SOLAR-ENERGY-BASED TECHNOLOGIES FOR FAMILY AGROINDUSTRIES: APPLICATIONS BEYOND NATURAL PROCESSES IN PIAUÍ, BRAZIL

Tecnologias com energia solar para agroindústrias familiares: aplicações além dos processos naturais no Piauí-Brasil

Osvaldo Augusto Vasconcelos de Oliveira Lopes da Silva

Electrical Engineer. PhD in Development and Environment. Federal Institute of Education, Science, and Technology of Piauí, Teresina Central Campus, Department of Industry, Safety, and Cultural Production, Praça da Liberdade, 1597, Bairro Centro, Teresina-PI, CEP: 64000-040. osvaldo.augusto@ifpi.edu.br

Eugenia Cornils Monteiro da Silva

Production Engineer. PhD in Mechanical Sciences. University of Brasília, Faculty of Technology, University of Brasília. Asa Norte, Brasília. CEP: 70.910-900. eugeniacornils@gmail.com

Raimundo Batista dos Santos Junior

Political Scientist. PhD in Political Science. Federal University of Piauí, Ministro Petrônio Portella University Campus, Center for Human Science and Letters, Bairro Ininga, Teresina-PI. CEP: 64049-550. rjunior@ufpi.edu.br

Marcos Antônio Tavares Lira

Electrical Engineer. PhD in Development and Environment. Federal University of Piauí, Ministro Petrônio Portella University Campus, Center for Technology, Bairro Ininga, Teresina-PI. CEP: 64049-550. marcoslira@ufpi.edu.br

Resumo: A agroindústria familiar configura-se como estratégia de reprodução e fortalecimento da agricultura familiar e a utilização da energia solar para além dos seus processos naturais tem grande potencial de inserção e fortalecimento dessas ações através de sistemas de aquecimento e de geração de energia elétrica. Dessa forma, este artigo tem o objetivo avaliar estratégias para a implantação de tecnologias de energia solar aplicáveis à agroindústria familiar, utilizando como objeto de estudo o estado do Piauí. Utilizando-se os territórios de desenvolvimento do estado como unidade de análise, identificou-se os territórios com maior déficit de acesso à energia nos estabelecimentos agropecuários, assim como seu principal produto da agroindústria familiar, levantando-se a demanda de energia elétrica por meio de pesquisa bibliográfica e visita de campo. A partir de uma abordagem *botton-up*, identificou-se que os saberes tradicionais do seu processamento já se utilizam de energia solar e propôs-se para as casas de farinha, tecnologias que integram a agroindústria familiar e energia solar, alinhadas com a realidade local, destacando-se integrações para iluminação artificial, bombeamento de água e força motriz.

Palavras-chave: Agricultura familiar, Sistema fotovoltaico, Farinha de mandioca, Casa de farinha

Abstract: Family agroindustry is a strategy for the dissemination and strengthening of family farming. The use of solar energy besides its natural processes has great potential for integrating and strengthening these actions through heating systems and electricity generation. Thus, this article aims to evaluate strategies for implementing solar energy technologies applied in family agroindustry, adopting the state of Piauí in Brazil as a case study. Considering the state's development territories as the units of analysis, the locations with the greatest deficit in access to energy in agricultural establishments and the main products of family agroindustry were identified from a thorough literature review and field visits, including the electricity demand. Adopting a bottom-up approach, the study identified that traditional local practices already incorporate solar energy. Thus, technological approaches for integrating family agroindustry and solar energy were proposed for cassava flour mills considering the particular characteristics of the assessed sites, including applications concerning artificial lighting, water pumping, and motive power.

Keywords: Family farming, Photovoltaic systems, Cassava flour, Cassava flour mills.

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1 INTRODUCTION

Through the 2030 Agenda, in September 2015, the member countries of the United Nations once again agreed to eradicate hunger, while also committing to, among other objectives, making access to electricity universal and increasing the share of renewable energy. Brazil is a signatory to this agreement and, in this country, the agribusiness is of great importance in the calculation of its Gross Domestic Product, with a significant share of family farming, which can contribute to sustainable development.

In this context, this sector stands out, since it is responsible for a large portion of the production of relevant food to the population diet, in addition to contributing to the majority of the insertion of workers in rural areas and corresponding to the vast majority of agricultural establishments in absolute terms. Furthermore, with the signing of this global agreement, there was also a commitment to double agricultural productivity and the income of small food producers and, within this scenario, prioritizing Family Farming.

Although the agricultural sector has a low share of the country's electricity consumption, the use of renewable energy in the means of production and in the activities of family agroindustry can strengthen family farming and stimulate its reproduction, with emphasis on the use of solar energy beyond its natural processes. Thus, in this context, the northeast region stands out as having the greatest potential for the use of this energy source, especially due to the great relevance of family farming and the great availability of solar resources.

Thus, this article aims to evaluate strategies for implementing solar energy technologies applicable to family agroindustry, using the state of Piauí as a case study. Located in the Brazilian Northeast region, Piauí has 80.3% of its agricultural establishments associated with family farming. Therefore, the development of this research can contribute significantly to the development of innovative technologies and comply with the goals of Agenda 2030. This is because, although socio-environmental impacts manifest on a global scale, they become more noticeable at the local level, where mitigation actions are most effective.

2 THEORETICAL BASIS

Sustainable development can be understood as a set of processes and actions that should be conceived from a global perspective and executed at national, regional, and local levels, enabling the entire planet to develop equally, without one part advancing at the expense of others. Therefore, committed to universalizing access to energy, increasing the share of renewable energies, doubling the global rate of energy efficiency, and reinforcing international cooperation in research and technology transfer related to energy consumption and generation, the member countries of the United Nations (UN) signed the 2030 Agenda in September 2015. It consists of a global cooperation agreement comprising 17 Sustainable Development Goals (SDGs) and 169 targets to be pursued over the subsequent 15 years (UN, 2015).

Population growth and, primarily, economic development generate an increased demand for electrical energy, which must be met through increased energy efficiency and the construction of new power plants, with the latter option causing significant socio-environmental impacts. In Brazil, the percentage of renewable energy sources in its energy mix (47.4% in 2022) represents more than three times the percentage of these sources in the global energy mix (14.1% in 2020) (EPE, 2023). However, there is still a need to expand this scenario aiming to achieve the commitments of Agenda 2030. The Brazilian energy mix has a significant penetration of hydroelectric generation, which is a renewable energy source whose expansion could be encouraged. However, hydropower plants cause significant socio-environmental impacts associated with the implementation process. Thus, other renewable energy sources, such as wind and solar, have been gaining prominence while presenting the highest increments in the Brazilian matrix from 2022 to 2023 in absolute and relative terms.

Another relevant issue is the universalization of access to electrical energy, which has not yet been consolidated. In 2010, 84% of the world's population had access to electricity, but this index increased to 91% in 2020. However, it is estimated that 660 million people will still lack access to this asset in 2030, thus implying harmful impacts on health, productivity, and life quality (World Bank, 2023). In Brazil, universal access to electrical energy reaches 99.5% of the population, and although it presents better indicators compared to other public services such as water distribution (85.5%), sanitary sewage system (69.5%), and household garbage collection (92.2%) (IBGE, 2024), access to electricity must reach the entire population to ensure welfare, this being a problem that affects rural areas in particular (Leduchowicz-Municio, 2022).

It is estimated that agribusiness accounts for 24.1% of the Brazilian Gross Domestic Product (GDP) in 2023(CEPEA, 2024), withing the agricultural sector being responsible for 4.8% of all energy consumption in the country (EPE, 2023). Ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture are also commitments made by the Agenda 2030 (SDG 2), whereas one of its respective goals consists of doubling agricultural productivity and income for small food producers (UN, 2015). Within this scenario, priority is given to family farming, which accounts for 67% of the workforce in the sector at the national level in Brazil. It represents 77% of agricultural establishments and is responsible for a significant portion of the production of goods essential to the population's diet, such as cassava, coffee, banana, and beans (accounting for 80%, 48%, 48%, and 42%, respectively), for example (IBGE, 2019).

Despite its relevance, the participation of family farming in Brazil has been decreasing. The use of renewable energies in such activities has the potential to increase the autonomy of families involved, as well as enhance existing social technologies in Brazilian rural communities (Ortiz-Rodriguez *et al*, 2022). In Brazil, a family farmer is considered to be a rural family entrepreneur who engages in activities in rural areas, on land of up to four fiscal modules (a unit of measurement in hectares, defined by the Brazilian government for each municipality based on its agricultural activity, ranging from five to 110 hectares), utilizes family labor, and has family income linked to the establishment itself, in turn managed by the family (Brasil, 2006).

In this sense, family agroindustry establishes itself as a strategy for the reproduction and strengthening of family farming. It is understood as a form of organization in which the family farmer transforms agricultural production, contributing to the income generation of family members and stimulating the creation of markets for local products, thus providing economic sustainability and preserving local culture (Besen; Pelin; Andrade, 2020). Family agroindustry aims mainly at value addition while requiring strategic vision in the adoption of new technologies for its development (Schaeffer *et al*., 2021).

Thus, the use of solar energy, beyond its natural processes, has great potential for integration and strengthening of these actions through heating systems and electricity generation (Ortiz-Rodriguez *et al*., 2022) (Viana *et al*., 2019) (Verma *et al.*, 2021). In Brazilian rural areas, photovoltaic solar energy can be used for everyday activities such as lighting, food refrigeration or water consumption (Martin *et al.*, 2023) (Chowdhury; Naz, 2023), and also for agricultural activities such as irrigation or supplying water to animals (Gunasekaran; Chakraborty, 2023) (Gevorkov *et al*., 2023), or even in the processing of products in the agro-industry (Queiroz and Brito, 2020).

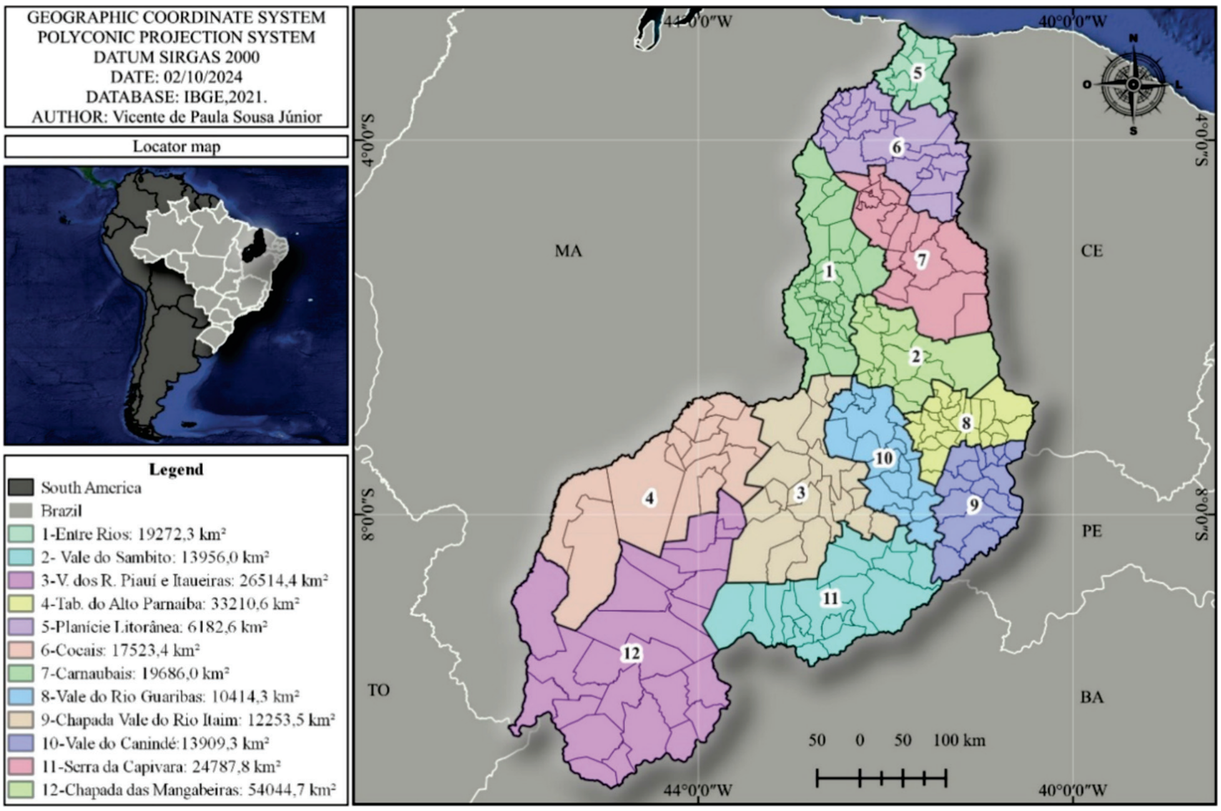
This is mainly due to the high availability of solar resources, whereas Brazil has a daily average of 5.15 kWh/m² (Global Horizontal Solar Irradiation), a level superior to that of leading countries in this type of generation, especially in Europe (Pereira et al., 2017). In the national context, the Northeast region has the highest irradiation average (5.48 kWh/m²) and lower interannual variability, with extreme values between 5.39 and 5.59 kWh/m², and 50% of annual averages within the range between 5.43 and 5.50 kWh/m² (Pereira et al., 2017). These indices highlight its potential compared to other regions of the country.

3 METHODOLOGY

The state of Piauí is divided into 12 development territories with various potentialities, among which agriculture stands out according to Figure 1. In the last agricultural census, a total of 245,601 agricultural establishments were identified in the state, with an average area of 40.76 hectares, of which 38.49% is meant for family farming, corresponding to an irrigated area of 3.33% and an annual agro-industrial production of R$118.74 million (IBGE, 2019). However, a low human development index (HDI) was observed in the state, that is, corresponding to 0.541 (UNDP, 2023) (Silva *et al.*, 2030). Thus, given the importance of family farming and agroindustry for its strengthening, the insertion of the latter activity in the state was initially identified, as well as the most relevant products for family agroindustry, adopting development territories as the units of analysis.

Considering an average daily global horizontal irradiation of 5.71 kWh/m² in Piauí municipalities, that is, 4% higher than the regional average (Pereira et al., 2017), the installation of 29,457 grid-connected photovoltaic generation systems was also observed, with an average power of 10.12 kW/system. In turn, rural systems represent 1.76% and 3.32% in the number of systems and installed power, respectively (ANEEL, 2023) (Silva *et al.*, 2023). On the other hand, a large portion of Piauí's agricultural establishments still lacks access to electricity, corresponding to an average of 18.54%). This lack of infrastructure is likely to affect citizenship and health issues, productivity, and quality of life (Leduchowicz-Municio, 2022) (Brazil, 2019). Thus, the use of renewable energy sources, the great potential for the use of solar energy, and the existence of rural photovoltaic energy generation systems already installed in the state can improve this condition. In this sense, it was checked which development territory has the highest percentage of agricultural establishments without access to this asset, as well as their main family agroindustry activity to develop a thorough analysis of the state's conditions.

Figure 1 – Development territories of the State of Piauí



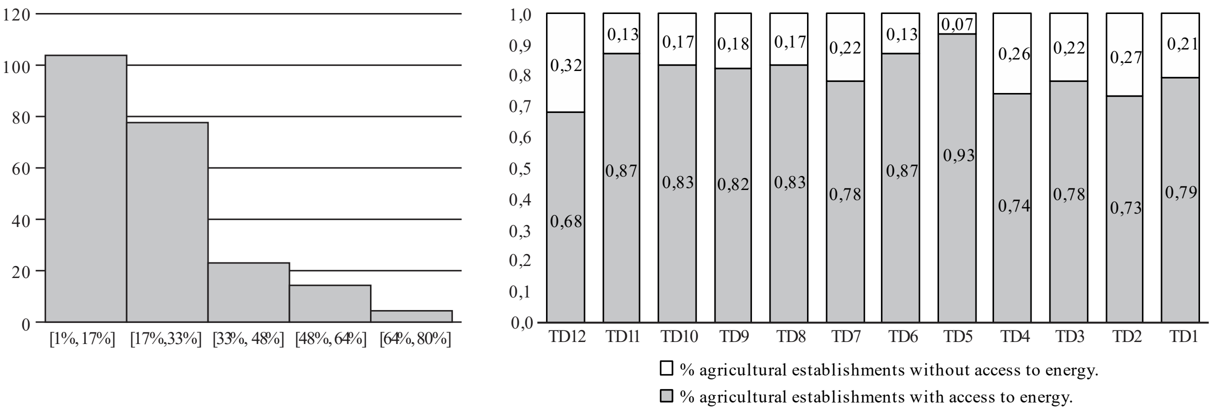
Source: Prepared by the authors from data provided by IBGE (2019, 2021).

Based on this diagnosis, the demand for electricity in this activity was assessed based on booklets prepared by the Brazilian Agricultural Research Corporation (EMBRAPA) and through technical visits to a local family agroindustry. In this sense, technological solutions were proposed for this activity aiming at integrating family agroindustry and solar energy in alignment with the local reality. A bottom-up approach was used to propose solutions for integrating standalone photovoltaic systems based on the identification of input and service flows. Finally, it is worth noting that this territorial approach was also used by Freitas et al. (2021), who evaluated the capacity for productive interaction among Piauí residents based on the spatiality of patent production from public research institutions. In addition, Morais et al. (2020) suggest that this approach is especially useful for assessing the potential of family farming in the state. It is, therefore, a quantitative and qualitative research, because it is structured with statistical data and uses field visits for a deeper understanding of the research problem.

4 RESULTS AND DISCUSSION

The universal access to electricity is a global commitment of the Agenda 2030. However, it constitutes a challenge in the state of Piauí, especially in rural areas. Among 223 municipalities in the state, 32.73% have more than a quarter of agricultural establishments without access to electricity, and in 7.63% of them, the lack of access to this infrastructure affects more than half of the establishments (Figure 2a). Palmeirais, located in the Entre Rios Territory, stands out, where almost eight out of 10 establishments do not have access to this asset (79.60%). In this context, this territory also stands out with the highest number of establishments without access to energy in absolute terms (7,674 establishments). The Chapada das Mangabeiras territory is also relevant in this scenario for it represents the greatest problem regarding this infrastructure in proportional terms (32.00%) (Figure 2b) (IBGE, 2019).

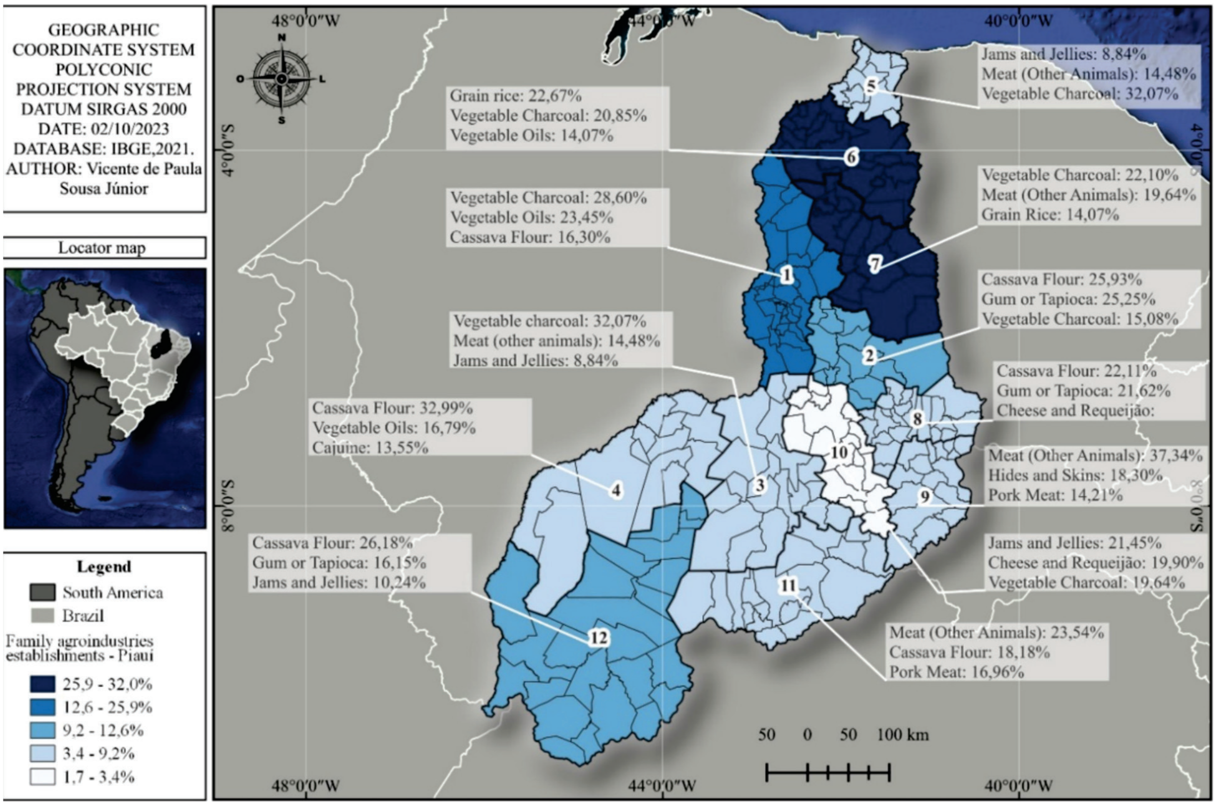
Figure 2 – Clustering of municipalities in terms of the percentage of agricultural establishments without access to electricity in Piauí (a), left figure, and percentages of agricultural establishments without access to electricity in the development territories of the state of Piauí (b), right figure



Source: prepared by the authors from data provided by IBGE (2019).

Considering the significant presence of family farming in the state (80.31% in relation to the number of agricultural establishments), it was observed that 37,484 Piauí agricultural establishments are directly involved in family agroindustry activities, among which 83.05% are owned by family farmers (IBGE, 2019). Family agroindustry promotes the strengthening of family farming, promoting economic sustainability, and preserving local culture (Besen; Pelin; Andrade, 2020) (Schaeffer *et al.*, 2021). The products processed in these establishments are intended for self-consumption and local trade. Thus, Piauí family farmers generated the equivalent of R$80.66 million in 2017, with 45.23% of the products intended for sale. Each territory has a specific production potential, with cassava flour, charcoal, and paddy rice standing out as the products with the highest production percentages with respect to the total production value of the state (14.83%, 9.54%, and 8.64%, respectively). Furthermore, considering the contribution of agroindustry, activities that benefited the largest number of agricultural establishments in proportional terms were listed in each of the territories (Figure 3).

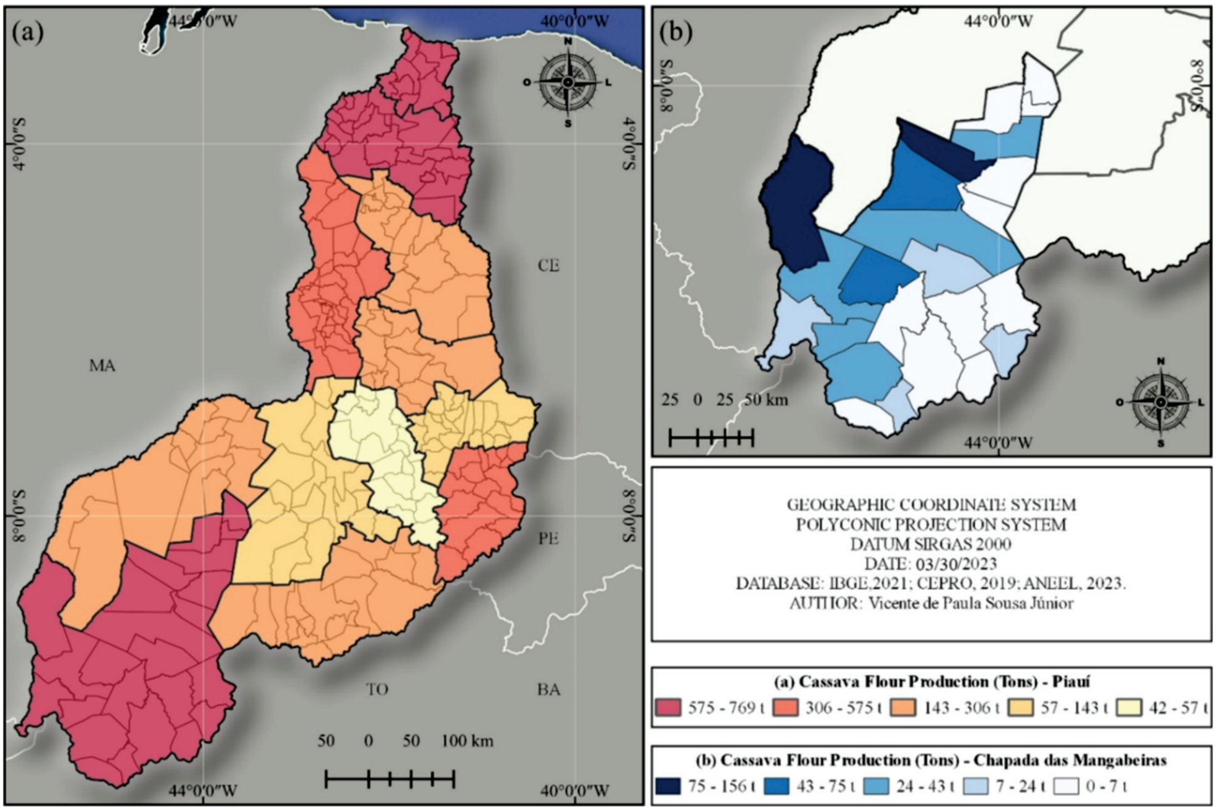
Figure 3 – Family agroindustry in the state of Piauí



Source: prepared by the authors from data provided by IBGE (2019, 2021).

The Chapada das Mangabeiras territory was chosen for the assessing strategies used in the implementation of solar energy technologies and application to family agroindustry, as it has the highest deficit in universal access to energy. With 24 municipalities, an average area of 2,251.86 km² per municipality, and 17,596 agricultural establishments (77.73% involved in family farming and 12.51% associated with family agroindustry), this activity generated R$9.78 million, with 56.46% destined for local trade (IBGE, 2019). Cassava flour, tapioca, or starch, as well as candies and jams, are the products with the greatest insertion in the family agroindustry of this territory. In particular, candy production is present in 26.18% of the establishments (average production of 23.96 tons per municipality). For this reason, following the proposed methodology, this first activity was selected for this study. The municipalities of Manoel Emídio and Santa Luz stand out with no production, while the municipality of Santa has the highest cassava flour production in the territory (27.13%) (Figure 4). Furthermore, starch and tapioca are usually considered byproducts of cassava flour (Oliveira et al., 2019). Thus, strengthening flour production also encourages the production of other derivatives, which are highly relevant to local markets and represent the second main activity for family agroindustry in this territory (16.15%) (Figure 4).

Figure 4 – Cassava flour production from family agroindustry in Piauí and in the Chapada das Mangabeiras territory



Source: prepared by the authors from data provided by IBGE (2019, 2021).

Cassava (*Manihot esculenta*), also known as bitter cassava, is a tuber with a high starch content, native to Latin America (the Amazon region), which has been cultivated by indigenous peoples since pre-Columbian times. However, disseminated by European traders, it is now also produced in other countries in Asia and Africa, the latter continent currently accounting for more than 50% of global production, Cassava is a highly energetic food for the world's population, especially underdeveloped countries, being primarily cultivated by small-scale producers in limited areas with low productivity (Akano; Oderinde; Omotayo, 2023) (FAO, 2016). In Latin America, Brazil is the leading producer, accounting for over three-quarters of production. The northern region represented 36.2% of national production in 2017, followed by the southern, northeastern, southeastern, and central-western regions (25.8%, 20.0%, 10.9%, and 7.0%, respectively) (IBGE, 2019). Therefore, the worldwide relevance of cassava for achieving the UN's SDGs, especially in combating hunger (SDG 2) is evident, mainly in underdeveloped countries. This is true in the Brazilian case, specifically in the neediest regions, whereas the northern and northeastern regions stand out as the main consumers of this product.

Starch is stored in their roots in all cassava species. However, these roots contain toxic components in different concentrations, which allow for the classification into sweet or bitter cassava. Sweet cassava (also known as manioc or yucca) can be consumed fresh or processed, while bitter cassava must be processed to reduce its toxicity. In this work, we will focus on the latter type, which will be referred to simply as cassava and is characterized as an input, whose transformation into flour traditionally occurs in flour mills.

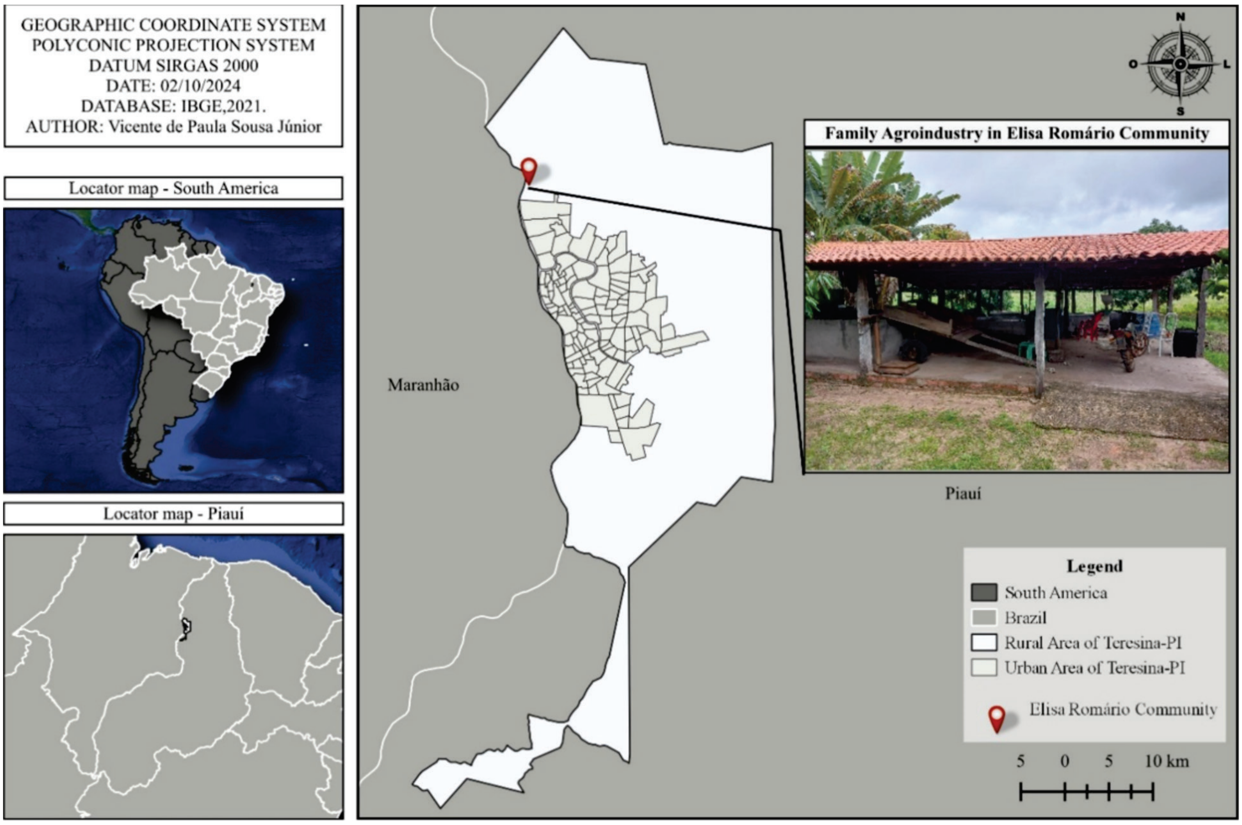
These establishments are classified as traditional (manual processing and rustic utensils), semi-mechanized (introduction of some machines powered by diesel, gasoline, or electricity), or mechanized (fully mechanized process), depending on the technological level employed. In these facilities, the most common cassava processing methods are maceration, dissolution or soaking in water, boiling, roasting or fermentation, or a combination of the aforementioned processes, resulting in various products. Thus, cassava derivatives include table flours (white, yellow, gum, or water), gum (starch), puba flour (obtained in the same way as gum, but using fermented cassava), and tucupi, the latter traditionally consumed only in the northern region of Brazil (Oliveira *et al*., 2019). Therefore, one can state that these processes consist of traditional knowledge that is primarily passed down from parents to children and strengthens family farming.

Inserted in all territories of the state (Figure 4), cassava flour production is present in 64.73% of the municipalities. As previously mentioned, it still corresponds to the main product of family agroindustry in the state in terms of added value (14.83%). Thus, for the introduction of solar energy technologies in rural areas, a family agroindustry located in the rural area of Teresina city was chosen as the study object (Figure 5) (22.4 km from the city's zero milestone). Being the capital of the state and located in the Entre Rios territory, Teresina was characterized from technical visits conducted in March 2023 (rainy season in the region). The semi-mechanized flour mill is located in the Elisa Romário Community and was installed in 2017, with an initial investment of R$15,000. It is owned by the Teresina residents João Alves de Lima and Maria das Dores de Sousa Lima (85 and 76 years old, respectively), who live in a house located on a separate lot and 20 m away from the studied agricultural establishment. The property has two hectares and the agroindustry is managed by the couple using family labor. It serves ten families belonging to the community and the population of the region, which in turn provides the cassava to be processed. The producers are remunerated in cash or with part of the processed product.

The family reported that traditional knowledge passed down from parents to children has been of great importance, However, the agricultural establishment, which has access to bank financing, also benefits from technical assistance provided by the municipal and state governments. This is a privileged scenario that comprises only 2.85% of the agricultural establishments in the state (IBGE, 2019). Bananas, mango, acerola, corn, beans, and cassava are produced on the property, in addition to the cassava processed in the flour mill. All products are primarily intended for self-consumption, and the family agroindustry produced 1,500 kg of white flour and 800 kg of cassava gum in 2022. However, a decrease in production was expected for 2023, since the families in the region prioritized the production of sweet cassava instead, which has a shorter production cycle (six to eight months). This is a more suitable choice for the region owing to the irregular distribution of rainfall, which allows for greater crop rotation. However, it is possible to intercrop cassava with other crops such as corn and beans, thus increasing efficiency in land use (Nwokoro *et al.*, 2022) (Batista *et al.*, 2022).

Cassava is mainly cultivated in the tropics. The ideal temperature range and rainfall regime for this purpose are between 20 °C and 27 °C and between 1,000 and 1,500 mm per year, considering a regular distribution, respectively. In the driest regions (with lower rainfall indices) and irregular rainfall distribution, such as the Brazilian Northeast region where the studied agroindustry is located, and in African countries, the world's largest producers and consumers, respectively, the main problem for cassava cultivation is water scarcity. This issue requires planting adaptation according to the rainy season or even irrigation of crops, which may cause a drastic reduction in production (Sousa; Silva, 2020). Although cassava cultivation is predominantly rainfed, with planting during the rainy season to favor root development at the beginning of the production cycle, cassava crop irrigation has been used. This technique has the potential to increase yield, tuber quality, and land use efficiency, reducing production time and providing greater flexibility in farm management, with benefits extended to intercropping. However, it must be planned according to the characteristics of each region and the availability of water resources. Sprinkler irrigation is the most used resource owing to its flexibility for intercropping irrigation but at the expense of lower water use efficiency (Silva, *et al.*, 2022) (Coelho Filho, 2020).

Figure 5 – Family agroindustry producing cassava flour in the state of Piauí



Source: prepared by the authors from data provided by IBGE (2019, 2021).

Therefore, it is necessary to encourage the intercropping of cassava with other short-cycle crops that provide greater food security for families. Depending on the characteristics of each region and the availability of water resources, the installation of irrigation systems focused on water use efficiency is also a must. On the farm, cassava planting is done traditionally with “manivas” (small stakes made from the plant’s stem) arranged in rows with a width of one meter and a distance of 30 cm between them, with a production cycle of approximately one and a half years, using a sprinkler irrigation system activated during dry periods. The water used comes from a tubular well with a flow rate of 58,000 l/h and a depth of 100 m, using a 20-HP pump operated by the municipal government that serves the entire community, but not exclusively.

In the studied family agroindustry, white flour and cassava starch are produced simultaneously (coproduction system) during June, July, and August. The process begins with the manual peeling and washing of cassava, which is subsequently crushed in a machine powered by a 3-HP three-phase electric motor (Figure 6a). The crushed cassava is then deposited on a stretched fabric supported by wooden stakes over concrete tanks for washing with water and, from this stage, the production of flour and starch become different processes (Figure 6b). For flour production, the crushed and washed cassava is wrapped in the fabric, with the ends tied, and taken to a manual press to remove excess moisture (Figure 7a). Then, the dry cassava is roasted in an open oven that is manually operated with the aid of a large-handled wooden paddle, since the cassava must be constantly stirred. In addition, it is noteworthy that the oven is fueled by biomass (wood collected in the local region) (Figure 7b)

Figure 6 – Electric cassava crusher (a), left, and motor identification plate (b)

Source: Prepared by the authors.

Figure 7 – Concrete tanks with stakes for washing cassava (a), left, and oven for roasting cassava flour and cooking tapioca (b)

Source: Prepared by the authors.

For the production of starch, the mixture of water with the residue from cassava washing after crushing is placed in tanks and left to settle overnight. After manually removing the water, the starch is spread on a tarpaulin stretched over a slab (Figure 8a) (Rayssa *et al.*, 2021). It is then left to dry in the sun, justifying the operation of the flour mill during the dry season only and showing that traditional knowledge already makes use of solar irradiation in the production process. Both products are consumed year-round, so after roasting, the white flour is weighed on a mechanical scale (Figure 8b) and packaged in 30-kg bags. Once dried, the starch is also weighed and packed in 40-kg bags or, alternatively, it can be cooked in the oven to produce "beiju" or tapioca for immediate consumption. However, during months when cassava processing does not occur, the infrastructure of the flour mill is also used. It allows for the storage of complementary production (such as corn and beans) and processing of fodder for animal feed, also serving as a breakroom. Furthermore, it is noteworthy that adopting good production practices is a must as claimed by EMBRAPA. Thus, one can ensure good quality and food safety of products regarding infrastructure, equipment, utensils, handlers, production, transportation, and documentation (Rayssa *et al.*, 2021).

Figure 8 – Slab for drying cassava starch (a), left, and mechanical scale for weighing (b)

Source: Prepared by the authors.

The electrical energy supply to the agroindustry consists of a three-phase system (220 V/380 V). Analyzing the last energy bills, an average energy consumption of only 1.54 kWh/month was identified. The low energy consumption could indicate good efficiency. However, although its artificial lighting system is efficient, the driving force used has low efficiency. In addition to the 3-HP, four-pole, three-phase motor with an efficiency of 85.1% used for cassava crushing, other equipment also consumes electrical energy in the flour mill: three 15-W fluorescent lamps (turned on only at night) and a forage crusher for animal feed and coconut oil production, powered by a 7.5-HP, two-pole, three-phase motor with an efficiency of 86.7%. The International Electrotechnical Commission (IEC) classifies three-phase induction motors according to the efficiency based on the rated power and number of poles as IE1 (standard efficiency), IE2 (high efficiency), IE3 (premium efficiency), and IE4 (super premium efficiency). The first motor belongs to the IE2 efficiency class, while the second motor is classified as IE1 (IEC, 2014). Therefore, one can state that the motors have a low performance since the minimum efficiency for motors to be marketed in Brazil must be IE3 as of 2021 (Souza *et al.*, 2022).

Electricity utilities must bill residential consumers for the highest value obtained from either active power consumption or the availability cost tariff, which is equivalent to 30 kWh, 50 kWh, or 100 kWh, for single-phase, two-phase, or three-phase installations, respectively (BRASIL, 2021). Therefore, even with such a low consumption, the unit must pay for the minimum monthly consumption of 100 kWh. Therefore, it is recommended for the agricultural establishment to replace the three-phase motors with lower power and single-phase motors with a higher efficiency. In addition, changing the energy supply to a single-phase system (220 V) would yield a monthly saving that could make the replacement of motors feasible. However, special care must be taken in selecting single-phase motors, since minimum efficiency standards are not established for such devices in Brazil (*Souza et al.*, 2022).

In the state of Piauí, the main driving factor for the installation of grid-connected photovoltaic microsystems in rural areas is the presence of irrigation systems (Silva *et al*., 2023), which also exist in the assessed agricultural establishment. Furthermore, the electricity supply by the local utility enables the installation of grid-connected photovoltaic systems in the facility. Moreover, the processes that require electricity (artificial lighting, water pumping, cassava crushing, babassu coconut processing, and forage production for animal feed) also allow for the installation of standalone photovoltaic systems. However, even with the existence of 505 rural photovoltaic systems connected to the utility grid (1.76% of the total systems in the state), installed in 138 municipalities of Piauí (61.16%), with an average power of 12.69 kW/system (ANEEL, 2023), the low energy consumption in this specific agroindustry does not make installation feasible (Morais *et al.*, 2021).

However, lack of access to electrical energy and high energy consumption may make the installation of such systems feasible in other locations, reducing energy poverty and becoming an alternative for universal access, strengthening family farming, and positively contributing to the objectives of Agenda 2030. Traditionally, standalone photovoltaic systems rely on using battery banks that require a high initial investment and have a short lifespan. Thus, for artificial lighting, commercial light-emitting diode (LED) lamps can be used. Such devices are simple, easy to install, and cost-effective, while also reducing risks associated with inhaling toxic gases and fire from the burning of lamp fuels (Martin *et al.*, 2023) (Chowdhury; Naz, 2023).

As for water collection aimed at irrigation systems and processing inputs in agroindustry, as well as human and animal consumption, the use of solar pumping systems connected to an elevated reservoir is proposed to provide autonomy and replace battery banks, this being an alternative well-established in the photovoltaic market (Gunasekaran; Chakraborty, 2023) (Gevorkov *et al*., 2023). As an alternative to energy storage systems, the use of high-efficiency induction motors connected directly to a solar inverter is also suggested. The motors can be powered directly by the photovoltaic modules, which can even be integrated into the pumping system (Pena *et al*., 2022) (Feijão; Almeida; Brito, 2022). Queiroz and Brito (2020) evaluated the feasibility of this type of system for a cassava crusher. Good results were obtained considering the availability of 200 Wp of solar irradiation. Another possibility consists of using the same photovoltaic generator for pumping systems when the crusher is not active. This is an innovative solution, as such devices were initially designed for the industrial environment for controlling the speed of alternating current motors. Later, they were adapted for a direct connection to the photovoltaic generator aiming to supply water pumping systems.

5 CONCLUSION

The agricultural sector accounts for around a quarter of the Brazilian GDP. In this scenario, family farming stands out. This activity is associated with 77% of Brazilian agricultural establishments, corresponding to 67% of the sector's workforce and being responsible for supplying a large part of the Brazilian diet. The state of Piauí has a great vocation for this type of production. Although it has high solar irradiation levels and several rural micro and mini photovoltaic solar energy systems installed, a large portion of its agricultural establishments do not have access to electricity.

Thus, adopting Piauí as the object of study and using its development territories as units of analysis, it was possible to assess the integration of photovoltaic solar energy and family agroindustry as strategies for strengthening family farming, increasing access to electricity and reducing poverty, as well as contributing to Agenda 2030. Family agroindustry emerges as a strategy for the reproduction and strengthening of family farming, stimulating the creation of markets for local products, providing economic sustainability, preserving local culture, and adding value while requiring the integration of technologies for its development.

The universal access to energy is a global commitment. However, it poses a challenge, especially in underdeveloped countries and, particularly, in rural areas. Increasing the use of renewable energy sources is also one of the goals of Agenda 2030, which can contribute to universal access to electricity. Thus, owing to the high availability of solar resources and the existence of various systems already installed in rural areas, the use of solar energy beyond its natural processes has great potential for the integration and strengthening of family agroindustry and family farming through heating and electricity generation systems.

Cassava is a highly energy-rich food. Even though it is a tuber that originated in Latin America (Amazon region), it is strongly present in the diet of the world population, especially in countries in Asia and Africa. It is often cultivated by small producers in small areas with low productivity, having great relevance in fighting hunger at a global level. Thus, the material and energy flows of cassava processing were assessed in this work. It was observed that traditional knowledge of its processing already incorporates the use of solar energy. In addition, the main demand for electrical energy arises from the crushing process and irrigation of crops. The latter is necessary to increase yield, tuber quality, and land use efficiency, reducing production time and providing greater flexibility in the management of the agricultural establishment, with benefits extended to intercropping. Therefore, both the aforementioned processes require taking action for the improvement of energy efficiency, especially through the use of motors with a higher efficiency, as well as the use of renewable energy sources.

Flour mills may lack access to electrical energy supply from local energy utilities, thus requiring the implementation of structural projects. Alternatively, when this asset is readily available, there is the possibility of installing grid-connected photovoltaic systems, which requires a proper feasibility study. However, in either case, standalone photovoltaic systems can be installed, thus contributing to ensuring access to electricity and reducing energy poverty. It is therefore recommended to use LED lamps associated with photovoltaic generators and energy storage systems, thus enabling artificial lighting and contributing to reducing the emission of harmful gases and the risk of fire resulting from the burning of lamp fuels.

The use of solar pumps and elevated reservoirs has been suggested for water collection aimed at irrigation systems, processing inputs in agroindustry, and human and animal consumption. They should be properly sized to provide autonomy while not requiring energy storage systems. Finally, the use of solar inverters is proposed, whereas power crushers or other multi-use motors could be directly connected to the inverters in rural areas. These systems can benefit from other applications when not used for cassava processing, either integrated or not with solar pumping systems. Therefore, it proves to be an innovative solution, since this technology was not developed for this specific purpose.

REFERENCES

AKANO, O. I.; ODERINDE, F. O.; OMOTAYO, A. O. Agricultural yield, food nutrition and dietary energy supply in Nigeria: Evidence from nationally representative data. **Journal of Agriculture and Food Research**, v. 11. 2023. https://doi.org/10.1016/j.jafr.2023.100525.

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

______. **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, 2021. Available at: https://www.in.gov.br/en/web/dou/-/resolucao-normativa-aneel-n-1.000-de-7-de-dezembro-de-2021-368359651 Accessed: Jan. 2024.

BATISTA, N. S.; FERREIRA, J. R.; LATAWIEC, A. E.; SILVA, C. S. R. A.; GUERRA, J. G. M.; ESPÍNDOLA, J. A. A.; JESUS, E. C.; JESUS, E. C.; ARAÚJO, E. S. O cultivo da mandioca em consorcio aumenta a eficiência do uso da área. In: DIAS, A. (org.). **Ensino, pesquisa e extensão em Agroecologia e Agricultura Orgânica:** dez anos do Programa de Pós-Graduação em Agricultura Orgânica. Seropédica: PPGAO, 2022. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1148240/o-cultivo-da-mandioca-em-consorcio-aumenta-a-eficiencia-do-uso-de-area Accessed: Jan. 2024.

BESEN, F.; PLEIN, C.; ANDRADE, M. Family agroindustry as a family farming reproduction strategy. **Emancipação**, v.19. 2020. Available: https://revistas.uepg.br/index.php/emancipacao/article/view/14576. Accessed: Jan. 2024.

BRASIL. **Lei Nº 11.326, de 24 de julho DE 2006**. Estabelece as diretrizes para a formulação da Política Nacional da Agricultura Familiar e Empreendimentos Familiares Rurais. Brasília, 2006. Available at: https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2006/lei/l11326.htm. Accessed: Jan. 2024.

CEPEA - CENTRO DE ESTUDOS AVANÇADOS DE ECONOMIA APLICADA. **PIB do Agronegócio Brasileiro**. São Paulo: USP, 2024. Available at: https://www.cepea.esalq.usp.br/br/pib-do-agronegocio-brasileiro.aspx. Accessed: Jan. 2024.

CHOWDHURY, A.; NAZ, A. Reducing energy poverty, carbon footprint, human health risk and achieving the sustainable development goals, by use of solar lamps at Indian Sundarbans. **Materials Today:** Proceedings. 2023. https://doi.org/10.1016/j.matpr.2023.06.032.

COELHO FILHO, M. A. **Irrigação da cultura da mandioca.** Cruz das Almas: EMBRAPA, 2020. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1121941/irrigacao-da-cultura-da-mandioca Accessed: Jan. 2024.

EPE - EMPRESA DE PESQUISA ENERGÉTICA. **Brazilian Energy Balance**. Brasília, 2023.

FAO - FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. **Cassava in the Caribbean Region** - A look at the potential of the crop to promote agricultural development and economic growth. Bridgetown: UN, 2016.

FEIJÃO, A. T.; ALMEIDA, A. M. G.; BRITO, A. U. Photovoltaic acai (Euterpe oleracea Mart.) berry juice extractor machine. **Journal of Physics**: Conference Series, v. 2180, 2022. https://doi.org/10.1088/1742-6596/2180/1/012004.

FREITAS, R. A. B.; OLIVEIRA JUNIOR, A. M.; BUENO, P. H. C.; MORAIS, M. A. C.; MELO, H. C. S.; COSTA, D. L. V. Patentes e espaço geográfico: Uma análise espacial do território piauiense. **Research, Society and Development**, v. 10, n. 9. 2021.

GEVORKOV, L., DOMÍNGUEZ-GARCÍA, L. J.; ROMERO, L. T. Review on Solar Photovoltaic-Powered Pumping Systems. **Energies**, v. 16, n. 94. 2023. https://doi.org/10.3390/en16010094.

GUNASEKARAN, V.; CHAKRABORTY, S. Technical and environmental aspects of solar photovoltaic water pumping systems: a comprehensive survey. **Water Supply**, v. 23, n.7. 2023. https://doi.org/10.2166/ws.2023.165.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo agropecuário 2017:** Resultados definitivos. Rio de Janeiro, 2019.

______. **Geociências -** downloads. 2021. Available at: https://www.ibge.gov.br/geociencias/downloads-geociencias.html Acesso: mar. 2023

______. **Pesquisa Nacional por Amostra de Domicílios Contínua Anual -** PNADC/A. 2024. Available at: https://sidra.ibge.gov.br/pesquisa/pnadca/tabelas. Accessed: Jan. 2024.

IEC - INTERNATIONAL ELECTROTECHNICAL COMMISSION. **IEC 60034-2-1:** Rotating electrical machines – Part 2-1: standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), 2ª edição. Paris, 2014. Available at: https://webstore.iec.ch/publication/121. Accessed: Jan. 2024.

LEDUCHOWICZ-MUNICIO, A.; LÓPEZ-GOZÁLEZ, A.; DOMENECH, B.; FERRER-MARTÍ, L.; UDAETA, M. E. M.; GIMENES, A. L. V.; Last-mile rural electrification: Lessons learned from universalization programs in Brazil and Venezuela. **Energy Police**, vol. 167. 2022. https://doi.org/10.1016/j.enpol.2022.113080.

MARTIN, T.; NANJEBE, D.; ATWINE, D. Assessment of the proportion of households with burn victims, associated risk factors and knowledge of burn injury prevention strategies in South Western Uganda. A population based cross sectional survey. **Burns,** v. 49. https://doi.org/10.1016/j.burns.2023.03.016.

MORAIS, F. H. M.; SILVA, O. A. V. O. L.; MORAES, A. M.; BARBOSA, F. R. **Energia solar fotovoltaica: fundamentos para análise de viabilidade técnico-econômica.** Teresina: EdUESPI, 2021. Available at: https://editora.uespi.br/index.php/editora/catalog/book/63 Accessed: Jan. 2024.

MORAIS, M. D. C.; SOUSA, A. M. B.; ARAÚJO, C. F. S. Agricultura Familiar no Piauí: uma leitura do censo agropecuário 2017. **Revista Econômica do Nordeste**, v. 51, p. 91-112, 2020.

NWOKORO, C. C.; KREYE, C.; NECPALOVA, M.; ADEYEMI, O.; BARTHEL, M.; PYPERS, P.; HAUSER, S.; SIX, J. Cassava-maize intercropping systems in southern Nigeria: Radiation use efficiency, soil moisture dynamics, and yields of component crops. **Field Crops Research**. v. 283. 2022. https://doi.org/10.1016/j.fcr.2022.108550.

OLIVEIRA, L. A.; MOTA, J. S.; JESUS, J. L.; SASAKI, F. F. C.; VIANA, E. S. **Processamento de aipim e mandioca-brava.** Brasília: EMBRAPA, 2019. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1117995. Accessed: Jan. 2024.

ORTIZ-RODRÍGUEZ, N. M.; CONDORÍ, M.; DURAN, G.; GARCÍA-VALLADARES; O. Solar drying Technologies: A review and future research directions with a focus on agroindustrial applications in medium and large scale. Applied Thermal Engineering. **Applied thermal engineering**, v. 215. 2022. https://doi.org/10.1016/j.applthermaleng.2022.118993.

PENA, A. G. L.; BRITO, A. U.; GUEDES, P. M. L.; MONTEIRO, F.; MALHEIROS, J. B.; MALHEIROS, F. B.; GUEDES, M. C.; DIAS JÚNIOR, A. F.; FRANÇOIS, D. E.; POGANIETZ, W.; PARMENTIER, M. J. Sistema fotovoltaico isolado de configuração mista para famílias ribeirinhas. **Revista Brasileira de Energia Sola**r, v. 13, n. 2. 2022. https://doi.org/10.59627/rbens.2022v13i2.399.

PEREIRA, E. B.; MARTINS, F. R.; GONÇALVES, A. R.; COSTA, R. S.; LIMA, F. J. L.; RÜTHER, R.; ABREU, S. L.; TIEPOLO, G. M.; PEREIRA, S. V.; SOUZA, J. G. **Atlas Brasileiro de Energia Solar**. 2. ed. São José dos Campos: INPE, 2017. http://doi.org/10.34024/978851700089.

PINHO, J. T.; GALDINO, M. A. **Manual de engenharia para sistemas fotovoltaicos**. Rio de Janeiro: CEPEL-CRESESB, 2014.

PNUD - PROGRAMA DAS NAÇÕES UNIDAS PARA O DESENVOLVIMENTO. **Atlas do Desenvolvimento Humano no Brasil**-Ranking. Brasília: PNUD, IPEA, FJP, 2023. Disponível: http://idhm.org.br/ranking. Accessed: Feb. 2023.

QUEIROZ, A. O.; BRITO, A. U. Direct Connection Photovoltaic System in multi-motor application for the rural sector. **Engenharia Agrícola,** v. 40, n. 3. 2020. http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v40n3p303-314/2020

SANTOS, R. S.; BRAGA, A. C. C.; FIGUEIREDO, E. L.; SILVA, N. S.; BRAGA, L. A. C. Hygienic-sanitary diagnosis and corrective measures in the processing of cassava flour. **Revista verde de agroecologia e desenvolvimento sustentável**, v.16, n. 3. 2021. https://doi.org/10.18378/rvads.v16i3.8309.

SCHAEFFER, S. M.; PADILHA, A. C. M.; SECCHI, M.; SOUZA, M. Inovações na produção e beneficiamento de chás: o caso da agroindústria familiar "Consórcio Santa Gema de Plantas Medicinais". **Espacio Abierto**, v. 30, n. 1. 2021.

SILVA, O. A. V. O. L.; MORAIS, F. H. M.; LOPES, W. G. R.; LIRA, M. A. T. Driving factors for the installation of mini and micro rural distributed generation systems: economic analysis - a case study in Piauí, Brazil. **Sustentabilidade em Debate**, v. 14, 2023. https://doi.org/10.18472/SustDeb.v14n2.2023.49414.

SILVA, R. B.; TEODORO, I.; SOUZA, J. L.; MAGALHÃES, I. D.; MORAIS, M. A. F.; TEODORO, I. P. O.; SILVA, J. C.; LOPES, J. H.; SANTOS, J. T.; ALMEIDA, B. V. L. R.; RAMOS, P. F. S.; GOIS, P. V. S.; CORDEIRO, L. R.; SANTOS JÚNIOR, J. C.; MARTINS, G. M. C.; SANTOS, W. M.. Growth, productivity and viability of irrigation in cassava crop in the Alagoas Coastal Plateaus. **Ciência Rural**, v.52, n.4. 2022. http://doi.org/10.1590/0103-8478cr20210145.

SOUZA, D. F.; SALOTTI, F. A. M.; SAUER, I. L.; TATIZAWA, H.; ALMEIDA, A. T.; KANASHIRO, A. G. An assessment of the impact of Brazilian energy efficiency policies for electric motors. **Energy Nexus**, v. 5. 2022. https://doi.org/10.1016/j.nexus.2021.100033.

SOUZA, L. D.; SILVA, A. F. **Sistema de produção de mandioca no Semiárido**. Cruz das Almas: EMBRAPA, 2020. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1131107/sistema-de-producao-de-mandioca-no-semiarido. Accessed: Jan. 2024.

UN - UNITED NATIONS. **Transforming our world**: the 2030 Agenda for Sustainable Development. Nova York, 2015.

VERMA, S.; MISHRA, S.; CHOWDHURY, S.; GAUR, A.; MOHAPATRA, S.; SONI, A.; VERMA, P. Solar PV powered water pumping system – A review. **Materials Today: Proceedings**, n. 46. 2021. https://doi.org/10.1016/j.matpr.2020.09.434.

VIANA, L. A.; OLIVEIRA FILHO, D., TOLEDO, O. M.; SILVA, S. C.; DALVI, G. G. Decrease in off-peak electrical energy demand by agroindustries due to photovoltaic solar generation. **Engenharia Agrícola,** v. 39, 2019. https://doi.org/10.1590/1809-4430-Eng.Agric.v39n4p537-547/2019.