiranga	0,289	260		
Group II	Murituba	0,300	260		
	Arara	0,300	260		
	Sacambu	0,300	260		
	Campinas	0,300	260		
	Caviana	0,300	260		
	Careiro	0,300	260		
	Santana do Uatumã	0,300	260		
	São Sebastião do Uatumã	0,300	260		
	Urucará	0,300	260		

Table 3
Economic evaluation of diesel replacement with natural gas in 14 ISs of the Amazon. For cities that did not have a specific consumption stated in (ONS, 2019), the used values are in (Bonfim, 2008). The average exchange rate was US$ 1.00 equaled R$3.94 in 2019. Source: Elaborated by the authors.

Isolated systems	Total load (MWh)	Amount of natural gas (m^3)	Amount of diesel (litres)	Total natural gas cost (US$)	Total diesel cost (US$)	Total savings (US $)	% savings
Coari	100279.00	30083700.00	26072540.00	$13.537.665,00	$25.551.089,20	$12.013.424,20	47,02%
Codajás	23887.00	5685106.00	6210620.00	$2.558.297,70	$6.086.407,60	$3.528.109,90	57,97%
Anori	16325.00	5387250.00	4244500.00	$2.424.262,50	$4.159.610,00	$1.735.347,50	41,72%
Anamã	9883.00	2856187.00	2569580.00	$1.285.284,15	$2.518.188,40	$1.232.904,25	48,96%
Caapiranga	8786.00	2539154.00	2284360.00	$1.142.619,30	$2.238.672,80	$1.096.053,50	48,96%
Murituba	388.00	116400.00	100880.00	$52.380,00	$98.862,40	$46.482,40	47,02%
Arara	668.00	200400.00	173680.00	$90.180,00	$170.206,40	$80.026,40	47,02%
Sacambu	1350.00	405000.00	351000.00	$182.250,00	$343.980,00	$161.730,00	47,02%
Campinas	1030.00	309000.00	267800.00	$139.050,00	$262.444,00	$123.394,00	47,02%
Caviana	2037.00	611100.00	529620.00	$274.995,00	$519.027,60	$244.032,60	47,02%
Careiro	9581.00	2874300.00	2491060.00	$1.293.435,00	$2.441.238,80	$1.147.803,80	47,02%
Santana do Uatumã	657.00	197100.00	170820.00	$88.695,00	$167.403,60	$78.708,60	47,02%
São Sebastião do Uatumã	8456.00	2536800.00	2198560.00	$1.141.560,00	$2.154.588,80	$1.013.028,80	47,02%
Urucará	16715.00	5014500.00	4345900.00	$2.256.525,00	$4.258.982,00	$2.002.457,00	47,02%

operation of the natural gas thermal plant only at the beginning of 2020. The rest of the ISs, which form the second study group, presented a lower saving, about US$5 million (R$ 19 million) per year, with a possible replacement of diesel with natural gas. It happened due to most cities showing a lower total demand load. However, the amount saved is relevant and corresponds to a savings of 47.02%. The highlight of this second group goes to Careiro - a north city of the Coari-Manaus pipeline with high demand -, São Sebastião de Uatumã and Urucará – these last two municipalities near the production fields of Azulão and Japiim.

Finally, the analysis also considered the influence of specific consumption on fuel's total cost savings. Cities with lower specific consumption showed a significantly higher economic growth level than municipalities such as Codajás. It is worth highlighting that the investment in machinery with better efficiency allows this replacement to achieve better economic results during the operation.

Concerning environmental effects, it is possible to observe significant savings in CO_2 emissions from the variables (Table 4) and the results (Table 5, Fig. 6). While the emission factor calculated for diesel combustion is approximately 727 kg/MWh, those using natural gas have an emission factor of roughly 550 kg/MWh – with a variance in the cases studied between 437kg/MWh and 606kg/MWh. As seen in the economic evaluation, it is possible to note that the group of systems connected to the pipeline significantly contributes to reducing CO_2 emissions due to replacing fossil fuels. This value reaches more than 30000 tons of CO_2 per year. The second group, on the other hand, contributes 7000 tons per year.

The percentage of CO_2 emissions savings varies from 16.75% (Anori) to 39.96% (Codajás). ISs have a lower specific consumption and reduce GHG in the atmosphere, favoring natural gas as a substitute for diesel. As shown in the previous study, replacing petroleum derivatives for burning in electric power generators is necessary for a more significant environmental impact and to foster social development (Frota and Rocha, 2010; Medeiros et al., 2017).

Concerning environmental impacts, it is possible to notice a decrease of about 24% in total CO_2 emissions, resulting in a total reduction of almost 40 000 tons of CO_2 emissions per year. In addition, reducing diesel transport contributes to a lower environmental

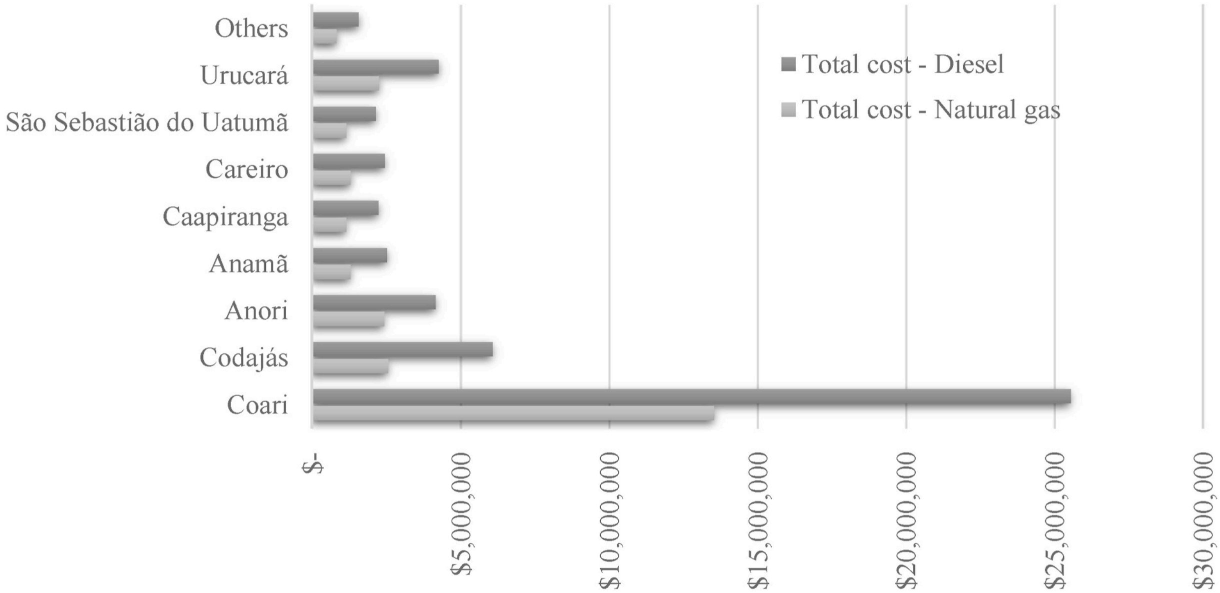

Fig. 5. Relationship between total costs for diesel fuel (dark grey) and natural gas (light grey). The decrease varies between 47% and 58%. The average exchange rate was US$ 1.00 equalled R$3.94 in 2019. Elaborated by the authors.

Table 4
Variables for an environmental assessment for each isolated system grouped I and II. Source: Elaborated by the authors base on (EPE, 2020a; IPCC, 2006).

	Isolated Systems	Calorific value of natural gas (TJ/m^3)	Calorific value of diesel (TJ/l)	Natural gas CO_2 emission factor (kg/TJ)	Diesel CO_2 emission factor (kg/TJ)	Net electricity (MWh)
Group I	Coari	0,0000286	0,00003778	64 200	74 100	100279
	Codajás					23887
	Anori					16325
	Anamã					9883
	Caapiranga					8786
Group II	Murituba					388
	Arara					668
	Sacambu					1350
	Campinas					1030
	Caviana					2037
	Careiro					9581
	Santana do Uatumã					657
	São Sebastião do Uatumã					8456
	Urucará					16715

impact since the vessels run on petroleum products, reducing CO_2 and avoiding fuel spills on waterways. In addition to the municipalities with natural gas thermal power plants (Coari, Anori, Anamã, Codajás, and Caapiranga), which already have the benefits of using natural gas, some other municipalities have a high economic and environmental impact with natural gas entry. Specifically, the municipalities of Careiro (located to the north of the Coari-Manaus gas pipeline), São Sebastião do Uatumã, and Urucará (situated near the production areas of Azulão and Japiim) are prime examples of this trend, given their greater total annual load in comparison to the other ISs. Lastly, the study's results indicate significant financial savings, with a potential economy of more than 40% (over 90 million Brazilian reais per year) based on 2019 data.

6. Conclusions

The guarantee of access to modern energy services and environmentally sustainable practices are some of the challenges encountered by the energy planning agencies of ISs in the northern region of Brazil. It is essential to use tools that assist in this management to achieve decarbonization and affordability of electrical systems using local energy sources. There are notable advantages of environmental influences – exclusively CO_2 emissions in electricity generation with diesel replacement. In summary, this assessment presented in the results recognizes natural gas as an effective option for economic and environmental gains through diesel

Table 5
Environmental assessment of replacing diesel with natural gas in 14 ISs in Amazonas. Source: Elaborated by the authors.

Isolated systems	Total load (MWh)	Emission factor - Natural gas (kg/MWh)	Emission factor - Diesel (kg/MWh)	Total emissions - Diesel (tons of CO_2)	Total emissions – Natural gas (tons of CO_2)	% of savings
Coari	100279.00	550.84	727.87	72990.02	55237.28	24.32%
Codajás	23887.00	437.00	727.87	17386.62	10438.54	39.96%
Anori	16325.00	605.92	727.87	11882.47	9891.64	16.75%
Anamã	9883.00	530.64	727.87	7193.53	5244.30	27.10%
Caapiranga	8786.00	530.64	727.87	6395.06	4662.19	27.10%
Murituba	388.00	550.84	727.87	282.41	213.72	24.32%
Arara	668.00	550.84	727.87	486.22	367.96	24.32%
Sacambu	1350.00	550.84	727.87	982.62	743.63	24.32%
Campinas	1030.00	550.84	727.87	749.71	567.36	24.32%
Caviana	2037.00	550.84	727.87	1482.67	1122.05	24.32%
Careiro	9581.00	550.84	727.87	6973.72	5277.56	24.32%
Santana do Uatumã	657.00	550.84	727.87	478.21	361.90	24.32%
São Sebastião do Uatumã	8456.00	550.84	727.87	6154.86	4657.87	24.32%
Urucará	16715.00	550.84	727.87	12166.34	9207.22	24.32%

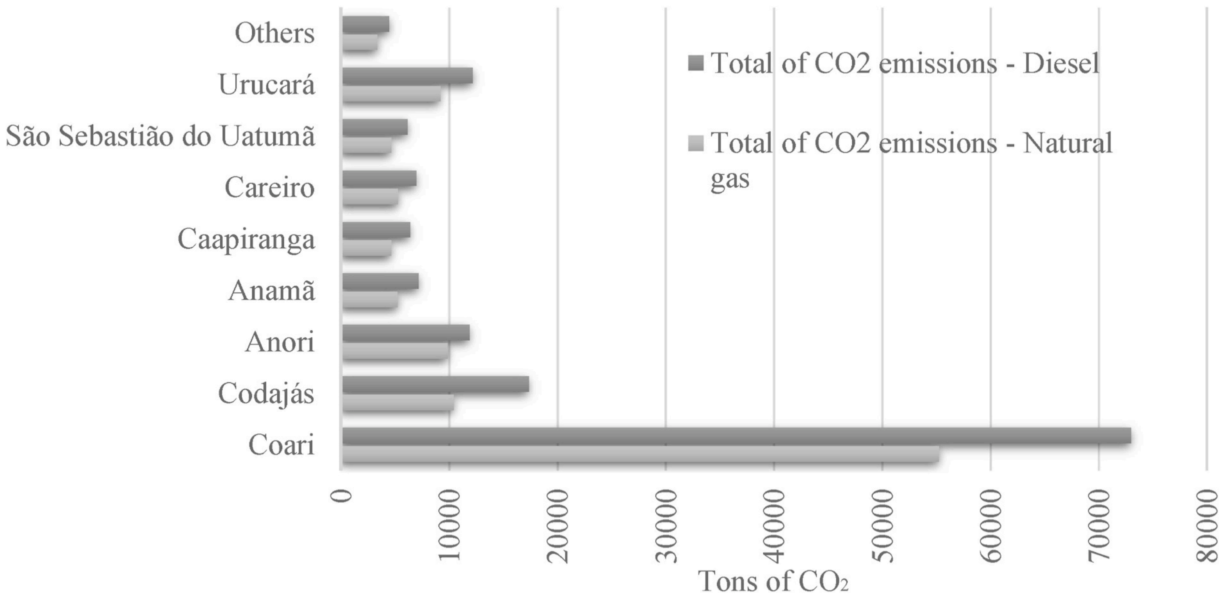

Fig. 6. The ratio between total CO_2 emissions according to the fuel used for electricity generation: diesel (dark grey) and natural gas (light grey). Source: Elaborated by the authors.

replacement in electricity generation for ISs. The analysis conducted does not address the direct environmental impacts of natural gas infrastructure. It is recommended that future studies take into account this aspect for a more comprehensive assessment. Moreover, further research should investigate the potential of renewable energy sources for electricity generation in Amazonas state, allowing for a comparison with the findings of this study.

Furthermore, this study expanded its analytical scope by comparing the specific consumption characteristics of each IS and suggested opportunities for further investment in better generators and potential implementation of natural gas plants in other ISs with lower specific consumption, leading to more significant financial savings and reduced environmental impacts. The municipalities with lower specific consumption have the potential to contribute more actively to the economy by conserving financial resources and minimizing environmental damage.

This study highlights natural gas as a viable alternative for greater investment, and future analyses can explore the role of LNG in achieving energy access in other regions and neighboring states that are not connected to the SIN. The advantages presented in this research could also support implementing hybrid systems that involve natural gas in isolated and remote regions. The significant economy achieved through replacing diesel with natural gas in ISs is of utmost importance, as the entire Brazilian society subsidizes the fuel cost for these systems. These financial savings can contribute to regional development and enhance the attractiveness of investments in a more sustainable economy. Furthermore, the environmental gains resulting from reduced CO_2 emissions are crucial for promoting environmentally responsible practices and supporting sustainable development in the region. These economic and environmental benefits underscore the importance of adopting natural gas as a viable alternative in ISs, aligning with the goals of achieving affordable, decarbonized, and environmentally sustainable energy solutions for the northern region of Brazil. In conclusion, this assessment emphasizes the viability of natural gas as an alternative for increased investment in supplying electricity generation in ISs in Amazonas state, where production infrastructure is already well-developed.

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.

Data availability

No data was used for the research described in the article.

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