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Electricity generation potential from natural gas pressure reduction turbines in Brazil

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Abstract This paper addresses the urgent need to meet increasing energy demand while avoiding greenhouse gas emissions by improving energy efficiency. One significant challenge is the energy losses that occur during gas pressure reduction at city gates in natural gas distribution systems. To tackle this issue, this study proposes installing pressure reduction turbines (PRTs) parallel to existing reduction valves, which can generate electricity and enhance system efficiency. This research mainly focuses on Brazil's natural gas supply, where the potential for installing PRTs is evaluated. The methodology analyzes the country's distribution network and estimates the electricity generation capacity achievable from PRTs. The results indicate a potential power generation of 66 MW, capable of avoiding the emission of 235,800 tons of CO_2 annually and generating 333 GWh/year of electricity, all at a LCOE of $27/MW. These contribute to the environment using the energy efficiency achieved through the installation of PRTs, consequently, Brazil can help to a cleaner and more sustainable energy future.

Highlights
- Methodology for estimating a country generation potential from pressure reduction turbines.
- Investment costs for natural gas pressure reduction turbine of USD 1500/kW.
- Levelized electricity cost of around $27/MW.
- Brazilian potential for electricity generation of 333 GWh/year.

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Nomenclature

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ANP	Biofuels National Agency
FU	Federated Unit
GASBOL	Brazil-Bolivia pipeline
LCOE	Levelized cost of electricity
ONS	National Electric Systems Operator
PRT	Pressure reduction turbine
TEP	Ten-Year Energy Expansion Plan
TPS	Thermal Power Stations
WEBMAP	Platforma from the Brazilian Energy Research Office
E	Energy
Φ	Heat flow
$\dot{W}$	Work flow
h	Enthalpy
V	Speed
g	Gravitational acceleration
$\dot{m}$	Mass flow
η	Efficiency
p	Pressure
Subscripts 1	Inlet
2	Outlet
s	Isentropic
r	Real
g	Generator
e_med	Average generation potential
e_max	Maximum generation potential
ref	Refrigeration
red	Reducer
e	Eletrical

Introduction

One of the industrialization consequences, demographic expansion, and concentration in urban areas has been the consistent increase in electric power consumption (Koc et al., 2019; Neseli et al., 2015). Energy efficiency is one of the sustainability pillars because it allows better use of natural resources (Esquivel-Patiño et al., 2017; Gibson et al., 2016; Hunt et al., 2020; Johansson & Söderström, 2014; Seifert et al., 2019). The increase of energy efficiency indicators in the various economic segments is a global aspiration, especially in the energy transition we are experiencing (Afana syeva and Mingaleeva 2015; Pfeifer et al., 2021). There are many studies intended to increase the efficiency of natural gas plants. He and Lin (2020) show the energy savings from waste heat from the gas turbine exhaust. A recent study suggests integrating energy storage heat systems to combine heat and power plants (Pfeifer et al., 2019). Energy storage systems can be used to store the cold resulting from gas expansion. The use of rolling piston expanders can increase the efficiency of PRT (Kolasiński et al., 2017). Another alternative is the inclusion of pressure reduction turbines (PRT) for power generation (Ebrahimi et al., 2021; Hannachi et al., 2021; Lee & Gurgenci, 2020; Leite et al., 2021; Li et al., 2019; Pagaimo et al., 2021; Sheikhnejad et al., 2020; Tahadjodi Langroudi et al., 2020).

There are reports of the use of turboexpanders in the USA at some natural gas delivery points (Hedman, 2008). A study done in Iran showed positive results in relation to the use of turbo expanders in the city gate, with energy production ranging from 0.2 to 1.1 MWh in the months. As expected, the difference is due to the consumption variation during the year in the analyzed station (Ardali & Heybatian, 2008). There is also a study in Russia that calculated the possible inclusion of a PRT, with power generation results of around 1.1 to 1.7 MW (Poživil, 2004).

The Brazilian energy matrix is predominantly renewable, with hydropower representing 65.2% in 2021 (Antunes Campos et al., 2020; Brazilian Energy Research Company 2021a; Flórez-Orrego et al., 2014; Szklo & Tolmasquim, 2003). Cogeneration has significant participation due to the strong presence of mills that process sugarcane (Borges et al., 2021; Ensinas et al., 2007; Flórez-Orrego et al., 2014; Landini and de Mello Sant'Ana 2017; Lora & Salomon, 2005; Renó et al., 2014; Vendrusculo et al., 2009). Waste gasification has been studied as a promising alternative to reduce landfills and contribute to electricity generation (Carneiro & Gomes, 2019; Gotelip Correa Veloso et al. 2018a, b; Luz et al., 2015; Morawski et al., 2021; Real Guimarães et al., 2021; Renó et al., 2013). Natural gas represents 8.3% of the Brazilian supply. Its demand has been growing over the last years. In 2020, there was a 6% reduction in consumption compared to 2019, mainly attributed to the fall in industrial consumption that year, regressing about 13.3% as the main consequence of the economic effects of the COVID-19 pandemic. In the year 2021, there was an increase in gas consumption due to

Fig. 1 Brazilian energy supply by source in 2020 (Brazilian Energy Research Company 2021a)
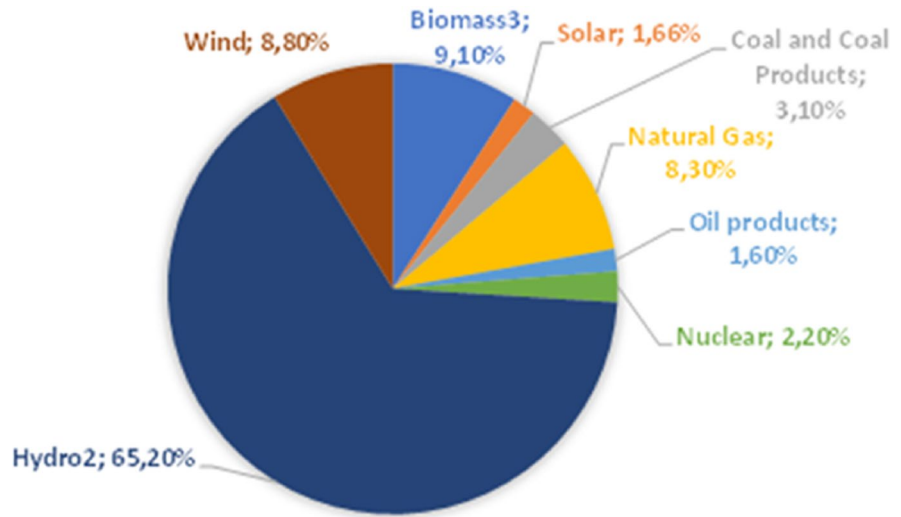
the water crisis in Brazil, causing the National Electric Systems Operator (ONS) to increase the frequency and intensity of gas-fired thermal power stations (TPS) (Brazilian Energy Research Company 2021a). According to the latest energy balance for 2021, the energy matrix is distributed as shown in the chart in Fig. 1.

According to the Energy Planning and Development of the Mines and Energy Ministry, gradual economic growth is expected for a 10-year horizon, mainly in the service, construction, transformation, and industrial sectors (Brazilian Energy Research Company 2021b). Figure 2 presents a perspective of thermoelectric

demand for natural gas from 2021 to 2031, including existing facilities and those planned for entry into the system. These thermoelectric plants should operate at peak demand to ensure system reliability. This contributes to a rapid expansion of this energy matrix in Brazil and, consequently, to the demand for natural gas.

Currently, the Brazilian natural gas transportation network has 9409 km (Centro Brasileiro de Infraestrutura 2019), as shown in Fig. 3. The system has 16 national and 3 international natural gas processing plants and several delivery points to final consumers. The Brazil-Bolivia pipeline (GASBOL) and

Fig. 2 Maximum demand for gas in thermoelectric per subsystem (Brazilian Energy Research Company 2021b)
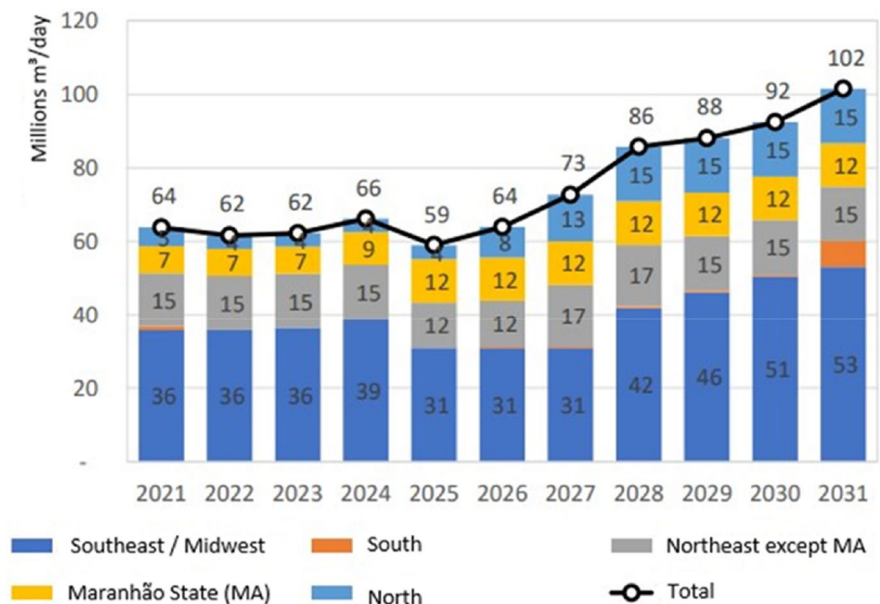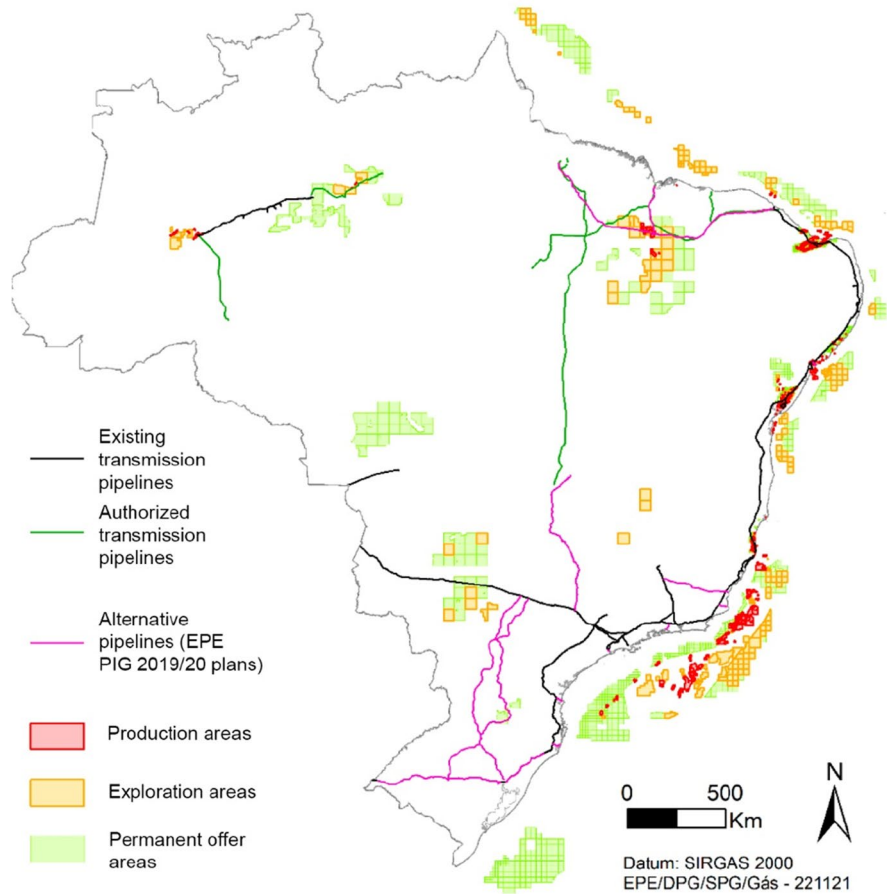
Fig. 3 Brazilian natural gas transmission and production network (Brazilian Energy Research Company 2019)

Uruguaiana-Porto Alegre are interconnected and are part of an integrated grid. The Lateral-Cuiabá, Uruguaiana-Porto Alegre, and Urucu-Coari-Manaus pipelines (as well as the Urucu Processing Pole) are considered isolated systems. The isolated system in Maranhão, in the Parnaíba Basin, also deserves mention (Brazilian Energy Research Company 2022). Natural gas consumption is expected to increase due to growth in the agriculture, livestock industry, and services sectors (Brazilian Energy Research Company 2021b). Consequently, the demand for natural gas is expected to increase, which justifies the development of new pipelines and the increase in the capacity of existing pipelines. The Brazilian 10-year energy plan 2031 foresees large investments in natural gas, with the projects for the natural gas infrastructure expansion amounting to approximately R$ 137.86 billion (R$ 8.87 billion foreseen and R$ 128.99 billion in indicative projects) (Brazilian Energy Research Company 2022).

Given the large demand for natural gas in Brazil and the perspective of increased consumption over the next few years, this paper seeks to quantify the national potential for power generation through the use of PRT, increasing the energy efficiency of natural gas transportation process.

This article presents a modeling approach to estimate the generation potential at each natural gas delivery point in Brazil. It demonstrates the methodology employed using the example of the Brazilian transmission network, utilizing historical data on gas consumption and each delivery point's characteristics. This methodology fills a gap in the literature by providing an estimate for real transmission lines, emphasizing Brazil's non-application of PRTs at any city gate. It not only benefits gas distribution companies in Brazil but also serves as a valuable resource for other countries looking to assess the potential of pressure-reducing turbines in their own contexts, because of the dadas range used. This article shows

that Brazil has the potential to generate 333 GWh/year of electricity with PRTs, quantifying the potential of each federation state and the main natural gas delivery points. This article has five sections. The "Methodology" section presents the methodology used to determine the generation potential in Brazil. The "Results" section shows the results obtained. The "Discussion" section discusses these results and, the "Conclusions" section concludes the paper.

Methodology

The first step in the methodological development was to identify the natural gas transmission pipelines and delivery points in Brazil and their respective utilities. To calculate the PRT power capacity and estimate of electric generation, the inlet and outlet pressures and the natural gas consumption at the city gates were found. With this data, it was possible to obtain the power capacity of each point and the estimated annual generation. Figure 4 presents a flowchart of the methodological framework.

Pressure reduction valves and turbines

Natural gas is transported by pipelines under high pressure. This is necessary to reach the flow demanded by consumers and overcome the pressure losses due to the extensive gas pipeline in the country. At the delivery points (city gate), the gas must have lowered pressure before being supplied to the consumers (industry, commerce, TPSs, etc.). The pressure lowering is typically performed by a pressure-reducing valve, as shown in Fig. 5a. Besides lowering the pressure, other physical processes are also performed at the city gate, such as filtration and flow measurement, and the gas is then distributed to consumers.

The natural gas arrives at the city gate with pressures higher than the distribution pressures to consumers and must be reduced to be delivered to consumers. Pressure-reducing valves perform this by imposing a controlled pressure drop on the system, causing the gas to flow through a throttled section. As a consequence of the pressure reduction, a gas temperature decrease is observed after the valve. This is an isenthalpic process, with no work performed.

Currently, city gates use pressure-reducing valves that perform this function without taking advantage of the pressurized natural gas enthalpy, i.e., without doing any work but simply giving the process a pressure loss. This article evaluates the use of pressure-reducing turbines (recovery turbines) installed in parallel to the current reducing valves to take energy advantage, as illustrated in Fig. 5b. Its operation is substitutive to the valve, obtaining in the pressure-lowering process shaft work and generating electrical power and cold.

To perform the thermodynamic modeling of the pressure-reducing turbine, one must consider the irreversibilities that exist in the systems. It is desirable to have some parameters to quantify the degree of energy degradation in engineering devices working in isolation under steady-state flow conditions, such as turbines. However, in the first place, it is necessary to adopt an ideal process that serves as a
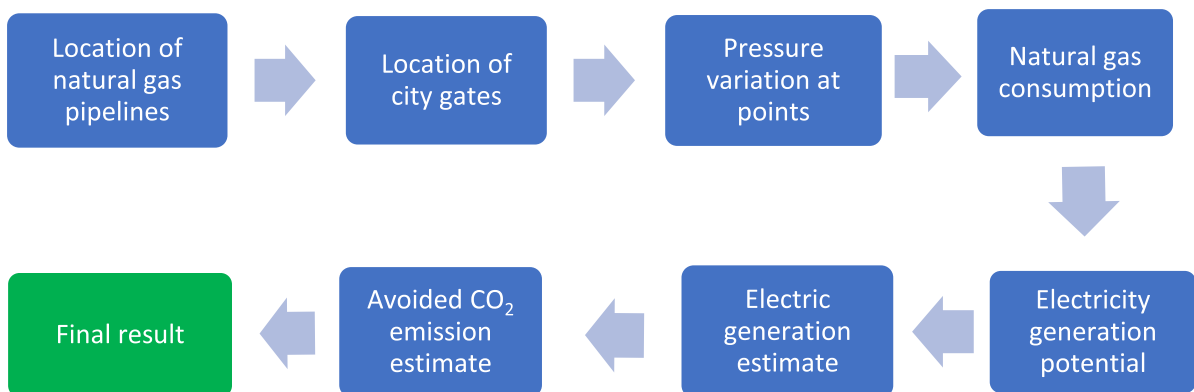

Fig. 4 Methodology framework to estimate the electric generation potential with natural gas pressure-reducing turbines in Brazil
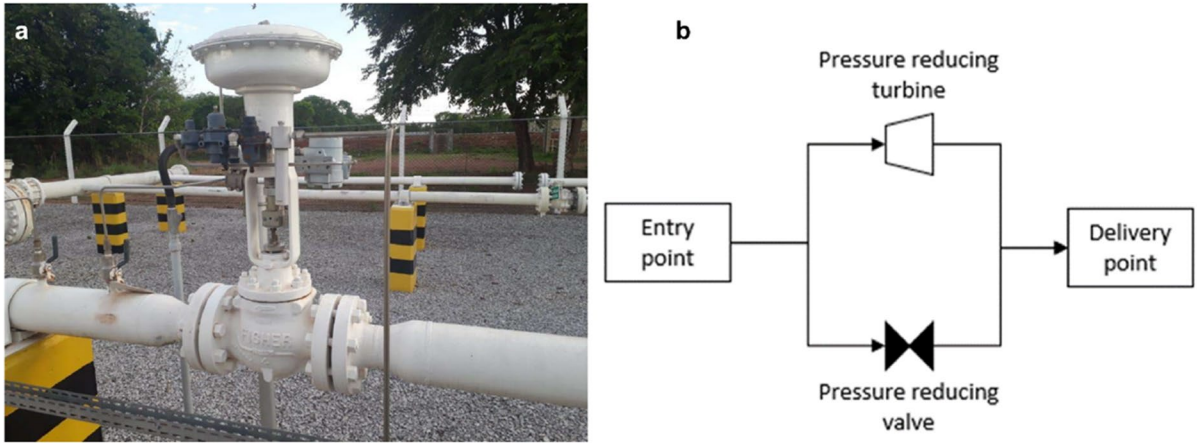
Fig. 5 **A** Pressure-reducing valve in the city gate of a thermal electric power plant. **b** Simplified flowchart of the pressure-reducing turbine in the pressure-reduction process

model, although some heat transfer between these devices and their surroundings is inevitable. The process that can serve as a suitable model for devices with steady-state and adiabatic flow is the isentropic process.

The mathematical model that describes the pressure-reducing turbine behavior follows the mass and energy conservation laws (first thermodynamics law), as presented in Eq. 1.

$$\frac{dE}{dt} = \Phi + \dot{W} + \sum \dot{m}_1 \cdot \left(h_1 + \frac{V_1^2}{2} + g.Z_1 \right)$$
$$- \sum \dot{m}_2 \cdot \left(h_2 + \frac{V_2^2}{2} + g.Z_2 \right) \quad (1)$$

where dE/dt is the energy variation over time. ϕ is the heat flow, $\dot{W}$ is work, h_1 is the inlet-specific enthalpy, h_2 is the outlet-specific enthalpy, V_1 is the inlet speed, V_2 is the outlet speed, g is the gravitational acceleration, Z_1 is the inlet height, and Z_2 is the outlet height.

Since the model adopts a steady-state operation, that is, there is no variation in the total energy over time, therefore $dE/dt = 0$. The model can be simplified by considering that the input and output velocities are equal ($V_1 = V_2$), and there is no differential in the inlet and outlet heights ($Z_1 = Z_2$). The energy conservation general equation was reduced to Eq. 2.

$$\Phi + \dot{W} + \sum \dot{m}_1 \cdot h_1 - \sum \dot{m}_2 \cdot h_2 = 0 \quad (2)$$

The kinetic and potential energy variations in a fluid stream flowing through the turbine are small compared to the enthalpy variation and can be neglected. Considering that there is no change in the gas mass in the turbine $(\dot{m}_1 - \dot{m}_2 = 0))$, Eq. 2 can be simplified to Eq. 3.

$$\dot{W} = \dot{m}.(h_1 - h_2) \quad (3)$$

Isentropic efficiency (η_s) shows how close the real process is to the ideal process. For a turbine operating under steady-state and isentropic conditions, the efficiency is the ratio between the actual work produced (w_r) and the isentropic work (w_s), as shown in Eq. 4.

$$\eta_s = \frac{\text{real turbine work}}{\text{turbine is entropic work}} = \frac{w_r}{w_s} \quad (4)$$

The isentropic turbine efficiency can be given by the enthalpy variation, as Eq. 5, where h_2 e h_{2s} are respectively the enthalpy values in the output state for the real and isentropic processes. Figure 6 shows a typical enthalpy versus entropy plot for ideal and real processes.

$$\eta_s = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (5)$$

Knowing the isentropic efficiency (η_s) value, it is possible to determine the output enthalpy of the actual process (h_2), and by the difference between the
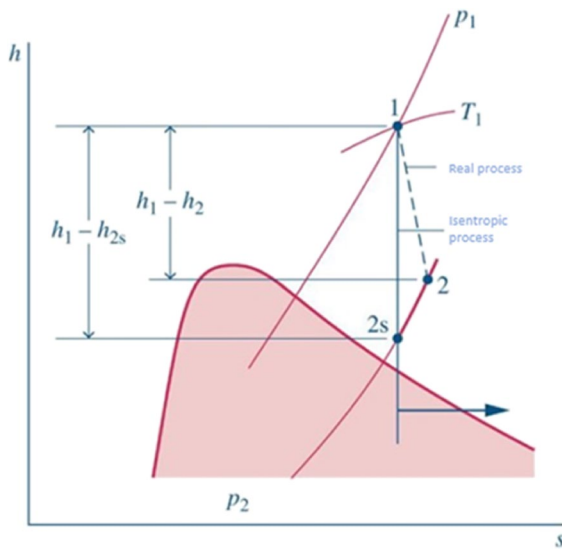
Fig. 6 Enthalpy (h) × entropy (s) graph for the real and ideal processes

inlet and outlet enthalpy, multiplied by the gas mass flow (Eq. 2), it is possible to find the shaft work ($\dot{W}$) done by the turbine. To obtain the electrical power of the pressure-reducing turbine ($\dot{W}_e$), the shaft work was multiplied by the speed reducer efficiency (η_r) that typically exists between the turbine connection and the generator, and by the generator efficiency (η_g) itself, as presented in Eq. 6.

$$\dot{W}_e = \dot{W}.\eta_r.\eta_g \qquad (6)$$

The isentropic efficiency depends on each turbine design. For large and well-designed turbines, the efficiency obtained is above 90%. In the smaller turbines case, this efficiency varies between 70 and 80%, and the value of 75% was used in this paper (Vankeirsbilck et al., 2011). For the gear reducer and generator efficiency, this paper considered the values of 98% and 96% (Burger & Kranzer, 2009), respectively. The conversion efficiency of the turbine shaft work to electrical energy can be estimated to be about 91.2%.

To make the pressure reduction turbine installation viable, it must be guaranteed that the natural gas will be delivered at the same pressure conditions provided by the existing valve. On the other hand, it must be taken into account that the natural gas leaves the reduction turbine at temperatures considerably lower than those

at the valve outlet due to the shaft work. Therefore, the need for heating this gas before the firing process must be evaluated, and it can be used, for example, in the cooling process due to its low delivery temperature. This refrigeration could be stored and then used in many possible applications.

Mathematical models

The system's mathematical model was used in a computational algorithm implemented in the EES software (Engineering Equation Solver), which allows the verification of the energy generation capacity with the implementation of the pressure-reducing turbine at the natural gas delivery points in all the transportation pipelines in Brazil. The software makes calculations easier as it has a vast thermodynamic database and allows for easy input variation data without the need to modify the algorithm.

The first step was to map all the existing natural gas delivery points in Brazil and which are the transport operators. This information is available on the WEBMAP platform from the Brazilian Energy Research Office (Brazilian Energy Research Company 2021c). To obtain the data for average inlet pressure and natural gas volume at each delivery point, the data released by the Petroleum, Natural Gas, and Biofuels National Agency (ANP) were used [37]. Knowing the utility for each delivery point, it was possible to access the technical operating reports where the average delivery pressure at these points is provided. These data are presented in Table 1 for TPSs.

The gas inlet temperatures in all city gates were considered equal due to the unavailability of this information for all points. As a reference for this temperature, the value of 30 °C informed by TPS Cuiabá was considered. Some points with inconsistent values were eliminated from the analysis, and the following criteria were adopted for exclusion: average inlet pressure value is lower than the outlet pressure; there is no flow data for the entire period evaluated; there is no information on outlet pressure.

With all model input parameters properly identified (inlet pressure, outlet pressure, temperature, average flow, and maximum flow), it was possible to calculate the average generation potential ($\dot{W}_{e\_med}$) and maximum ($\dot{W}_{e\_máx}$) of each delivery point using

Table 1 Input data to the TPSs generation potential model

City gate	City	FU	Average inlet pressure (bar)	Outlet pressure (bar)	Average volume (10^3. m^3/dia)	Maximun volume (10^3. m^3/dia)
Termoaçu (TPS JSP)	Alto do Rodrigues	RN	57	39	812	890
Termobahia (TPS Celso Furtado)	São Francisco do Conde	BA	160	37	1100	1318
Termofortaleza	Caucaia	CE	77	28	3	72
Termopernambuco	Ipojuca	PE	55	36	2009	2420
Termorio I (TPS GLB)	Duque de Caxias	RJ	81	36	3326	5932
Termorio II (CEG Metropolitano)	Duque de Caxias	RJ	171	38	1841	2784
TPS Aparecida	Manaus	AM	65	53	877	1010
TPS Baixada Fluminense	Japeri	RJ	80	41	2133	2488
TPS CHESF	Camaçari	BA	37	38	1510	2314
TPS Cubatão (TPS Euzébio Rocha)	Cubatão	SP	24	53	1204	1496
TPS Cuiabá	Cuiabá	MT	48	28	412	2277
TPS Ibirité (TPS Aureliano Chaves)	Betim	MG	45	38	769	1083
TPS Juiz de Fora (Igrejinha)	Juiz de Fora	MG	47	35	438	529
TPS Linhares	Linhares	ES	77	43	1016	1210
TPS Mário Lago	Macaé	RJ	80	68	4074	5432
TPS Mauá	Manaus	AM	48	43	2352	2570
TPS Norte Fluminense	Macaé	RJ	81	47	3250	3841

Eq. 6 for the average and maximum flows. In addition, the annual electric generation (E_{annual}) of these same points was also calculated using the average generation potential ($\dot{W}_{e\_med}$) multiplied by the number of hours in the year (8.760 h) using Eq. 7.

$$E_{annual} = \dot{W}_{e\_med}.8760 \qquad (7)$$

Another point that can be analyzed based on these data is the refrigeration capacity. Assuming an isentropic efficiency of 75%, the energy calculation is performed by Eq. 8.

$$\dot{W}_{ref} = \dot{m}(h_1 - h_{iso,2})\,0,25 \qquad (8)$$

Finally, one can estimate the total CO_2 emission avoided for each delivery point using the PRT energy generated in kWh (Eq. 9). The methodology takes into account the emission factor calculated over electricity reductions (United States Environmental Protection Agency 2019).

$$CO_2\,avoided = E_{annual}\,0.000709\ (tons/year) \qquad (9)$$

The data for the average and maximum gas flows supplied at each delivery point and the average pressures were obtained for the data period from 05/01/2021 to 11/31/2021. Since these data do not cover the 12 months of the year, the annual electricity generation estimates presented in the following section were calculated based on the average potential for the available period.

Results

In total, 147 delivery points were analyzed. Those with inconsistent data were eliminated from the analysis, such as points with volumes close to zero and points for which the outlet pressure values were not available. Brazil's potential was calculated by considering 15 delivery points for TPS and 132 points for other consumers. To facilitate the analysis of the results, the TPS was separated from the other consumers due to some of the particular operating characteristics, such as gas volume or operating model through dispatch, being subject to the decisions made by ONS. Models like this one aim to operate the Brazilian electrical system at the lowest cost, with reliability and optimization of all the energy resources available in the country.

There is a dependence of some TPSs on hydric and climatic conditions since they operate with greater intensity to compensate a lack of hydroelectric generation. In this way, their dispatch model can change considerably annually and interannually, and the generation values obtained for these TPSs should be analyzed properly. Table 2 shows the maximum power, average power, annual generation, avoided CO_2 emissions, and average cooling potential, calculated for each natural gas delivery point in TPS. Figure 7 presents the maximum and average power in thermal power stations with the implementation of the pressure-reducing turbine, classified by order of average power.

Analyzing Fig. 7, it is possible to identify which TPS work with the lowest capacity factor, the main ones being Termorio I, Termorio II, and TPS Cuiabá. The total maximum power for the TPS is 15.4 kW, compared to approximately 10.6 kW for the average power. Considering the thermoelectric production cost of around R\$ 1340 per MWh, the use of these turbines will provide a R\$ 125,000 cost reduction in the plant while avoiding 65.8 tons of CO_2 per year. Another interesting point is evident from Table 2, where the maximum and average power are close in most cases. This indicates a relatively small variation in flow rate from the maximum, making the turbine application advantageous.

For the other consumer delivery points, the results of the analysis for the 21 largest consumers concerning average generation potential are presented in Fig. 8. The data for the other 109 consumers was summarized in a single point in Table 3. Figure 9 presents the distribution by federation state, considering the total turbine installed capacity. Figure 10 presents the Brazilian power potential with natural gas pressure reduction turbines.

Analyzing Table 3, the annual production capacity is around 23.4 MWh avoiding 51.1 tons of CO_2 per year. Figure 10 shows that São Paulo and Rio de

Table 2 Potential power generation using natural gas PRT at the delivery points of thermal power stations (TPS)

City gate	City	FU	Average power (kW)	Maximum power (kW)	Annual average generation (MWh)	CO_2 emission avoided (tons/year)	Average cooling potential (kW)
Termorio I (TPS GLB)	Duque de Caxias	RJ	2174	3876	19,044	13,502	795
Termorio II (CEG Metropolitano)	Duque de Caxias	RJ	1760	2661	15,418	10,931	644
TPS Norte Fluminense	Macaé	RJ	1482	1751	12,982	9204	542
TPS Baixada Fluminense	Japeri	RJ	1167	1362	10,223	7248	426
Termobahia (TPS Celso Furtado)	São Francisco do Conde	BA	1037	1242	9084	6441	379
Termopernambuco	Ipojuca	PE	763	918	6680	4736	278
TPS Mário Lago	Macaé	RJ	598	797	5234	3711	218
TPS Linhares	Linhares	ES	497	592	4355	3088	181
Termoaçu (TPS JSP)	Alto do Rodrigues	RN	265	290	2321	1645	96
TPS Mauá	Manaus	AM	236	258	2069	1467	86
TPS Cuiabá	Cuiabá	MT	195	1076	1704	1208	71
TPS Aparecida	Manaus	AM	166	191	1452	1030	60
TPS Ibirité (TPS Aureliano Chaves)	Betim	MG	131	185	1148	814	47
TPS Juiz de Fora (Igrejinha)	Juiz de Fora	MG	120	145	1049	743	43
Termofortaleza	Caucaia	CE	2	57	21	15	0.857
TOTAL			10,592	15,400	92,783	65,783	3,874

Fig. 7 Maximum and average power in thermal power stations with the implementation of the pressure-reducing turbine, classified by order of installed capacity
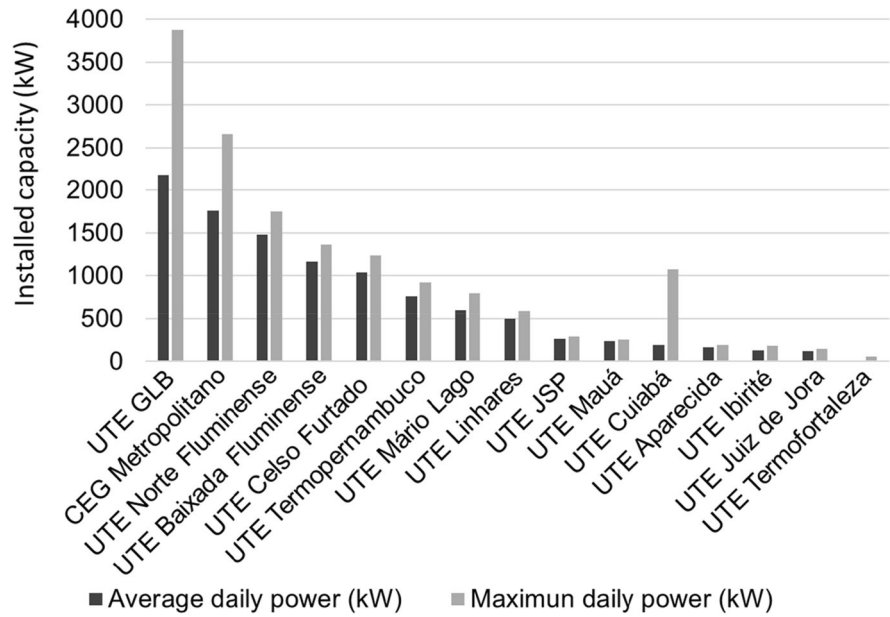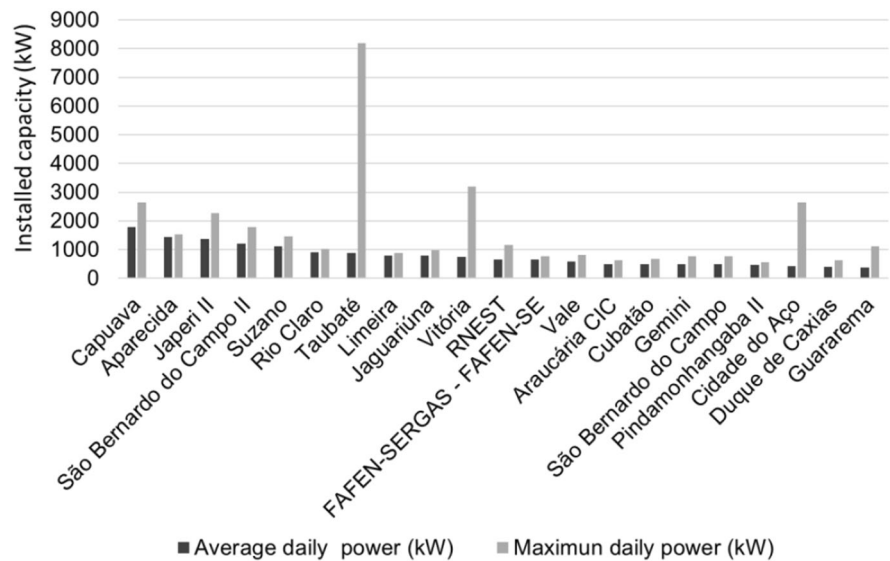

Fig. 8 Maximum and average power for the 15 largest delivery points (concerning average power) with the implementation of the pressure-reducing turbine (except TPSs)

Janeiro are the states with the highest potential for PRT generation.

To better visualize the energy potential and the geographical location, Fig. 10 shows in scale the relation of the energy potential with the Brazil map. As anticipated, there is a concentration of energy potential in the Brazilian Southeastern region, which can be attributed to its high natural gas consumption.

Cost estimation

A market analysis was conducted in Brazil, considering possible suppliers to develop and locally produce a PRT with a power output of 1.6 MW, and SICHUAN ZJ-TIBO, ROTOFLOW.

AIR PRODUCTS and SIMMS MACHINERY have presented their offer. These turbine manufacturers are great candidates to supply natural gas

Table 3 Potential power generation using natural gas pressure-reducing turbines at other delivery points

| City gate	City	FU	Average power (kW)	Maximum power (kW)	Annual average generation (MWh)	CO_2 emission avoided (tons/year)	Average cooling potential (MW)
Capuava	Mauá	SP	1782	2635	15,610	11,068	0.652
Aparecida	Manaus	AM	1430	1532	12,527	8882	0.523
Japeri II	Japeri	RJ	1370	2279	12,001	8509	0.501
São Bernardo do Campo II	São Bernardo do Campo	SP	1202	1797	10,530	7465	0.440
Suzano	Suzano	SP	1120	1455	9811	6956	0.410
Rio Claro	Rio Claro	SP	919	1028	8048	5706	0.336
Taubaté	Taubaté	SP	889	8190	7790	5523	0.325
Limeira	Limeira	SP	796	890	6972	4943	0.291
Jaguariúna	Jaguariúna	SP	785	977	6877	4876	0.287
Vitória	Vitória	ES	750	3188	6571	4659	0.274
RNEST	Ipojuca	PE	660	1164	5777	4096	0.241
FAFEN-SERGAS-FAFEN-SE	Laranjeiras	SE	650	780	5691	4035	0.238
Vale	Vitória	ES	575	821	5041	3574	0.211
Araucária CIC	Araucária	PR	497	641	4352	3086	0.182
Cubatão	Cubatão	SP	491	683	4297	3046	0.179
Gemini	Paulínia	SP	490	765	4294	3045	0.179
São Bernardo do Campo	São Bernardo do Campo	SP	486	763	4256	3017	0.178
Pindamonhangaba II	Pindamonhangaba	SP	469	555	4112	2915	0.172
Cidade do Aço	Volta Redonda	RJ	425	2649	3723	2640	0.156
Duque de Caxias	Duque de Caxias	RJ	389	630	3403	2413	0.142
Guararema	Guararema	SP	381	1124	3334	2364	0.139
Others			10,824	16,544	94,815	67,224	3.959
TOTAL					27,378	51,090	10.014
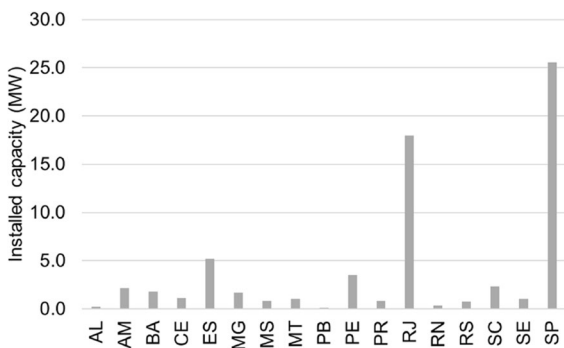
Fig. 9 Brazilian potential for electricity generation with natural gas pressure reduction turbine

pressure-reducing turbines. In addition to these candidates, companies outside the country were consulted, considering equipment already available on the market. Considering only the turbine's cost, the average value that best represents the equipment cost in Brazil today is USD 1500/kW. When analyzing this value, one must consider the power considered in the analysis—1.6 MW. The estimated cost of the energy generated by the PRT can be obtained using the simple LCOE methodology, considering, lifespan = 20 years; discount rate = 3%; capital cost = 1500 USD/kW; capacity factor = 57.1%; fixed O&M cost = 25 USD/kW-yr; variable O&M cost = 0.002 USD/kWh. The estimated value is $27/MWh in a 20-year

Fig. 10 Brazilian potential for natural gas pressure reduction turbines (in MW)

Power potential (MW)

0.1   1   2   3   4   5   6   7
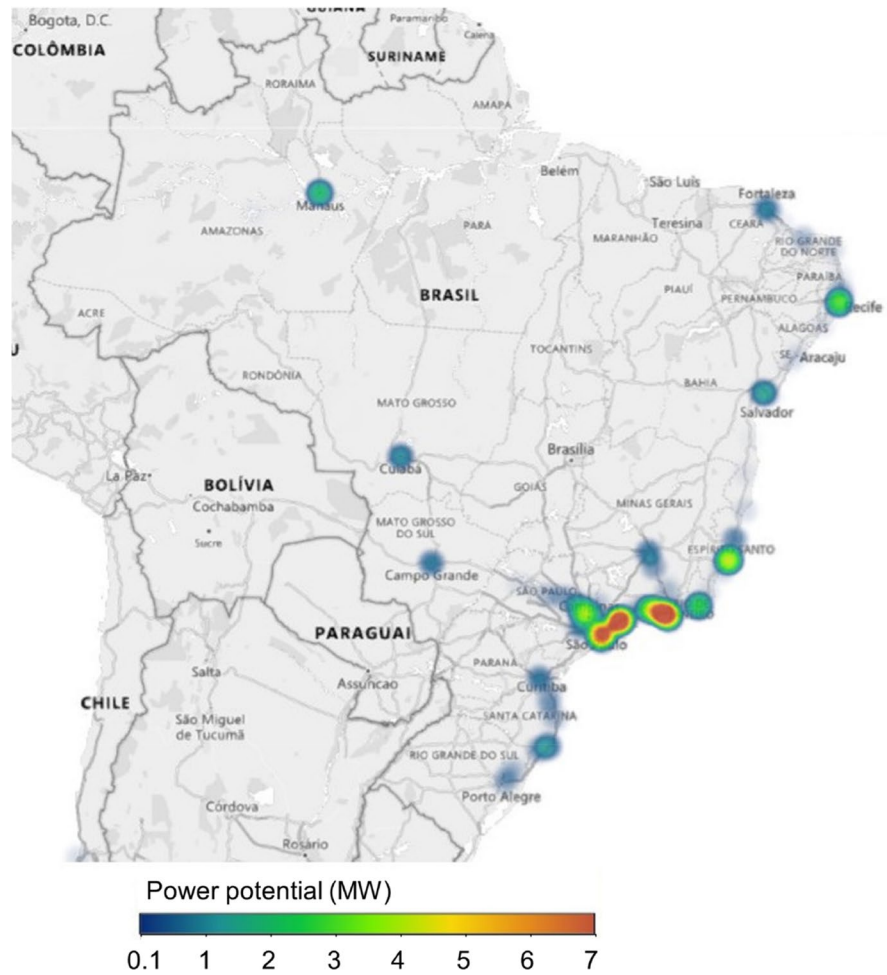
performance analysis. As a comparison, in Brazil, the LCOE for solar photovoltaic energy is estimated at \$30/MWh and for wind energy at \$27/MWh (Brazilian Energy Research Company 2021d).

Discussion

Brazil has a power potential of about 66 MW to be installed through PRTs, considering the maximum natural gas volume at each delivery point. Considering the average gas volume consumed between May and November 2021, the average power supplied by the PRTs would be 38 MW, representing a potential energy generation of about 333 GWh/year. Of this amount, about 93 GWh (28%) corresponds to the generation potential at TPS delivery points, while 240 GWh (72%) corresponds to the potential at the

other delivery points. Moreover, São Paulo and Rio de Janeiro are the states with the greatest potential for PRT installation, which is related to the fact that they concentrate the largest industrial activity in Brazil. As shown in Fig. 2, according to the PDE, there is a forecasted increase of approximately 60% in natural gas consumption concerning 2021, which would raise the energy production by the PRTs to 533 GWh per year. If we consider the year 2020, when natural gas-fired TPS generation was 53,464 GWh, the generation potential using PRT for the year 2031 would be equivalent to about 1% of Brazil's thermoelectric generation. To quantify the contribution relevance of generation through PRT, let us consider the generation of the Pernambuco TPS, which, according to ONS data, generated a total of 2497 GWh in 2020. The PRT generation potential for Brazil was estimated at 333 GWh or 13% of the total generated by

this TPS in 2020. If we consider the estimate for the year 2031 (533 GWh), the amount would represent 21% of the generation realized in 2020.

It is important to note that, in addition to contributing to electricity generation, PRTs can also be employed in refrigeration services due to the low gas exit temperature after passing through the turbine's expansion chamber (Poživil, 2004b). Because they are sometimes far from large consumption centers, this cooling can be used by nearby industries or even a cogeneration system in the operation of the generating plant (Hedman, 2008). As an example, TPS Cuiabá may use this potential to contribute to cooling the water in the condensate cooling tower of its steam turbine, further increasing the TPS efficiency. PRTs can also be used as an energy storage device, considering that the pipeline operator can control the gas pressure with a compressor and PRTs in both pipeline ends.

From the technological challenges point of view, the natural gas risk leakage must be taken into account for the implementation of the PRTs (Liu et al., 2021). Methane, the main natural gas component, is a potent greenhouse gas, and its leakage also creates an explosions risk (Hendrick et al., 2016; Luna & Nicholas, 2022). One way to significantly decrease this risk is to use a magnetic shaft (Seo et al., 2019). Another relevant point is the possibility of gas freezing in the turbine (Romero Gómez et al., 2014). These factors have to be well analyzed by the equipment manufacturer in order not to generate damages to the PRT.

In addition to natural gas transportation infrastructure, future applications such as hydrogen transportation and distribution are worth mentioning (Wietschel & Ball, 2010). Hydrogen is a gas with very low volumetric energy density. For transportation, depending on the tank material used, a pressure of approximately 700 bar is required (Abdalla et al., 2018), and a negative part is the loss of 20% of the energy contained in the hydrogen by performing compression (Edwards et al., 2008). Due to high transport and distribution pressures, pressure-reducing turbines can be an alternative for delivery points.

Conclusions

This paper presented a summary of the potential power generation from the substitution of pressure regulating valves by pressure reduction turbines for the natural gas delivery points in Brazil, increasing the energy efficiency of the Brazilian energy matrix through the production of 333 GWh/year of electricity. The methodology employed in this paper is a major contribution to the literature, which lacks in analyzing a continental natural gas distribution network potential identification. The proposed method can easily be extrapolated to other countries.

Counting on a total of 147 viable delivery points, it is possible to install 66 MW of pressure reduction turbines in the natural gas transportation pipelines, avoiding the emission of 235,800 tons of CO_2 per year and having 13.89 MW of average cooling potential. The São Paulo and Rio de Janeiro states stand out, representing 65% of the potential for PRT installation in the country since they are the states with the most significant economic activity.

The use of PRTs is an option for electrical generation without the need to burn fuel and without CO_2 emissions. In addition, the low temperature of the output gas from the PRTs could be used as a cold source for cooling systems for natural gas consumers. Importantly, energy efficiency helps reduce dependence on imported energy resources, strengthening Brazil's energy security by minimizing the impact of global geopolitical events that typically affect the oil and gas sector. The introduction of PRTs in Brazil would contribute to new market creation. On the other hand, Brazil has great potential for nationalization of this technology since it has numerous manufacturers of steam turbines with the capacity for development. Additionally, a study such as the one proposed presents results aligned with the energy transition process in the country.

The PRT use in the natural gas delivery points into various transportation pipelines in Brazil presents a great potential for energy increase for the Brazilian energy matrix, including as a measure of energy efficiency for a potential that until now is unexploited in the country. It is, therefore, not only an additional source of energy but also a renewable and clean energy source. It is estimated that the current cost in Brazil for the acquisition of natural gas PRTs would be around USD 1500/kW and the energy generated cost (LCOE) would be around $27/MW.

Declarations

Conflict of interest The authors declare no competing interests.

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