Driving factors for the installation of mini and micro rural distributed generation systems: economic analysis – a case study in *Piauí*, Brazil

Fatores impulsionadores para a mini e microgeração distribuída rural: análise econômica – um estudo de caso no Piauí, Brasil

Osvaldo Augusto Vasconcelos de Oliveira Lopes da Silva [1]

Fabrício Higo Monturil de Morais [2]

Wilza Gomes Reis Lopes [3]

Marcos Antônio Tavares Lira [4]

[1] Doctor in Development and Environment, Professor, Departamento de Indústria e Produção Cultural, Instituto Federal de Educação, Ciência e Tecnologia do Piauí, Teresina, PI, Brazil
E-mail: osvaldo.augusto@ifpi.edu.br

[2] Master in Electrical Engineering, Professor, Departamento de Indústria e Produção Cultural, Instituto Federal de Educação, Ciência e Tecnologia do Piauí, Teresina, PI, Brazil
E-mail: fabricio@ifpi.edu.br

[3] Doctor in Agricultural Engineering, Professor, Departamento de Construção Civil e Arquitetura, Universidade Federal do Piauí, Teresina, PI, Brazil
E-mail: wilza@ufpi.edu.br

[4] Doctor in Development and Environment, Professor, Departamento de Engenharia Elétrica, Universidade Federal do Piauí, Teresina, PI, Brazil
E-mail: marcoslira@ufpi.edu.br

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ABSTRACT

The agricultural sector has a low representation in the Brazilian energy mix and in terms of distributed generation systems installed in rural areas. However, this sector represents a large portion of the gross domestic product. This work proposes an approach for identifying the driving factors for inserting mini and micro distributed generation systems in the agricultural sector. A methodology was developed based on a territorial approach, using indicators in Piauí to determine the major factors that drive its installation. It is observed that the main driving factor for rural microsystems is the total irrigated area of agricultural establishments. As for mini rural systems, the main driving factor is the average area of agricultural enterprises. In addition, it is reasonable to state that the proposed methodology applies to other states, from a regional and national perspective, as well as to other types of consumers.

Keywords: Farming. Photovoltaic Systems. Countryside areas.

RESUMO

O setor agropecuário tem baixa representatividade na matriz energética brasileira e nos sistemas de geração distribuída instalados no meio rural. No entanto, esse setor representa uma grande parcela do produto interno bruto. Este trabalho propõe uma abordagem para identificar os fatores determinantes para a inserção de mini e microssistemas de geração distribuída no setor agrícola, por meio de um enfoque territorial, usando indicadores do Piauí para determinar os principais fatores que impulsionam sua instalação. Observa-se que o principal fator impulsionador dos microssistemas rurais é a área total irrigada dos estabelecimentos agropecuários, enquanto que, com relação aos minissistemas rurais, o principal fator impulsionador é a área média dos empreendimentos agrícolas. Além disso, é razoável afirmar que a metodologia proposta se mostra aplicável a outros estados, do ponto de vista regional e nacional, bem como a outros tipos de consumidores.

Palavras-chave: Agricultura. Sistemas Fotovoltaicos. Áreas rurais.

1 INTRODUCTION

In September 2015, member countries of the United Nations (UN), including Brazil, committed to Agenda 2030, a global cooperation agreement composed of 17 Sustainable Development Goals (SDGs) and 169 targets to be pursued over the next 15 years. Since its publication, among other contributions, the 2030 Agenda has stimulated research development in quantitative and qualitative terms, considering that energy is one of the most prominent themes (GARLET *et al.*, 2022). In this context, the aim is to promote universal access to electric energy, increase the share of renewable energies, double the global energy efficiency rate, and strengthen international cooperation in research and technology transfer (UN, 2015).

Universal access to electricity is relevant to sustainable development, but it has not yet been consolidated. According to the World Bank, the number of people without access to electricity worldwide decreased from 1.2 billion in 2010 to 733 million in 2022. However, in 2030, it is estimated that 670 million people will remain without access to electricity. It corresponds to an increase of 10 million compared with the projection presented in 2021, resulting in a significant impact on health, productivity, and life quality (WORLD BANK, 2023). This aspect is a major challenge for underdeveloped countries, where complex energy solutions are required due to geographic, social, and environmental issues, especially in rural regions (LEDUCHOWICZ-MUNICIO *et al.*, 2022). In Brazil, 99.5% of the population has access to electricity, which corresponds to a better scenario when compared with other essential public services such as water supply (85.5%), sewage (68.3%), and garbage collection (84.4%) (LAMIN, 2021).

Population growth and economic development increase the electricity demand, which must be met by increasing energy efficiency indices and building new generating plants, but the latter often causes significant socio-environmental impacts. In Brazil, the percentage of renewable energy sources in the energy matrix corresponding to 44.7% in 2021 represents more than three times that of the world matrix in 2019, 14.1%. However, this portion can still be significantly increased (EPE, 2022). Once the use of renewable energies generates few socio-environmental impacts and such resources are virtually infinite (MENDES *et al.*, 2022), their promotion should be encouraged in world economies. In this scenario, they will reduce both greenhouse gas emissions and transmission losses, given that the plants are closer to consumer centres, with the possibility of reducing the share of thermal power plants.

Although power generation based on renewable energies is an alternative for sustainable development, its entire life cycle must be considered to assess socio-environmental impacts properly. The implementation process must consider the extraction and treatment of materials, equipment production, and the installation and implementation of facilities. Other important issues include operation, maintenance, equipment decommissioning, and disposal (MOTUZIENĖ *et al*., 2022).

The Brazilian matrix has a large insertion of hydroelectric generation, a renewable source. However, it causes great socio-environmental impacts in its implementation process (MENDES *et al*., 2022). In this way, other renewable energy sources have been gaining prominence in the Brazilian and global matrices, such as wind and solar, whose participation increased in absolute and relative terms in the Brazilian matrix from 2020 to 2021, respectively. In 2021, 570.8 TWh was consumed in Brazil, whereas the agricultural sector is responsible for 33.9 TWh (5.0%), corresponding to an increase of 1.4 TWh (4.2%) compared with the previous year (EPE, 2022).

According to the last agricultural census carried out in Brazil, the participation of agriculture in the Brazilian gross domestic product (GDP) increased by 8.36% in 2021 and reached a total of 27.4%. This is the highest amount reported since 2004, corresponding to 27.53%. In this sense, it is evident that this sector has an important role in inducing national economic development and in its foreign policy (AZEVEDO JÚNIOR; SANTANA, 2022; CEPEA, 2022), being responsible for 5.0% of the overall energy consumption in Brazil (EPE, 2022). For instance, in the state of Piauí, this activity uses an area of 10 million hectares (2.8% of all occupied Brazilian territory), being responsible for the direct occupation of 670 thousand people, that is 4.4% of all Brazilians directly involved with such activity (IBGE, 2019). It is worth mentioning that the agricultural census in Brazil occurs every 10 years, as promoted by the Brazilian Institute of Geography and Statistics (IBGE), thus being an important tool for decision-making (MORAIS *et al*., 2020).

Sustainable development can be considered as a set of processes and actions that must be considered from a global perspective and executed at national, regional, and local levels, thus allowing the entire planet to develop equally (BOFF, 2017). Ending hunger, achieving food security and improved nutrition, and promoting sustainable agriculture consist of one of the Sustainable Development Goals, SDG 2. The latter aims to develop technology and increase investments in rural infrastructure, agricultural research, and extension services to enhance agricultural productive capacity in developing countries, particularly in least-developed countries (UN, 2015). Within this scenario, family farming stands out in Brazil, accounting for 67% of all agriculture workers and 77% of agricultural establishments. It plays a key role in the production of cassava, coffee, bananas, and beans, representing 80%, 48%, 48%, and 42% of the total amount, respectively, also considering that such products are of great relevance to the population's diet (IBGE, 2019).

Even so, the participation of family farming in Brazil has been decreasing. In this sense, the application of renewable energy sources in the activities mentioned above has the potential to increase the autonomy of all involved families, in addition to improving the social technologies that already exist in Brazilian rural communities (BORGES; LUNA, 2017; GONZÁLEZ *et al*., 2022). As an attempt to contribute to 2030 Agenda goals, especially regarding the increased participation of renewable energy in rural areas, this article aims to develop a methodology for identifying the factors that drive the insertion of mini and micro distributed generation (DG) systems in the agricultural sector, taking the state of *Piauí* as the object of study. Although the present study has a local nature, one can apply the introduced methodology in other territories and subsidise sustainable development at a global level. The research can significantly contribute to inserting DG in the agricultural sector, which is responsible for more than a quarter of the Brazilian GDP, and promoting family farming.

2 METHODOLOGICAL PROCEDURES

The state of *Piauí* is divided into 12 development territories (DTs) (Figure 1) with different potentialities, among which agriculture stands out (MORAIS *et al.*, 2020). Regarding the number of municipalities and area, the largest territories in the state are *Entre Rios*, with 31 municipalities, and *Chapada das Mangabeiras*, with 54,044.7 km².

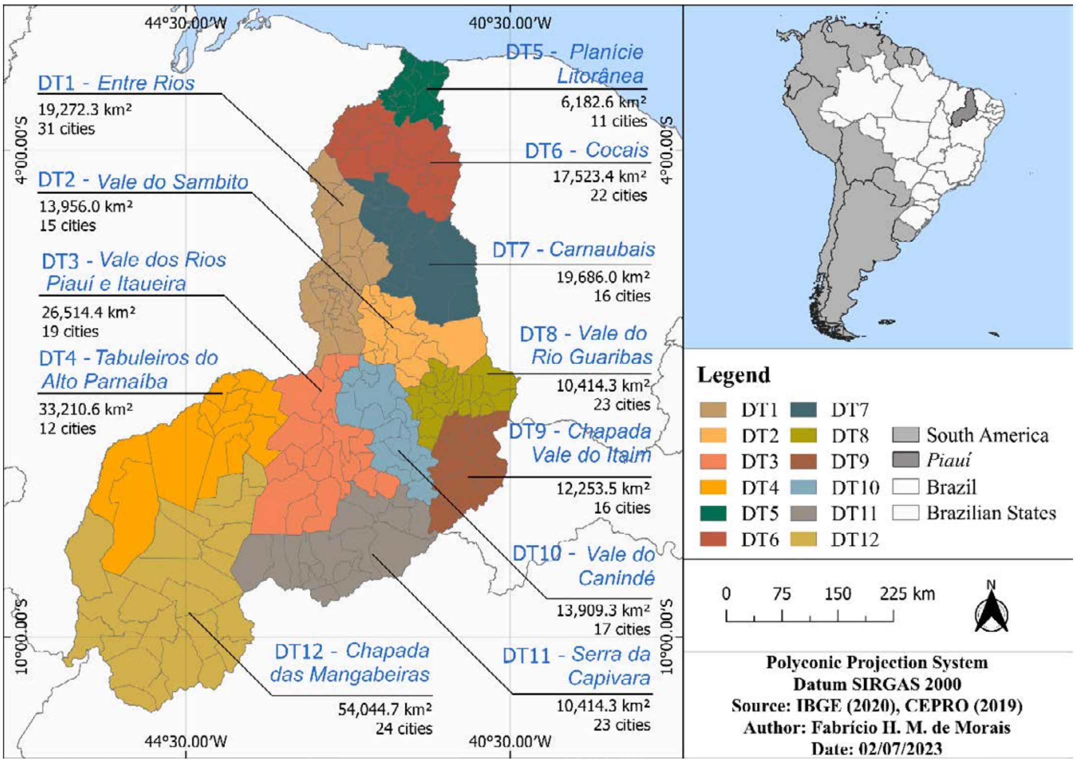

Figure 1 | Piauí's development territories

Source: Cepro (2019).

Thus, initially, the environmental and socioeconomic characterisation of the territories was performed from the analysis of the Human Development Index (HDI) from municipalities, obtained from the United Nations Development Programme – UNDP (PNUD, 2023) which were handled using spreadsheets and geographic information software (MICROSOFT, 2021; OSGEO, 2023). Notably, Freitas *et al*. (2021) also used this territorial approach which evaluated the productive interaction capacity of people from *Piauí* based on the spatiality of patent production by public research institutions. This approach is also suggested by Morais *et al*. (2020) specifically for family farming studies in *Piauí* since it can be understood as a key activity in the local economy.

The human development concept and related measurement indicators were presented in 1990 in the first Human Development Report of the UNDP and became a popular measure of the human development level of a country. The HDI comprises three other indicators: life expectancy or longevity, which evaluates the opportunity to have a long and healthy life; education, which measures access to knowledge; and income, which measures access to decent living standards.

Furthermore, these indices have been adapted locally to countries such as Argentina, China, India, South Africa, and Brazil. Under the responsibility of the Brazilian Institute for Economic and Applied Research (Ipea) and the João Pinheiro Foundation, a methodology was developed to assess the human development of Brazilian municipalities through the HDI. It takes into account longevity, education, and income, thus serving as a reference for several studies that evaluate such issues from a subnational perspective (DINIZ *et al*., 2021; PNUD, 2023; PROCÓPIO *et al*., 2020). The closer the HDI is to unity, the greater the human development. However, one can adopt intervals to characterise human development as very low (HDI<0.5); low (0.5≤HDI<0.6); medium (0.6≤HDI<0.7); high (0.7≤HDI<0.8); and very high (HDI≥0.8) (DINIZ *et al*., 2021; PNUD, 2023; PROCÓPIO *et al*., 2020).

This index can direct actions to improve these environmental aspects, both from an integral perspective and concerning its secondary levels, and access to electricity can be seen as an infrastructure issue that can promote citizenship (FREITAS, 2022). Nevertheless, especially in rural areas, universal access is a challenge (LEDUCHOWICZ-MUNICIO *et al*., 2022). Thus, to its characterisation, using data from IBGE (2019), also treated by spreadsheet programs (MICROSOFT, 2021), the number of agricultural establishments which do not have access to this asset was determined, considering only those establishments where the use of electricity is desirable.

This research used the Pearson correlation coefficient (PCC) to determine the strength of linear association between two variables. Thus, the indicators are strongly correlated if the PCC is greater than 0.8 (SILVA; CASTRO, 2022). However, they are moderately correlated if it is between 0.5 and 0.8. The variables are weakly correlated if the PCC is lower than 0.5 (SILVA *et al*., 2022). Thus, using open data obtained from the Brazilian National Electric Energy Agency – Aneel (ANEEL, 2023), which were treated by spreadsheet, business intelligence and Geographic Information programs (MICROSOFT, 2021, 2022; OSGEO, 2023), one can determine the number of facilities and the installed power of mini and micro DG systems in rural areas for each of the territories. The total power of the rural systems in Piauí was correlated with the total power of residential, commercial, and industrial systems in the state using the PCC to determine the similarity level of the distributions (ANEEL, 2023).

Table 1 presents the average human development in *Piauí*'s territories obtained from Pnud (2023). The data are summarised in spreadsheets using business intelligence software (MICROSOFT, 2021, 2022). The main indicators include environmental and socioeconomic issues, in addition to aspects related to DG and agriculture in all municipalities (ANEEL, 2023; IBGE, 2019; PEREIRA *et al*., 2017; PNUD, 2023). The same data and tools were also used to evaluate the most correlated factors with the state's distribution of rural mini-generation and microgeneration systems, defined as driving factors for their installations. Using the PCC, the indicators of mini and micro DG rural systems were first correlated with the other types of DG systems in *Piauí* and later correlated with the environmental, socioeconomic, and farming indicators. Scatter plots were obtained to illustrate the study aiming to show the equations that describe the variation of indicators and the R^2 coefficient that determines the model suitability.

Table 1 | Matrix of indicators for identifying the driving factors of rural DG systems

U#	*Environmental Aspect*	*Environmental Indicator*
Ind.1	DG	Total rated power of micro DG systems
Ind.2	DG	Rated power of micro DG residential systems
Ind.3	DG	Rated power of micro DG commercial systems
Ind.4	DG	Rated power of micro DG industrial systems
Ind.5	DG	Total rated power of mini DG systems
Ind.6	DG	Rated power of mini DG residential systems
Ind.7	DG	Rated power of mini DG commercial systems
Ind.8	DG	Rated power of mini DG industrial systems
Ind.9	Environmental	Total area of municipalities (km^2)
Ind.10	Environmental	Average annual global horizontal irradiation
Ind.11	Socioeconomic	HDI
Ind.12	Socioeconomic	Income
Ind.13	Socioeconomic	Education

U#	Environmental Aspect	Environmental Indicator
Ind.14	Socioeconomic	Longevity
Ind.15	Socioeconomic	Number of agricultural establishments with access to electricity
Ind.16	Farming	Total area of agricultural establishments
Ind.17	Farming	Average area of agricultural establishments
Ind.18	Farming	Average area of agricultural establishments involved with family farming
Ind.19	Farming	Total area of agricultural establishments with access to irrigation
Ind.20	Farming	Total agroindustry production
Ind.21	Farming	Number of agricultural establishments with access to funding
Ind.22	Farming	Number of agricultural establishments associated with funding programs
Ind.23	Farming	Number of agricultural establishments whose owner lives on the property
Ind.24	Farming	Number of agricultural establishments whose producer is the owner

Source: Aneel (2023), IBGE (2019), Pereira et al. (2017) and Pnud (2023).

3 RESULTS AND DISCUSSION

The average HDI of the 224 municipalities in *Piauí* is 0.541, a low value (PNUD, 2023) (Table 2). A total of 78.6% have a low HDI, among which 2.7% and 17.9% correspond to municipalities with very low and medium development levels, respectively. Only two municipalities (0.9%) present a high HDI. It is also noteworthy that the *Entre Rios* territory, which comprises *Piauí*'s capital, *Teresina*, has the highest average HDI, 0.751. *Planície Litorânea* territory has the lowest average HDI in the state (0.541), whereas *Vale do Canindé* territory has the lowest HDI (0.485).

Table 2 | Average HDI of Piauí's development territories

TD	HDI	Education	Longevity	Income
TD1	0.595	0.496	0.562	0.760
TD2	0.584	0.480	0.552	0.755
TD3	0.562	0.446	0.539	0.741
TD4	0.596	0.489	0.569	0.763
TD5	0.541	0.401	0.531	0.750
TD6	0.553	0.424	0.530	0.756
TD7	0.571	0.456	0.539	0.761
TD8	0.572	0.452	0.562	0.739
TD9	0.545	0.420	0.535	0.722
TD10	0.574	0.466	0.551	0.741
TD11	0.564	0.454	0.531	0.748
TD12	0.576	0.463	0.548	0.756
Piauí	**0.569**	**0.454**	**0.546**	**0.749**

Source: Pnud (2023).

Improving human development in all development territories of *Piauí* is a challenge. In this sense, the HDI can direct actions to improve these environmental aspects, both from an integral perspective and concerning its secondary levels, that is, longevity, education, and income. Access to electricity can be seen as an infrastructure issue that can promote citizenship (FREITAS, 2022), but universal access is also a challenge in *Piauí*, especially in rural areas (LEDUCHOWICZ-MUNICIO *et al.*, 2022). Among 244,206 agricultural establishments where electricity is desirable, 18.54% do not have access to this asset.

In this context, *Entre Rios* and *Chapada das Mangabeiras* represent the territories with the largest number of establishments without access to electricity in absolute (7674 establishments) and relative (32.00%) terms, according to Figure 2.

The use of renewable energies in such activities can improve autonomy, contributing positively to universal access to electricity, especially in family farming (BORGES; LUNA, 2017; GONZÁLEZ *et al.*, 2022; JEAN; BRASIL JUNIOR, 2022). Furthermore, the lack of reliable records in off-grid systems makes a more accurate analysis of rural electrification trends somewhat complex. However, even in agricultural establishments where access to electricity is guaranteed, the legal framework created in 2012 has allowed the installation of distributed mini-generation and microgeneration systems to inject the generated energy into the grid (SILVA *et al.*, 2019). However, after a modified Brazilian regulation was established in 2022, the government incentives for this became less attractive (COSTA *et al.*, 2022; SOARES; BARRETO, 2022). As the penetration of this type of generation increases, generation and transmission costs decrease, making it a prominent alternative to supply the increasing demand and reduce the use of fossil fuels (ARNAWAN *et al.*, 2021; GIMENES *et al.*, 2022).

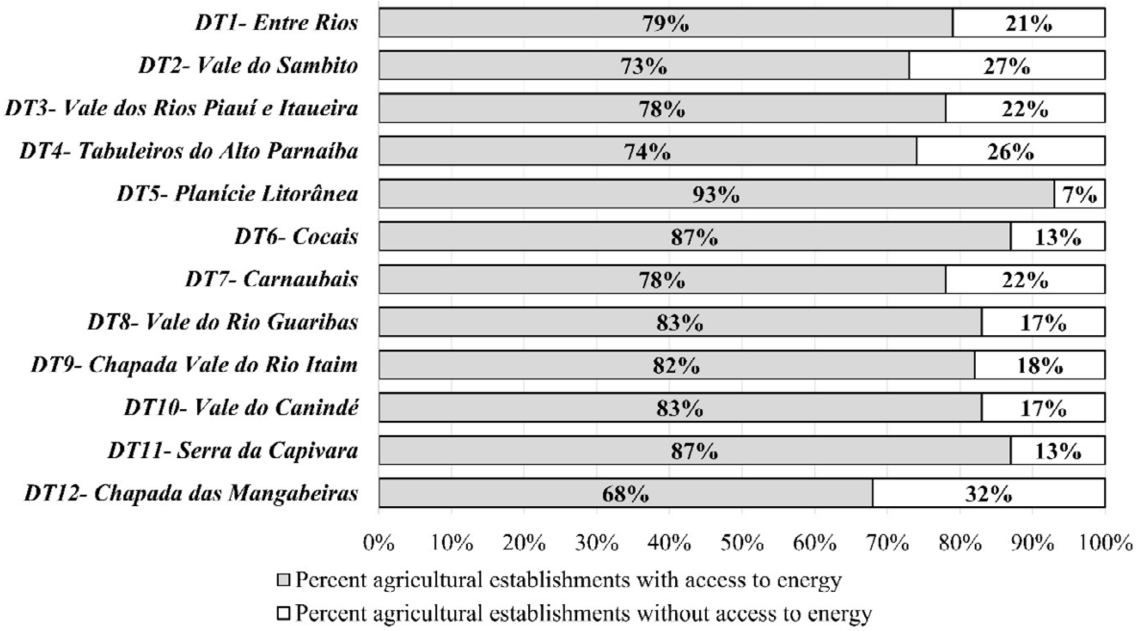

Figure 2 | Access to electricity in agricultural establishments in *Piauí*'s development territories

Source: IBGE (2019).

The Brazilian Northeast region, which comprises the state of *Piauí*, has the country's greatest solar potential for energy generation (ALMEIDA; ALMEIDA, 2022; MEDEIROS *et al.*, 2021). *Piauí* is no different, especially in the case of municipalities of the Southeast region (PEREIRA *et al.*, 2017; SILVA *et al.*, 2021). With a daily average solar irradiance of 5.71 kWh/m², that is, 4% higher than the Brazilian Northeast region's average (PEREIRA *et al.*, 2017), all mini and micro DG systems in the state consist of photovoltaic systems. In turn, there is also great potential for establishing wind power plants, especially in the municipalities of *Parnaíba* and *Paulistana*, where large farms are currently installed (LIRA *et al.*, 2017). By January 9, 2023, 29,457 DG units had been installed in the state, resulting in a total power of 298,103.76 kWh (Figure 3). 99.54% of the facilities correspond to microgeneration systems, which account for 86.92% of the total installed power. Rural systems represent 1.76% of the existing systems and 3.32% of the installed capacity in *Piauí*. In turn, they account for 8.41% of DG systems and 14.77% of the installed capacity in Brazil (ANEEL, 2023). The *Entre Rios* territory has the highest number of microgeneration systems and installed power. Similarly, the *Tabuleiros do Alto Parnaíba* territory has the highest number of facilities and installed power in terms of mini-generation systems.

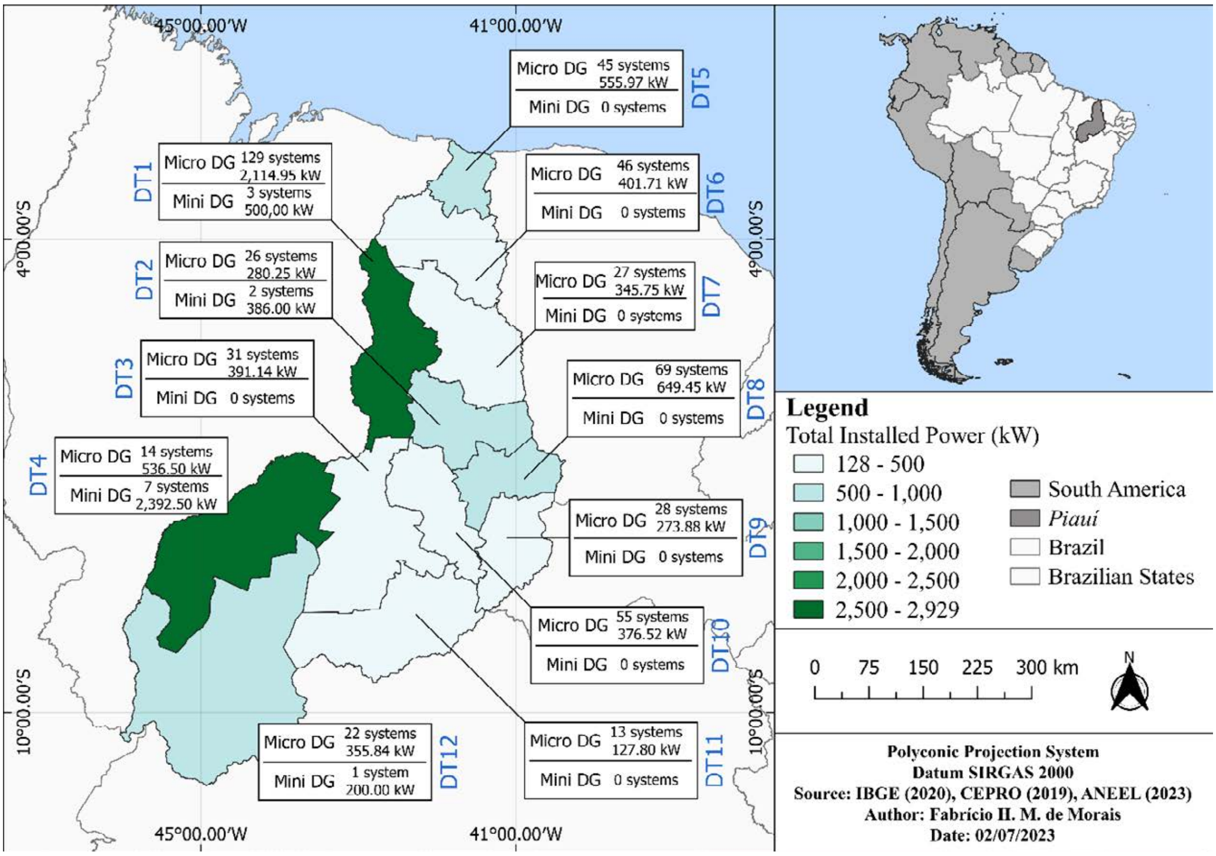

Figure 3 | Rural mini and micro DG systems in Piauí's development territories

Source: Aneel (2023).

The total installed power of rural DG systems in *Piauí* has a moderate correlation when compared with residential, commercial, and industrial systems, corresponding to correlation coefficients of 0.679, 0.678, and 0.661, respectively, thus denoting distinct dynamics for each system (ANEEL, 2023). Figure 4 represents the rural micro DG systems in the state in terms of installed power and the number of existing facilities up to January 9, 2023. Piauí has 505 systems installed in 138 municipalities (61.16%), with an average power of 12.69 kW/system. *Teresina*, which is *Piauí*'s capital and is located in the *Entre Rios* territory, stands out with 72 installed systems (14.26% of the total number of rural microgeneration systems), comprising an installed power of 1201.61 kW (18.75% of the total installed power of rural microgeneration systems) (ANEEL, 2023).

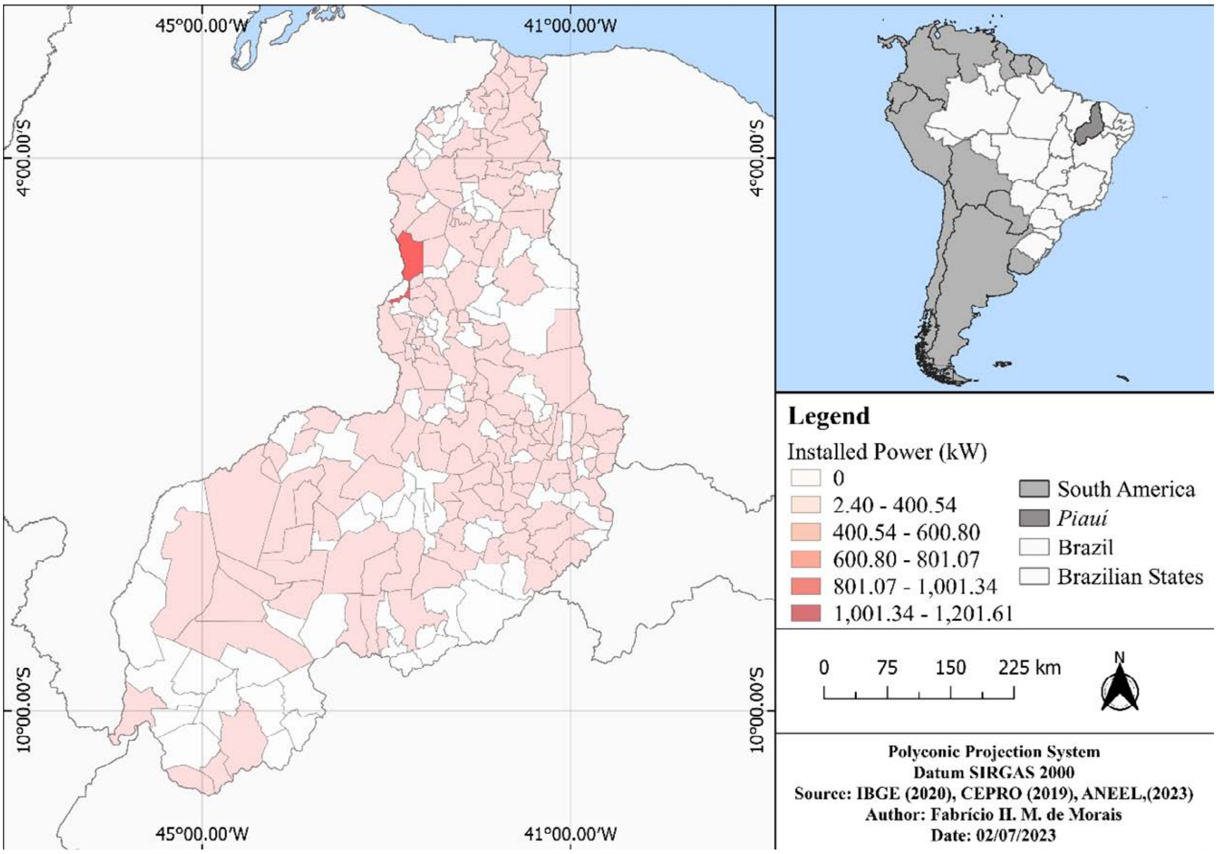

Figure 4 | Rural micro DG systems in Piauí's municipalities

Source: Aneel (2023).

Concerning rural mini DG systems, one could identify only 13 systems with an average power of 267.58 kW/system, 20.1 times greater than the average power of rural micro DG systems. The units are installed in six municipalities as shown in Figure 5: *Baixa Grande do Ribeiro* (three systems with a total of 892.5 kW), *Currais* (one system rated at 200.0 kW), *Sebastião Leal* (three systems with a total of 1380.0 kW), *Teresina* (three systems with a total of 500 kW), *Uruçuí* (one system rated at 120 kW), and *Valença do Piauí* (two systems with a total of 386.0 kW). Therefore, rural micro DG systems exist in only three development territories: *Tabuleiros do Alto Parnaíba* (seven systems with a total of 2,392.50 KW), *Entre Rios* (three systems with a total of 500 kW), and *Chapada das Mangabeiras* (one system rated at 200.0 kW) (ANEEL, 2023).

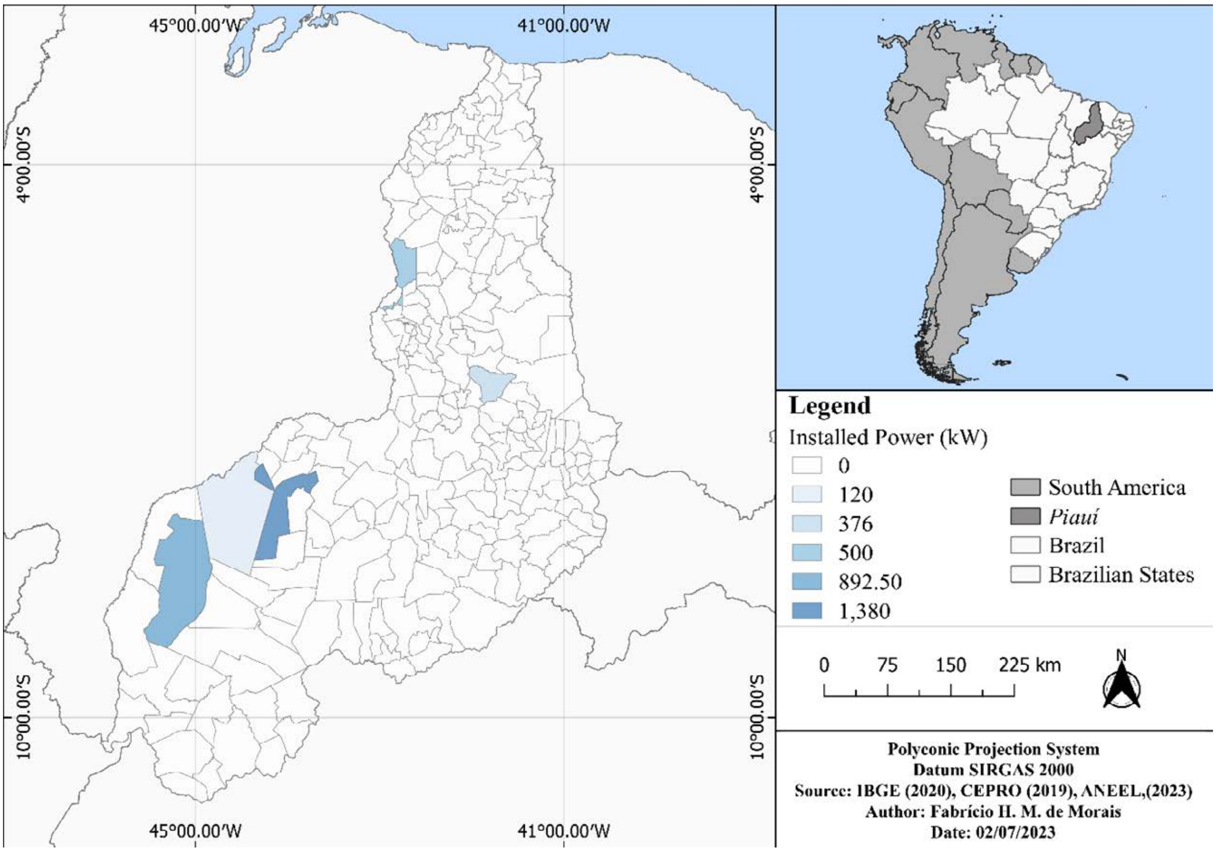

Figure 5 | Rural mini DG systems in *Piauí*'s municipalities

Source: Aneel (2023).

Identifying the factors that drive the installation of DG systems is essential to encourage its expansion. For instance, residential consumers have a high correlation between the degree of urbanisation and the domestic consumption of photovoltaic solar energy (FREITAS, 2022). From the perspective of the current Brazilian legislation, rural consumer units involve several activities such as rural and urban agriculture; rural residences; rural electrification cooperative enterprises; agro-industrial facilities with transformers rated at power levels less than 112.5 kVA; rural irrigation public service; agrotechnical schools; and aquaculture farming (ANEEL, 2021).

The matrix presented in Table 1 was used for the general characterisation of the agricultural sector in the development territories of *Piauí*. One could identify 245,601 agricultural establishments (AEs) in the state, with an average area of 40.76 ha, as shown in Table 3. *Tabuleiros do Alto Parnaíba* and *Chapada das Mangabeiras* territories stand out as the development territories with the largest projects, resulting in an average of 285.17 ha and 120.98 ha, respectively. In turn, *Entre Rios* territory has the largest irrigated area of 9345 ha and the highest annual agroindustry production corresponding to R$ 14.95 million (IBGE, 2019). However, it seems that the territories comprising the agricultural enterprises with the largest average areas are also the regions where family farming has the lowest representation, 10.61% and 24.52%, in contrast to an average of 38.49% when considering the state.

Table 3 | General characterisation of agricultural establishments in the Piauí's development territories

DT	Number of AEs	Average área of the AEs (ha)	Per cent area dedicated to family farming	Total irrigated area of the AEs (ha)	Annual agroindustry production of the AEs (xR$1000.00)
DT1	37,415	20.90	41.81%	9345	14,959.00
DT2	13,438	54.71	31.57%	2605	11,024.00
DT3	14,914	39.80	50.36%	2618	2814.00
DT4	5970	285.17	10.61%	1689	6949.00
DT5	15,244	10.76	54.27%	2919	9625.00
DT6	34,345	17.60	50.60%	2402	23,710.00
DT7	18,281	46.58	33.30%	1428	12,903.00
DT8	26,569	19.09	65.82%	1792	9173.00
DT9	20,773	32.49	73.35%	930	4737.00
DT10	18,054	31.12	65.08%	2397	1144.00
DT11	23,002	30.59	59.57%	1429	6582.00
DT12	17,596	120.98	24.52%	3825	15,127.00
Piauí	**245,601**	**40.76**	**38.49%**	**33,379**	**118,747.00**

Source: IBGE (2019).

Other aspects of agribusiness presented in Table 1 were also evaluated. In the development territories, 81.0% of agricultural enterprises have access to financing, and 13.92% are beneficiaries of government financing programs, resulting in standard deviations of 6.62% and 2.51%, respectively. Besides, 77.55% of producers live in the establishments, whereas 70.77% own the property, corresponding to standard deviations of 7.60% and 7.86%, respectively (IBGE, 2019). Unlike residential facilities where the installation of DG resources is often restricted to roofs, rural consumers have large areas available for this purpose, either on the ground or on the roof of sheds (HOLZBACH; RESENDE, 2022). However, the best alternative for rural electrification must rely on in-depth technical and economic studies (ALQANTANI; PATINO-ECHEVERRI, 2023).

The analysis of *Piauí*'s development territories shows that the distribution of rural micro DG systems strongly correlates with that of micro DG systems in general and with residential, commercial, and industrial systems, according to Table 4. However, rural mini DG systems present a weak correlation, unlike their microgeneration counterparts. It is reasonable to state that the configuration mechanism of the main microgeneration systems in the state has a similar behaviour. Future studies must be carried out to identify common driving factors, which could not be identified in the case of mini-generation systems installed in *Piauí.*

Table 4 | Correlation matrix associating rural, residential, commercial, and industrial mini and micro DG systems in Piauí's development territories

Total installed power of rural micro DG systems			*Total installed power of rural mini DG systems*		
	Correlation	Correlation Degree		Correlation	Correlation Degree
Ind.1	0.983	Strong	Ind.5	0.122	Weak
Ind.2	0.982	Strong	Ind.6	0.043	Weak
Ind.3	0.980	Strong	Ind.7	0.014	Weak
Ind.4	0.962	Strong	Ind.8	0.005	Weak

Source: Aneel (2023).

The fact that agribusiness aspects are strongly correlated with the total installed power of rural mini and micro DG systems in *Piauí*'s development territories was assessed in detail. Table 5 shows a moderate correlation between the availability of solar resources and socioeconomic indicators for rural micro DG systems. Among such aspects, human development and access to electricity are of major importance, the latter being a must for connecting the DG system to the electric utility network. Considering the state as a whole, Table 5 evidences that the factor that mainly explains the variance is the total irrigated area of agricultural establishments, which require electricity for water pumping systems. Besides, water is the main asset for increasing efficiency in the agricultural sector, where solar energy can bring prominent advantages (CHOWDHURY *et al*., 2022).

As for rural mini DG systems, one could identify a weak correlation involving all the analysed indicators. According to Table 5, the enterprises' average area is the state's main driving factor for installing mini DG systems in agricultural establishments. Large agricultural properties have a high energy demand, whereas large available areas enable the installation of high-power DG systems (HOLZBACH; RESENDE, 2022), thus corroborating the results of this study. The results obtained so far reflect the local reality of *Piauí*. However, the methodology can be applied to other sites with scientific relevance since similar data are available for all Brazilian municipalities.

Table 5 | Correlation matrix associating rural mini and micro DG systems with environmental, socioeconomic, and agribusiness factors

	Total installed power of rural micro DG systems		*Total installed power of rural mini DG systems*	
	Correlation	Correlation		Correlation
Ind.9	0.090	Weak	0.334	Weak
Ind.10	0.631	Moderate	0.267	Weak
Ind.11	0.698	Moderate	0.182	Weak
Ind.12	0.674	Moderate	0.218	Weak
Ind.13	0.722	Moderate	0.137	Weak
Ind.14	0.693	Moderate	0.194	Weak
Ind.15	0.505	Moderate	0.460	Weak
Ind.16	0.045	Weak	0.557	Moderate
Ind.17	0.125	Weak	0.907	Strong
Ind.18	0.126	Weak	0.354	Weak
Ind.19	0.918	Strong	0.049	Weak
Ind.20	0.264	Weak	0.065	Weak
Ind.21	0.505	Moderate	0.460	Weak
Ind.22	0.383	Weak	0.459	Weak
Ind.23	0.435	Weak	0.509	Moderate
Ind.24	0.487	Weak	0.527	Moderate

Source: Aneel (2023), IBGE (2019), PEREIRA et al. (2017) and Pnud (2023).

In addition, to better illustrate the study, scatter plots can be plotted as in Figures 6 and 7, which show the total power of the two types of rural DG systems as a function of the best correlation indices identified.

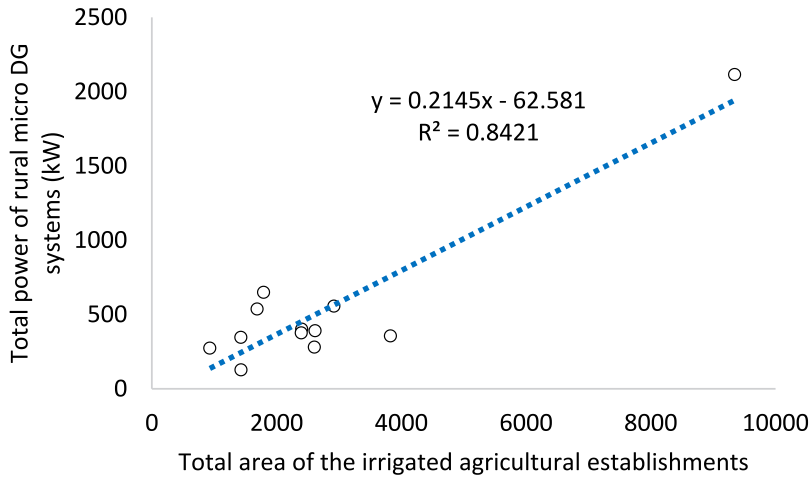

Figure 6 | Linear regression representing the total installed power of rural micro DG systems in Piauí's development territories

Source: Aneel (2023) and IBGE (2019).

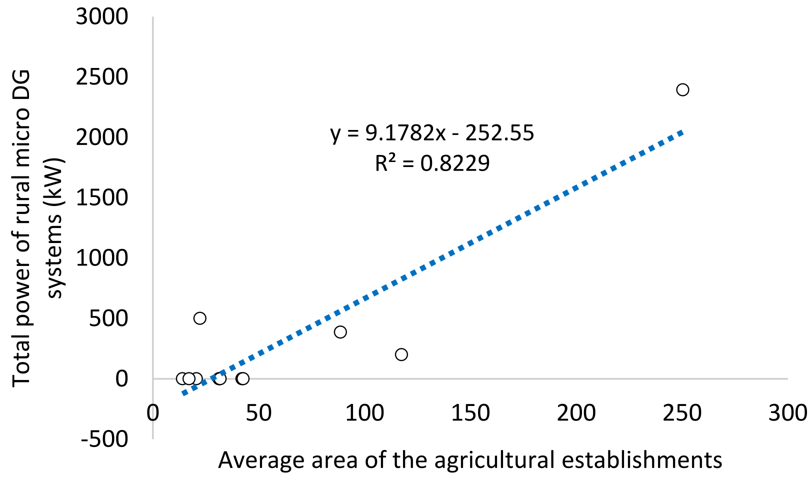

Figure 7 | Linear regression representing the total installed power of rural mini DG systems in Piauí's development territories

Source: Aneel (2023) and IBGE (2019).

The graphs also can show the equations that describe the behaviour of the assessed quantities and the R^2 coefficient that determines the model suitability. For the studied systems, the linear regressions evidence that the larger the total irrigated area of agricultural establishments, the higher the installed power of rural micro DG systems (R^2 equals 0.8421). Similar behaviour occurs with the installed power of rural mini DG systems in relation to the average area of agricultural enterprises (R^2 equals 0.8229). Finally, the data used in this research are available for all Brazilian municipalities. Thus, the described methodology can be promptly extended to other Brazilian states and regions.

4 CONCLUSIONS

The agricultural sector has a low representation in the national energy matrix, only 5.0%, corresponding to 8.41% and 14.77% of DG systems in terms of the number of units and installed power, respectively. However, this sector has an important role in the 2030 Agenda and is responsible for 27.4% of the Brazilian GDP, which evidences the great potential for the expansion of mini and micro DG. In addition, increasing investments in rural infrastructure and developing technology to enhance agricultural productivity in developing countries, particularly in least-developed countries, are some key targets of the UN Agenda.

Based on this assumption, it was possible to develop a methodology that allows characterising the state of *Piauí* based on a territorial approach from environmental, socioeconomic, and agricultural indicators, correlating them with mini and micro DG systems that exist in rural areas to determine the factors that drive their installation. This solution applies to other states and can be extended to other studies from a regional and national perspective since identifying factors that drive the installation of DG systems is a key issue in encouraging its expansion.

It has been observed that the average HDI of the state is somewhat low, that is, 0.541, whereas a large portion of agricultural establishments does not have access to energy (18.54% on average). In turn, this scenario could be improved using renewable energy sources. A total of 245,601 agricultural establishments were identified in the state, with an average area of 40.76 ha, where 38.49% is dedicated to family farming activities. Besides, the state comprises an irrigated area of 33,379 ha (3.33%) and an agroindustrial production of R$ 118.74 million annually.

In this context, *Entre Rios*, which aggregates 31 municipalities with an average area of 621.68 km², stands from the positive and negative points of view. This territory has the highest HDI (0.595), in contrast to the highest number of agricultural establishments without access to energy in absolute terms (7674 units, corresponding to 21%). In addition, *Planície Litorânea*, which comprises 11 municipalities with an average area of 562.05 km², has the lowest HDI (0.541). In turn, *Chapada das Mangabeiras*, with 18 municipalities and an average area of 1377.1 km², has the highest number of agricultural establishments without access to energy in relative terms (5,653 establishments, that is, 32%). However, it is noteworthy that universal access to energy is not a reality in any of the territories studied, but this issue is of major importance for achieving the objectives of the UN Agenda 2030.

Considering an annual average global horizontal irradiation of 5.71 kWh/m² in the state, 4% higher than the average for the Brazilian Northeast region, all mini and micro DG systems consist of photovoltaic systems, which have an irregular distribution. Thus, it was possible to identify 29,457 systems, among which 99.54% correspond to micro DG units, with a total installed power of 298,103.76 kWh, thus representing 86.92% of the total installed power.

The present study has considered that rural DG systems are classified according to the criteria defined by Aneel. In this sense, consumers who develop rural and urban agriculture activities, rural residences, rural electrification cooperatives, agroindustrial facilities with transformers with rated power less than 112.5 kVA, public rural irrigation services, agrotechnical schools, and aquaculture farming can be considered agricultural establishments. Thus, 1.76% of the installed systems in *Piauí* are rural, representing 3.32% of the installed power. *Entre Rios* stands out again as the territory with the highest number and installed power of rural micro DG systems, 129 systems and 2,114.95 kW. In turn, *Tabuleiros do Alto Parnaíba*, which is a territory that comprises 12 municipalities and an average area of 2767.55 km², has the highest installed power and number of mini DG systems, that is, seven systems and 2,392.50 kW.

One can state that the distribution of rural micro DG systems in *Piauí* strongly correlates with the installation of micro DG systems. As for systems installed in residential, commercial, and industrial facilities, an average correlation of 0.98 denotes that the distribution of installed facilities is motivated by some common factors identified in the case of rural micro DG systems. However, a weak correlation was found for rural mini DG systems, where an average correlation of 0.05 denotes that the dispersion of existing systems is associated with particular configurations.

It has been observed that rural micro DG systems have a moderate correlation with the availability of solar resources and socioeconomic indicators. There is a strong correlation with the total irrigated area of agricultural establishments that usually rely on electricity as an important asset for water pumping systems. Overall, it is reasonable to state that this is the main factor that drives the installation of micro DG systems in the state. On the other hand, rural mini DG systems have a weak correlation with almost all the analysed indicators, except for the average area of agricultural establishments. Since the latter indicator presented a strong correlation, it is mainly responsible for driving the installation of mini rural DG systems in the state.

Considering that rural consumers are just one of seven types of consumers classified by the Aneel (rural, residential, commercial, industrial, governmental, public lighting, and public services), as well as that the study comprises a single Brazilian state, possible future work includes extending the methodology to wider regions while incorporating all other types of consumers. Thus, one can more clearly identify the main aspects associated with the strong correlation between the distribution of the various distributed micro DG systems.

REFERENCES

AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. **Relação de empreendimentos de Geração Distribuída**. Brasília: Aneel, 2023. Available at: https://dadosabertos.aneel.gov.br/dataset/relacao-de-empreendimentos-de-geracao-distribuida/. Accessed on: January 2023.

AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. **Resolução Normativa Aneel Nº 1.000, de 7 de dezembro de 2021**. Estabelece as Regras de Prestação do Serviço Público de Distribuição de Energia Elétrica; revoga as Resoluções Normativas Aneel nº 414, de 9 de setembro de 2010; nº 470, de 13 de dezembro de 2011; nº 901, de 8 de dezembro de 2020 e dá outras providências. Brasília: Aneel, 2021.

ALMEIDA, H. A.; ALMEIDA, E. C. V. Potencial da energia solar fotovoltaica no Semiárido nordestino. **Concilium**, v. 22, n. 2, p. 197–210. Available at: https://doi.org/10.53660/CLM-111-130

ALQANTANI, B. J.; PATINO-ECHEVERRI, D. Identifying Economic and Clean Strategies to Provide Electricity in Remote Rural Areas: main-grid extension vs. distributed electricity generation. **Energies**, v. 16, n. 2, 2023. Available at: https://doi.org/10.3390/en16020958.

ARNAWAN, H. *et al*. Evaluation of 20 kV Distribution Network Losses In Radial Distribution Systems Due to Distributed Generation Penetration. **Journal of Physics**. Conference Series, 2129, v. 2021. Available at: https://doi:10.1088/1742-6596/2129/1/012085.

AZEVEDO JÚNIOR, W. C.; SANTANA, A. C. O produto interno bruto do Brasil ajustado pela depreciação do solo agrícola. **Revista de Economia e Sociologia Rural**, v. 60, n. 2, 2022. Available at: https://doi.org/10.1590/1806-9479.2021.228505.

BOFF, L. **Sustentabilidade**: o que é – o que não é. Petrópolis: Vozes, 2017.

BORGES, F. F.; LUNA, F. M. Tecnologias sociais e energias renováveis na agricultura familiar: experiências no NDTS/IFPB e parceiros. **Revista Praxis: saberes da extensão**, v. 5, n. 10, p. 112-119, 2017. Available at: http://dx.doi.org/10.18265/2318-23692017v5n10p112-119.

CENTRO DE ESTUDOS AVANÇADOS EM ECONOMIA APLICADA. **PIB do agronegócio cresceu abaixo das projeções**. São Paulo: USP, 2022.

CHOWDHURY, H. *et al*. A simulation study of techno-economics and resilience of the solar PV irrigation system against grid outages. **Environmental Science and Pollution Research**, v. 29, p. 64846–64857, 2022. Available at: https://doi.org/10.1007/s11356-022-20339-2.

COSTA, V. B. F. *et al*. Socioeconomic and environmental consequences of a new law for regulating distributed generation in Brazil: a holistic assessment. **Energy Police**, v. 169, 2022. Available at: https://doi.org/10.1016/j.enpol.2022.113176.

DINIZ, M. T. M. *et al*. Análise da influência de Variáveis Socioeconômicas na distribuição de casos e óbitos de Covid-19 no Brasil. **Geografia Ensino & Pesquisa**, v. 25, n. 43, 2021. Available at: https://doi.org/10.5902/2236499461365.

EMPRESA DE PESQUISA ENERGÉTICA. **Brazilian Energy Balance**. Brasília: EPE, 2022.

FREITAS, B. M. R. What's driving solar energy adoption in Brazil? Exploring settlement patterns of place and space. **Energy Research & Social Science**, v. 89, 2022. Available at: https://doi.org/10.1016/j.erss.2022.102660.

FREITAS, R. A. B. *et al*. Patentes e espaço geográfico: uma análise espacial do território piauiense. **Research, Society and Development**, v. 10, n. 9, 2021. Available at: https://doi.org/10.33448/rsd-v10i9.17949.

GARLET, V. *et al*. Sustainable Development Goals – SDG: an analysis of the main characteristics of publications. **RISUS. Journal on Innovation and Sustainability**, v. 13, n. 2, p. 14-26, 2022. Available at: https://doi.org/10.23925/2179-3565.2022v13i2p14-26.

GIMENES, T. K. *et al*. Impact of distributed energy resources on power quality: Brazilian scenario analysis. **Electric Power Systems Research**, v. 211, 2022. Available at: https://doi.org/10.1016/j.epsr.2022.108249.

GONZÁLEZ, A. B. P.; VIGLIO, J. E.; FERREIRA, L. C. Energy communities in sustainable transitions – The South American Case. **Sustainability in Debate**, v. 13, n. 2, p. 156–174, 2022. Available at: https://doi.org/10.18472/SustDeb.v13n2.2022.41266

HOLZBACH, M.; RESENDE, A. S. Photovoltaic generators: use by rural customers in Mato Grosso State. **Revista Engenharia na Agricultura**, v. 30, 2022. Available at: https://doi.org/10.13083/reveng.v30i1.12689.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo agropecuário 2017**: resultados definitivos. Rio de Janeiro, IBGE, 2019. Available at: https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017/resultados-definitivos/. Accessed on: February 2023.

JEAN, W.; BRASIL JUNIOR, A. C. P. Solar model for Rural Communities: Analysis of Impact of a Grid-Connected Photovoltaic System in the Brazilian semi-arid region. J**ournal of Sustainable Development of Energy, Water and Environment Systems**, v.10, n. 3, 2022. https://doi.org/10.13044/j.sdewes.d9.0405.

LAMIN, H. **Universalização do serviço público de energia elétrica e os Programas Luz para Todos e Mais Luz Amazônia**. Brasília: Aneel, 2021.

LEDUCHOWICZ-MUNICIO, A. *et al.* Last-mile rural electrification: lessons learned from universalisation programs in Brazil and Venezuela. **Energy Policy**, v. 167, 2022. Available at: https://doi.org/10.1016/j.enpol.2022.113080.

LIRA, M. A. T. *et al*. Characterisation of Wind Behaviour in Piauí in Order to Utilise Wind Energy. **Revista Brasileira de Meteorologia**, v. 32, n. 1, 2017. Available at: https://doi.org/10.1590/0102-778632120150712.

MEDEIROS, S. E. L. *et al*. Influence of climatic variability on the electricity generation potential by renewable sources in the Brazilian semi-arid region. **Journal of Arid Environments**, v. 184, 2021. Available at: https://doi.org/10.1016/j.jaridenv.2020.104331.

MENDES, P. D. A. G. *et al*. Public Policies and Adaptation to Climate Change: three case studies in the Brazilian semi-arid region. **Sustainability in Debate**, v. 13, n. 3, p. 227-245, 2022. Available at: https://doi:10.18472/SustDeb.v13n3.2022.46064

MICROSOFT. **Power BI Desktop**, version 2.112.603.0. Microsoft Corporation, 2022.

MICROSOFT. **Microsoft Excel 2021 MSO**, version 2306. Microsoft Corporation, 2021.

MORAIS, M. D. C.; SOUSA, A. M. B.; ARAÚJO, C. F. S. Family Farming in Piauí: a reading of the agricultural census 2017. **Revista Econômica do Nordeste**, v. 51, p. 71-91, 2020.

MOTUZIENĖ, V. *et al.* A Review of the Life Cycle Analysis Results for Different Energy Conversion Technologies. **Energies**, v. 15, n. 22, 2022. Available at: https://doi.org/10.3390/en15228488

OPEN SOURCE GEOSPATIAL FOUNDATION. **QGIS Geographic Information System**, version 3.28.5. OSGEO Foundation, 2023.

PEREIRA, E. B. *et al*. **Atlas Brasileiro de Energia Solar**. 2. ed. São José dos Campos: Inpe, 2017. Available at: http://doi.org/10.34024/978851700089.

PROCÓPIO, G. B. *et al*. Análise da vulnerabilidade social sobre o indicador de crianças extremamente pobres nas regiões metropolitanas do Brasil. **Revista de Estudos Sociais**, v. 22, n. 44, p. 5-14, 2020. Available at: https://doi.org/10.19093/res7902

PROGRAMA DAS NAÇÕES UNIDAS PARA O DESENVOLVIMENTO. A**tlas do Desenvolvimento Humano no Brasil – Ranking**. Brasília: Pnud, Ipea, FJP. Available at: http://idhm.org.br/ranking/. Accessed on: February 2023.

SILVA, G. D. P. *et al*. Environmental licensing and energy policy regulating utility-scale solar photovoltaic installations in Brazil: status and future perspectives. Impact **Assessment and Project Appraisal**, v. 37, 2019. Available at: https://doi.org/10.1080/14615517.2019.1595933.

SILVA, O. A. V. O. L. *et al*. **Etiquetagem do uso da energia**: uma nova proposta de rotulagem ambiental. Teresina: EdUESPI, 2022.

SILVA, O. A. V. O. L. *et al*. Expansion of photovoltaic systems in multicampi higher education institutions: evaluation and guidelines. **Revista Brasileira de Ciências Ambientais**, v. 56, n. 4, p. 697-709, 2021. Available at: https://doi.org/10.5327/Z217694781009.

SILVA, S. A.; CASTRO, L. G. Two-dimensional statistical analysis applied. **Revista Ibero-Americana de Humanidades, Ciências e Educação**, v. 8, n. 4, 2022. Available at: https://doi.org/10.51891/rease.v8i4.5051

SOARES, A. M. de A.; BARRETO, C. G. Disputes and narratives on the distributed generation of electricity in Brazil: setbacks for the 2030 Agenda for sustainable development and the Paris Agreement. **Sustainability in Debate**, v. 13, n. 3, p. 32–71, 2022. Available at: https://doi.org/10.18472/SustDeb.v13n3.2022.45621

SUPERINTENDÊNCIA DE ESTUDOS ECONÔMICOS E SOCIAIS. **Piauí em Números**, 11. ed. Teresina: Cepro, 2019.

UNITED NATIONS. **Transforming Our World**: the 2030 Agenda for Sustainable Development United Nations. New York: UN, 2015.

WORLD BANK. **Report: Covid-19 Slows Progress Toward Universal Energy Access**. Washington: World Bank: 2023. Available at: https://www.worldbank.org/en/news/press-release/2022/06/01/report-covid-19-slows-progress-towards-universal-energy-access. Accessed on: July 2023.