SOLARIMETRIC ATLAS OF PARAÍBA

SECRETARIA DE ESTADO
DA INFRAESTRUTURA E
DOS RECURSOS HÍDRICOS

GOVERNO
DA PARAÍBA

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GOVERNO DA PARAÍBA

- July 2023 -

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PREFACE

Paraíba's strategic location makes it one of the regions with the highest incidence of solar radiation worldwide, with an average of 5.73 kWh/m² per day. Such an attribute gives the Paraíba significant potential for generating clean and renewable energy. With a focus on sustainable development, the State Government has supported initiatives that promote the use of renewable energy sources, not only for their environmental benefits but also to stimulate the local economy and generate employment, better income, and quality of life for the population.

Intending to consolidate the insertion of Paraíba in the national and international scenarios of investments in the solar energy sector, we launched this Solarimetric Atlas. This Atlas offers a web tool that quantifies and indicates, through georeferenced maps, the most promising regions in terms of solar energy resources in the state, including the estimation of the technical-economic potential. Fully interactive and available on the internet, the Atlas web is a fundamental tool to attract new investors in solar energy projects. Among its features, the user can access irradiation data and basic simulation of photovoltaic systems for photovoltaic energy generation in any location in the state, using search and selection tools directly on georeferenced maps.

Investors, small and medium-size local entrepreneurs, universities, schools, and public organizations will be able to obtain accurate information for making strategic decisions and developing innovative projects in solar energy. The State of Paraíba continues to advance and consolidate its economic leadership, building a sustainable future for the people of Paraíba.

João Azevêdo Lins Filho
Governor

SUMMARY

INTRODUCTION

Technological advances, the availability of scientifically established information, and the market scale produced critical conditions for the growth and consolidation of solar energy, today's fastest-growing energy source worldwide and in Brazil.

Research and Technological Development (R&D) projects have been carried out over the last two decades to meet the strong demand for reliable solarimetric data that would make it possible to understand the spatial distribution of the solar energy resource and its variability over time, taking into account attenuation by the atmosphere and the seasonal factors associated with the Earth's orbital movement around the Sun. In 2006, the National Institute for Space Research (INPE) launched the first edition of the Brazilian Atlas of Solar Energy with an innovative methodology using satellite data, which soon became a reference in the country. In its second revised and expanded edition of 2017, the Atlas points to Paraíba as one of the country's regions with the highest solar energy potential.

Over the past 20 years, public policies have been implemented to encourage power generation using renewable energy resources in Brazil. These policies aim to diversify the country's electricity mix, ensure greater energy security, and reduce greenhouse gas emissions in compliance with international commitments. The first Brazilian photovoltaic (PV) power plant connected to the SIN was installed in August 2011 in Tauá (Ceará). Since then, the continuous inclusion of new projects for photovoltaic plants began, driven, at first, by energy auctions and, later, by the free market. The Normative Resolution of the National Electric Energy Agency (ANEEL) no. 482/2012, revised in 2015 by Normative Resolution no. 687, established the basis of the market for distributed power generation in Brazil. The Resolution regulates the energy compensation system to promote the growth of photovoltaic generation in homes, commercial buildings, industrial establishments, and the public sector. Law 14,300, of January 6, 2023, established the legal regime for distributed micro and mini-generation, regulating the Electric Energy Compensation System (SCEE) and the Social Program for Distributed Renewable Energy (PERS).

The production chain and services of the photovoltaic industry have contributed to the growth of the local and regional economy, promoting environmental sustainability and boosting the quality of life and social development by generating qualified jobs. In addition, it has been promoting access to energy for the population yet to be served by the conventional electrical network and the expansion of essential services for the people in remote regions. Understanding the relevance of these aspects, the Government of the State of Paraíba invested in elaborating the Solar Energy Atlas of Paraíba and made it available through this document and the interactive Web tool. The web tool provides reliable information for the public on residential/commercial self-generation and for investors in new photovoltaic energy generation plants in Paraíba.

The Atlas was developed using modern computer modeling technology and ten years of satellite data. Thus, its interactive web version allows consultation and simulation of the use of solar resources in any specific location or region of Paraíba. The uncertainties in the estimates of incident solar irradiation were determined based on observational data acquired at solarimetric and meteorological stations operated by public institutions and private entrepreneurs who collaborated with this project.

The graphical interface of the interactive WEB tool was designed to offer an intuitive and friendly experience on digital platforms (computer, smartphone, or tablet) and provides a report that can be printed or stored on the user's equipment. An interactive tutorial is available to guide users in case of doubts about consultation or simulation procedures.

Undoubtedly, this Solar Energy Atlas of the State of Paraíba represents an important milestone in the dissemination of reliable and scientifically based information on the solar power potential, encouraging investment and job creation, in addition to contributing to the global effort to reduce greenhouse gas emissions through an inexhaustible, clean and abundant energy source in the region.

THE STATE OF PARAÍBA

Geography

Paraíba occupies an area of around 56,470 km² (about 0.7% of the Brazilian territory) located between latitudes 6° 1' 33" S to 7° 9' 18" S and meridians 34° 47' 34" W and 38° 45' 56" W as shown in Figure 1.1. Its borders meet the Atlantic Ocean to the east and the state of Ceará to the west. The southern and northern borders are delimited by the states of Pernambuco and Rio Grande do Norte, respectively.

The state of Paraíba comprises 223 municipalities, according to the division established by the Brazilian Institute of Geography and Statistics (IBGE). As shown in Figure 1.1, the territory of Paraíba is classified into Intermediate and Immediate Geographic Regions for purposes of territorial organization and planning of public policies. The geographic regions are named below, addressing the intermediaries' regions and their respective immediate members:

- João Pessoa: João Pessoa, Guarabira, Mamanguape - Rio Tinto e Itabaiana;
- Campina Grande: Campina Grande, Cuité - Nova Floresta, Monteiro e Sumé;
- Patos: Patos, Itaporanga, Catolé do Rocha - São Bento, Pombal e Princesa Isabel;
- Sousa-Cajazeiras: Sousa e Cajazeiras.

The Government of the State of Paraíba adopts a classic socioeconomic division that aggregates its main economic spaces in the following geoeconomic zones: Litoral-Mata, Agreste-Brejo, and Semiarid. The Litoral-Mata corresponds to most of the João Pessoa Intermediate Region, defined by the IBGE in 2021, and includes thirty of the 223 municipalities in the State, that is, with an area of 5,242 km² (9.3% of the State's territory). The Agreste-Brejo covers almost entirely the Campina Grande Mesoregion and part of Patos, as defined by the IBGE in 2021, bringing together 48 municipalities with a total area of 7,684 km² (13.6% of the entire surface of the State). The semi-arid zone of Paraíba covers an area of approximately 51,306 km² (87.0% of the state's total), including about 223 municipalities. This is according to the Ministry of National Integration and the Superintendence of Northeast Development (SUDENE), through the Resolution of the Deliberative Council (CONDEL) of SUDENE No. 107, of July 27, 2017, Technical Note No. 0023/2017-SUDENE /DPLAN/CGEP, of November 20, 2017, and CONDEL Resolution of SUDENE No. 115, of November 23, 2017.

Figure 1.2 presents the topography of the State of Paraíba. A lowland coastal strip, the Borborema Plateau in the central region and the Western Plateau characterize the Paraíba's relief. Approximately 90% of the territory of Paraíba has altitudes below 600 m, with the highest elevations located along the Planalto da Borborema, the highest point being the peak of Jabre, with an altitude of 1,090 m. The Atlantic Coast is about 120 km long, where cliff-type formations occur, with altitudes below 60 m. The Sertaneja Depression dominates the relief in the west of the Paraíba's territory, characterized by the Caatinga and the semi-arid climate, with elevations varying between 100 m and 400 m.

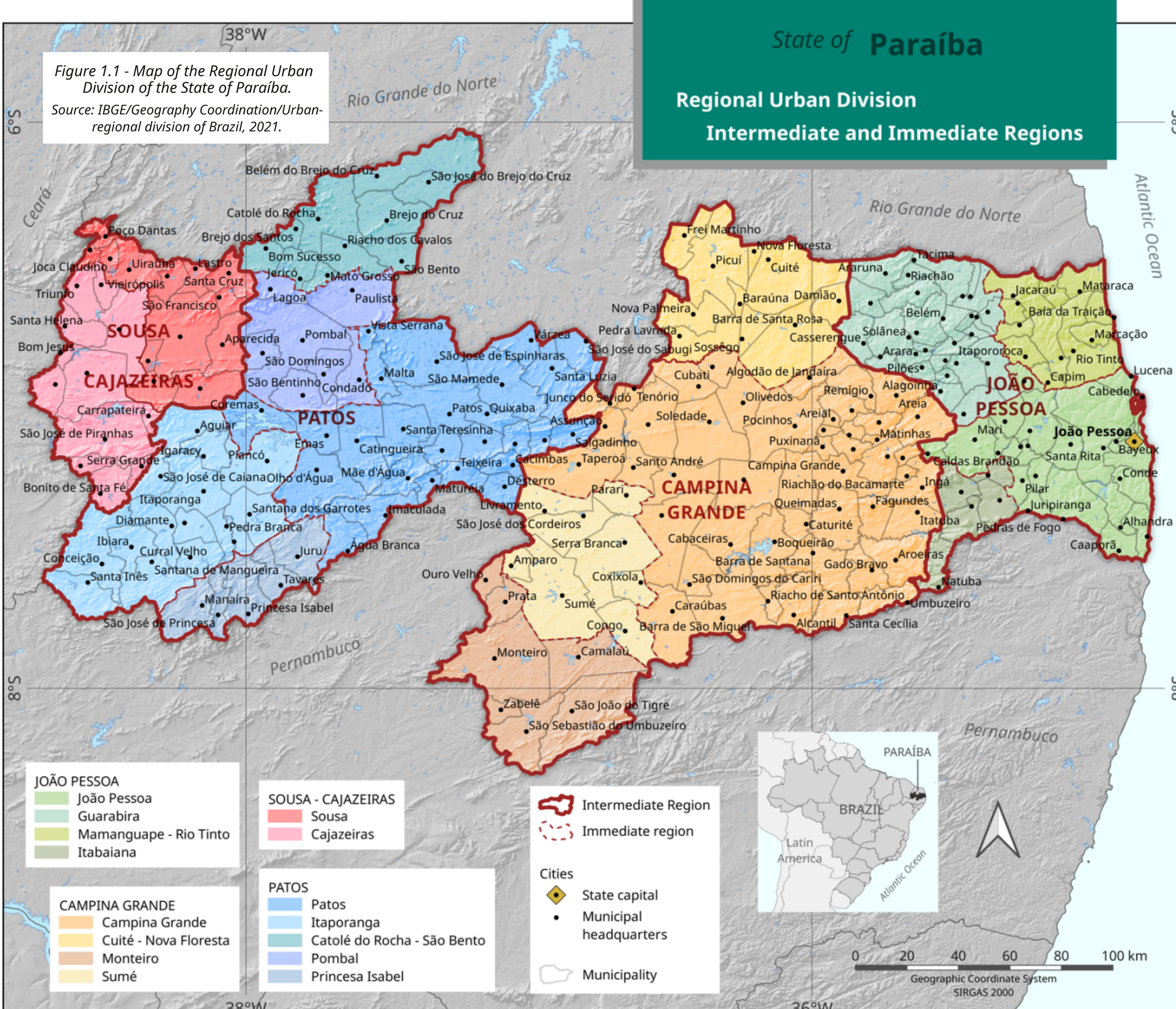


Figure 1.1 - Map of the Regional Urban Division of the State of Paraíba.

Source: IBGE/Geography Coordination/Urban-regional division of Brazil, 2021.

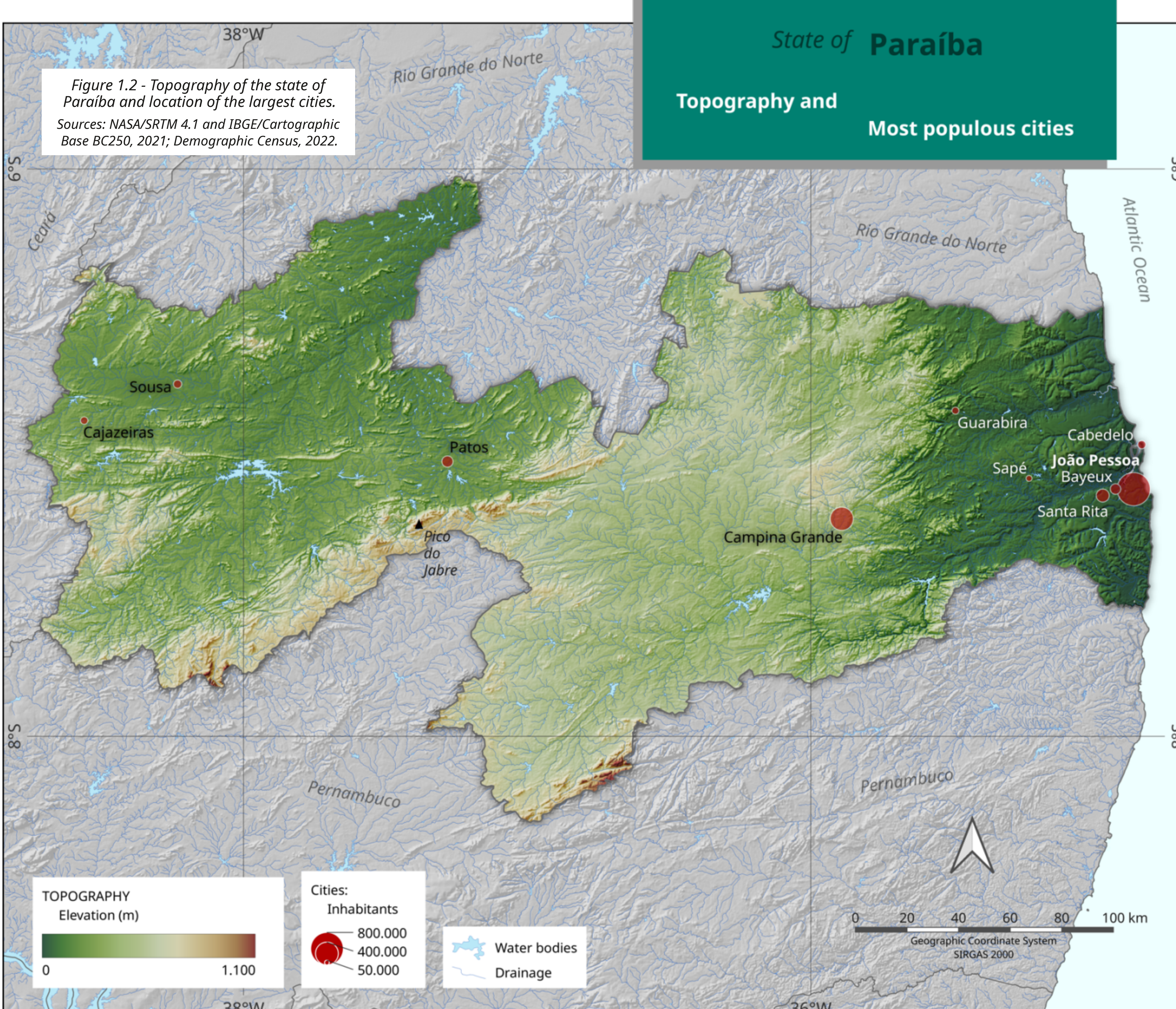


Figure 1.2 - Topography of the state of Paraíba and location of the largest cities.

Sources: NASA/SRTM 4.1 and IBGE/Cartographic Base BC250, 2021; Demographic Census, 2022.

Figure 1.3 shows the land slope map for Paraíba's territory. The land slope is critical for identifying the best location sites for large-scale photovoltaic power plants. The literature points out that places with land slopes greater than 5 degrees (or 8.7%) should be avoided due to aspects related to surface runoff and risks of soil erosion processes (Guarnieri, 2017; Al Guarni & Awasthi, 2017).

Vegetation

Paraíba's ecological richness is reflected in its diverse vegetation, which includes the Caatinga and Atlantic Forest biomes and a variety of species adapted to different climates and environments.

According to the Brazilian Forest Service (2019), Paraíba has at least 11 types of vegetation as forests, including Savannah-Steppic Wooded and Forested (Caatinga), Seasonal Semi Deciduous Forest, Open Ombrophilous Forest, Wooded and Forested Savannah, Mangrove, Palm grove, Sand-banks, and Planted Forests, where more than one typology occurs. The Savanna-Stépica (Caatinga) is the predominant typology, covering approximately 94% of the natural vegetation areas in the state (SFB, 2019).

There are significant differences in the number of plant species recorded in the State of Paraíba between the Flora and Funga Project of Brazil (2023), which indicates 2390 species, and the SpeciesLink platform (CRIA, 2023), which records 4318 species, including angiosperms, ferns, and lycophytes.

Climatic aspects

Paraíba, as part of the Brazilian Northeastern region, experiences high temporal and spatial precipitation variability. The most active atmospheric systems in the Semiarid Zone are the Intertropical Convergence Zone (ITCZ), the Southern Oscillation Events (ENSO) – El Niño and La Niña, the High-Level Cyclonic Vortex (VCAN) and the Frontal Systems (Cold Fronts), which are responsible for the rainfall distributed throughout the year. The ZCIT influence is more intense in the Semiarid region during March and April, when it is positioned over the Southern Hemisphere.

Among the typical precipitation regimes observed in the NEB, two of them affect the State of Paraíba: the first is characterized by a well-defined rainy quarter between February and May and comprises the regions of SousaCajazeiras and Patos, and the most to the west and north of the Campina Grande region, with the main meteorological phenomena being the ITCZ, the convergence of humidity from breezes and Trade Wave Disturbances (POAs) and local convection (Molion & Bernardo, 2002).

The second regime is characterized by a rainy four-month period between April and July, comprising the eastern portion of the state (João Pessoa region), caused by the increase in breeze circulation activity and maximum convergence of the trade winds with land breezes (Kousky, 1979), by the wave disturbances from the east (Ferreira et al., 1990) and by the displacement of a convergence zone observed over the east coast of the Northeast (Molion & Bernardo, 2000). These are the major weather systems responsible for precipitation in the state.

As shown in Figure 1.4, the annual distribution of precipitation shows high spatial variability. The state's central portion, including the intermediate region of Campina Grande and the west of the João Pessoa region, presents the lowest annual accumulated precipitation values between 400 and 600 mm. The region of Sousa-Cajazeiras and the west of the region of Patos present annual precipitation between 800 and 1000 mm, and the easternmost portions of the state present values above 700 mm, with emphasis on the region of João Pessoa, where the annual accumulated range from 1200 to 1600 mm. Precipitation is an important climatic element, as it promotes temperature regulation and controls extreme thermal amplitudes.

According to Francisco and Santos (2017), the Köppen climate classification shows the predominance of types "As" (tropical climate with dry summer) and "Bsh" (hot semi-arid climate) in the state of Paraíba, as shown in Figure 1.5. Type "As" is observed in the east of the João Pessoa region, in addition to a range in the western and northern portions of the Patos region. The "Bsh" climate type occurs in the state's

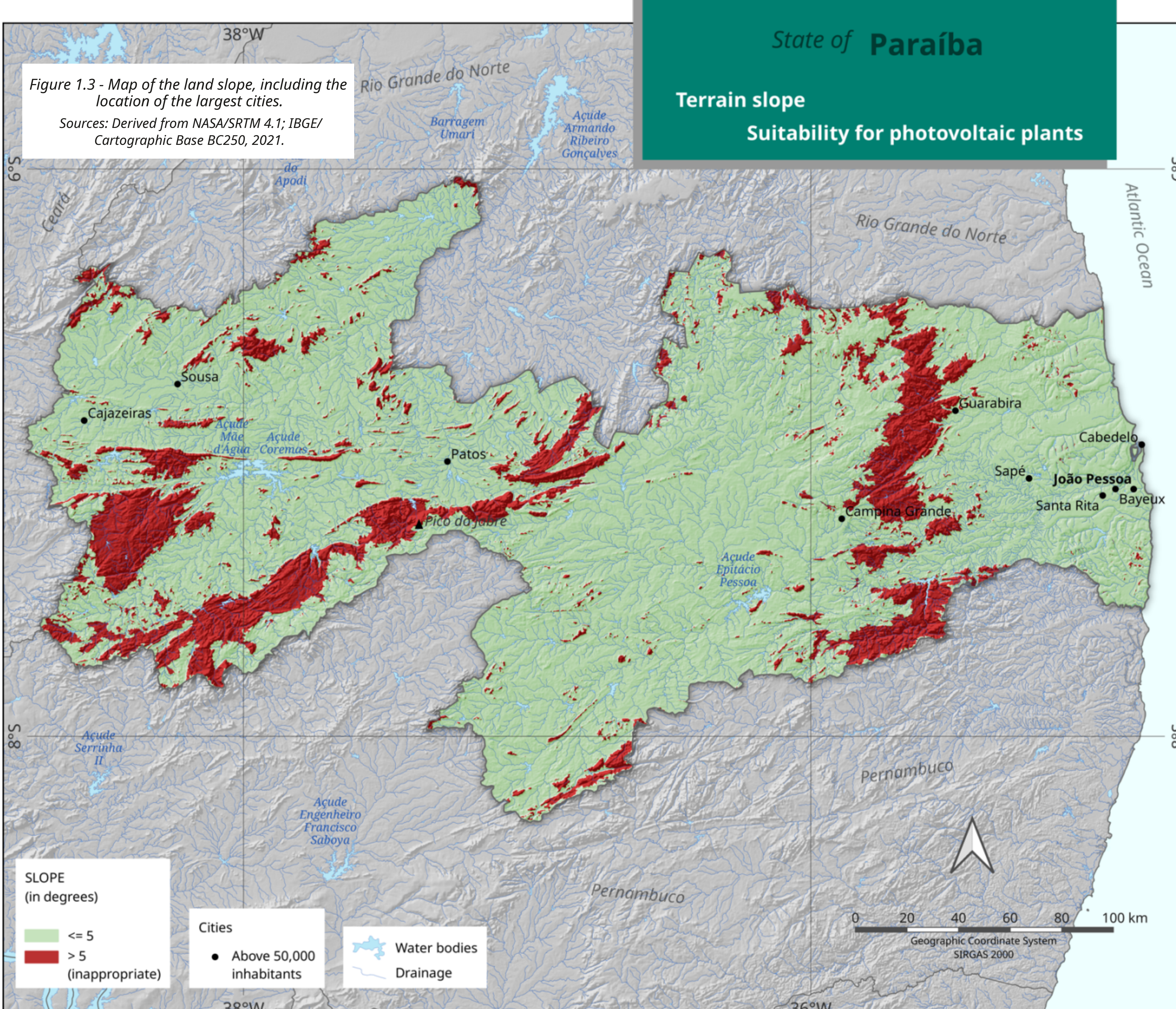


Figure 1.3 - Map of the land slope, including the location of the largest cities.

Sources: Derived from NASA/SRTM 4.1; IBGE/ Cartographic Base BC250, 2021.

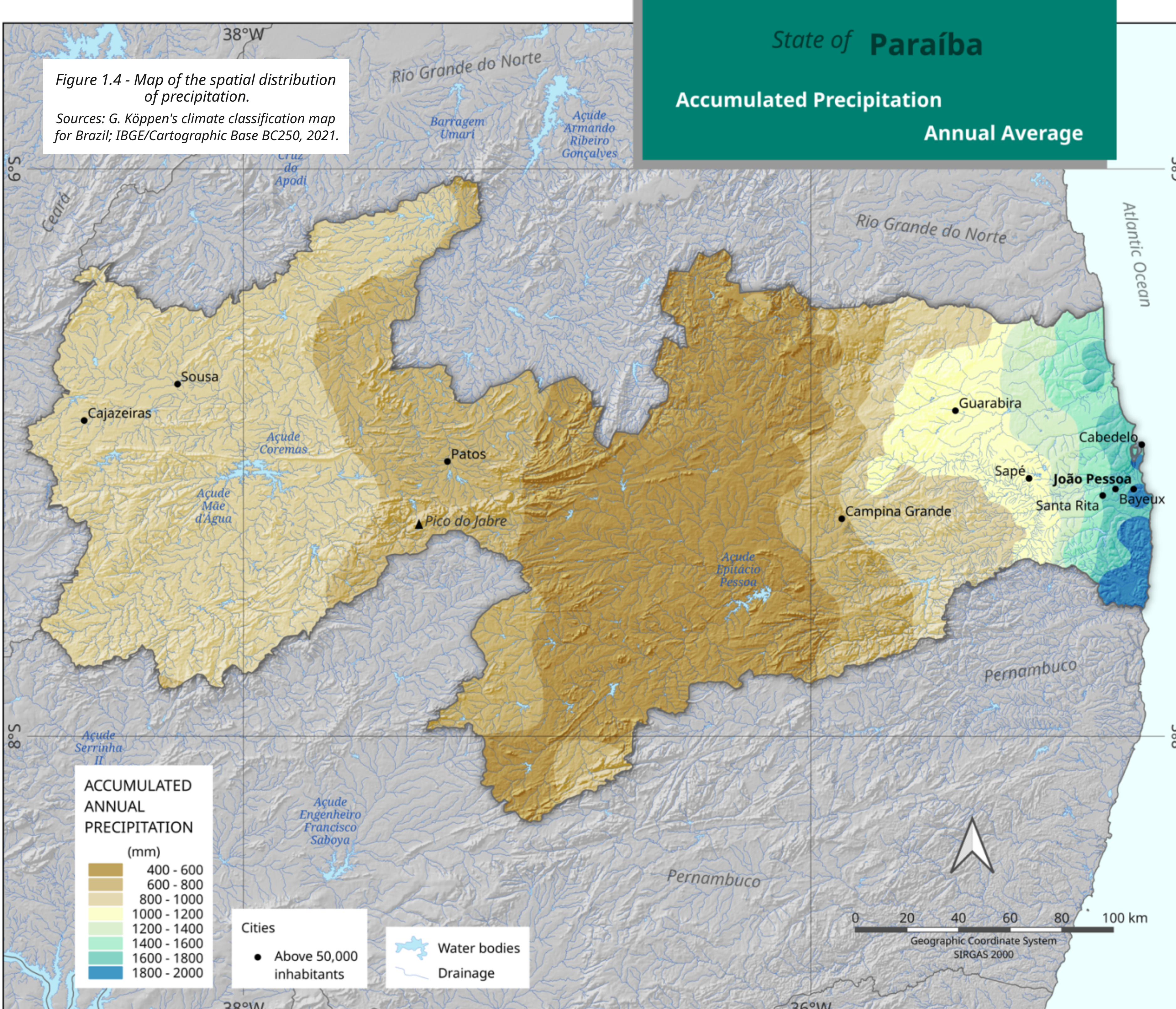


Figure 1.4 - Map of the spatial distribution of precipitation.

Sources: G. Köppen's climate classification map for Brazil; IBGE/Cartographic Base BC250, 2021.

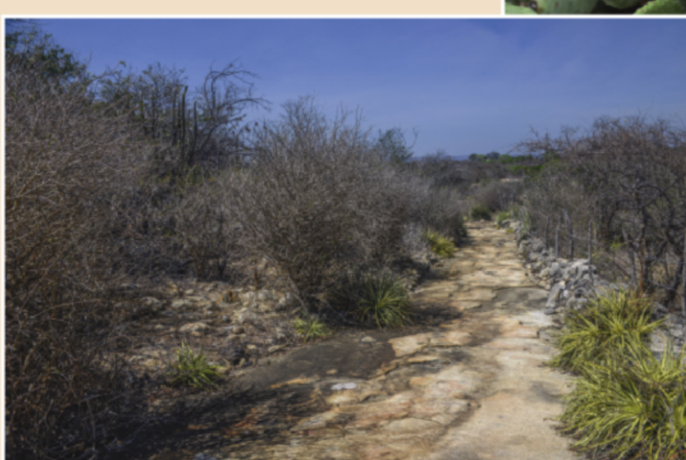
Vegetation

The coast of Paraíba

Borborema Plateau

Quipá cactus in Paraiba's Cariri

Atlantic Forest



Caatinga

Mangroves

central region, comprising the region of Campina Grande and the west of João Pessoa. It is noteworthy to mention that in Paraíba's central area, annual rainfall ranges between 400 and 600 mm (Figure 1.4), and is, therefore, one of the regions with the lowest rainfall totals in the country.

Figure 1.6 shows the average annual diurnal air temperature distribution in Paraíba. The map highlights the central-north portion of Campina Grande with the lowest values. In contrast, the eastern sector of Patos, with low altitudes, has the highest average diurnal air temperatures throughout the year. The temperature pattern is consistent throughout the year, with the lowest values occurring in June, July, and August and the highest in October, November, and December.

Hydrography

Paraíba territory has rivers and streams described as lotic bodies of water or natural watercourses (intermittent, ephemeral, perennial, and perennial), which have their terminologies established in Art. 2 of the Resolution of the National Water Resources Council (CNRH) No. 141, of July 10, 2012. Most of these lotic water bodies or natural water courses are represented in the framework of the water bodies of Paraíba, prepared by the Executive Agency for Water Management (AESA) and updated in partnership with SUDEMA in 2014. These aspects of water resources management are based on Guideline No. 201 of the State Licensing System for Polluting Activities (SELAP) in 1988. They can be viewed at the Spatial Database (BDE) of the SIG-WEB of the Executive Agency for Water Management (AESA) through the electronic address http://siegrh.aesa.pb.gov.br:8080/aesa-sig/.

The Government of Paraíba established, in Complementary Law 168/2021, the water and sewage micro-regions of Alto Piranhas, Espinharas, Borborema, and Litoral. The structure considers, among other aspects, the delimitation of watersheds, the division of the operational infrastructure of basic sanitation services, and the social, economic, and political particularities of the territories involved.

The low annual rainfall is a constraint factor for the hydrographic regions in the Semi-Arid Zone of Paraíba, causing less flow and surface runoff in rivers and streams. In these localities, the hydrographic characterization is characterized by intermittent and ephemeral rivers and streams.

The hydrographic basins of Paraíba are composed essentially of perennial rivers, the Abiaí, Guaju, Mamanguape, Miriri, Gramame, and Camaratuba, as well as the Baixo Paraíba hydrographic sub-basin.

Paraíba has numerous reservoirs and dams built to mitigate the impact of dry seasons, such as diffuse demands (human supply of rural populations, animal watering, and irrigation).

The Coremas Dam, the largest in the state in terms of storage capacity, with approximately 590 hm^3 and located in the Piancó River basin, benefits 112 municipalities spread across the Mesoregion of Sertão Paraibano (AESA, 2020). Figure 1.7 presents the map of water resources in Paraíba used to prepare the economic scenarios described later in this document.

Conservation units

Conservation Units are lawfully protected territories established by the Government that aim to conserve the environmental resources within their boundaries, including jurisdictional waters, with relevant natural characteristics. For them, a special administration regime is mandatory, to which adequate protection guarantees apply.

Such protected territories are classified into two groups, according to their type of use: Integral Protection and Sustainable Use. Each of these groups is subdivided into five and seven categories, respectively, which adapt to the environmental reality of each location.

In total, there are 40 Conservation Units in Paraíba, listed in Table 1.1, 17 of which are managed by the state through SUDEMA, another 16 at the federal level by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), and another seven that are in charge of municipalities. Among the CUs, some are private. Named Private Natural Heritage Reserves, nine are at the federal level and two at the state level.

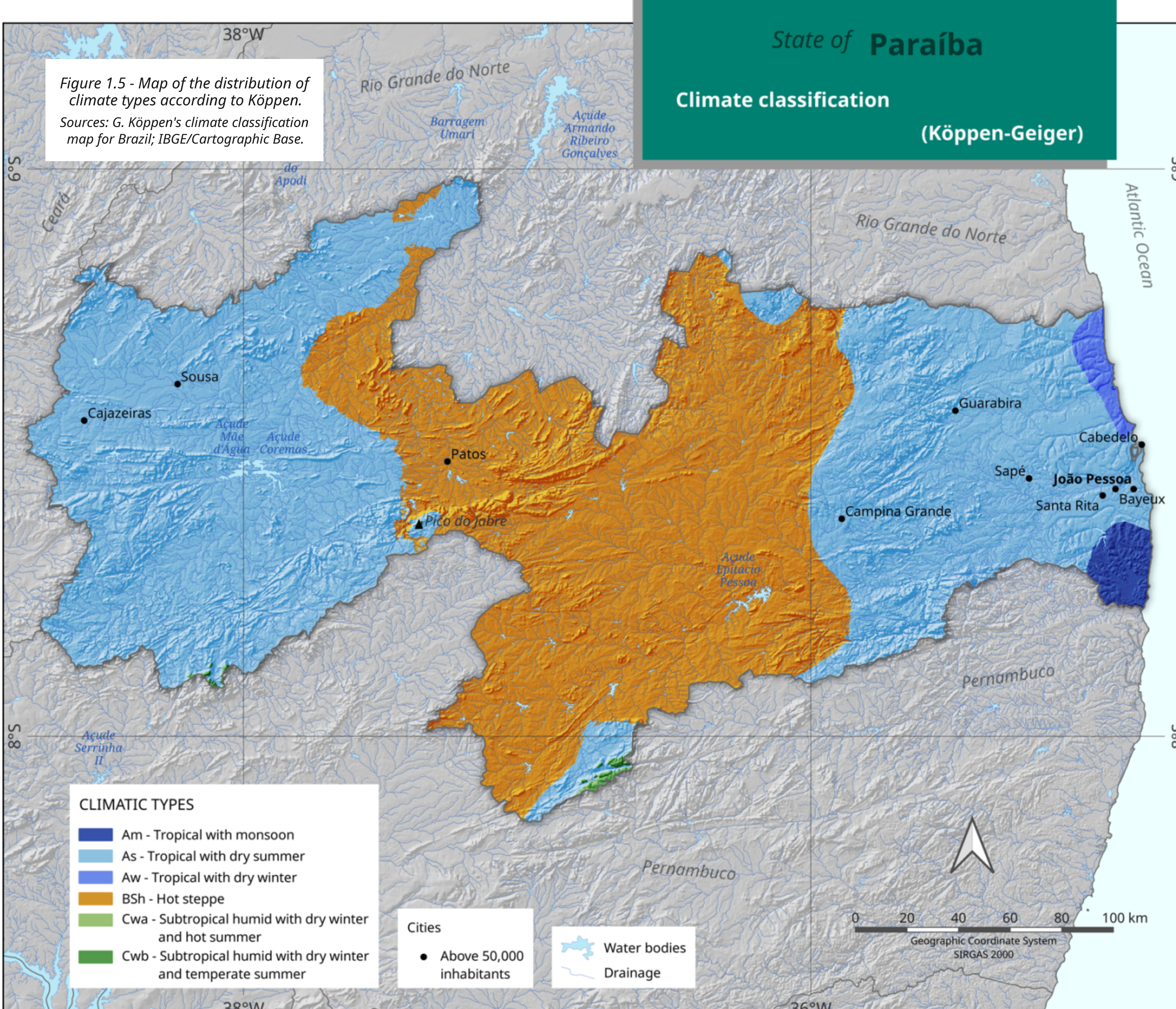


Figure 1.5 - Map of the distribution of climate types according to Köppen.

Sources: G. Köppen's climate classification map for Brazil; IBGE/Cartographic Base.

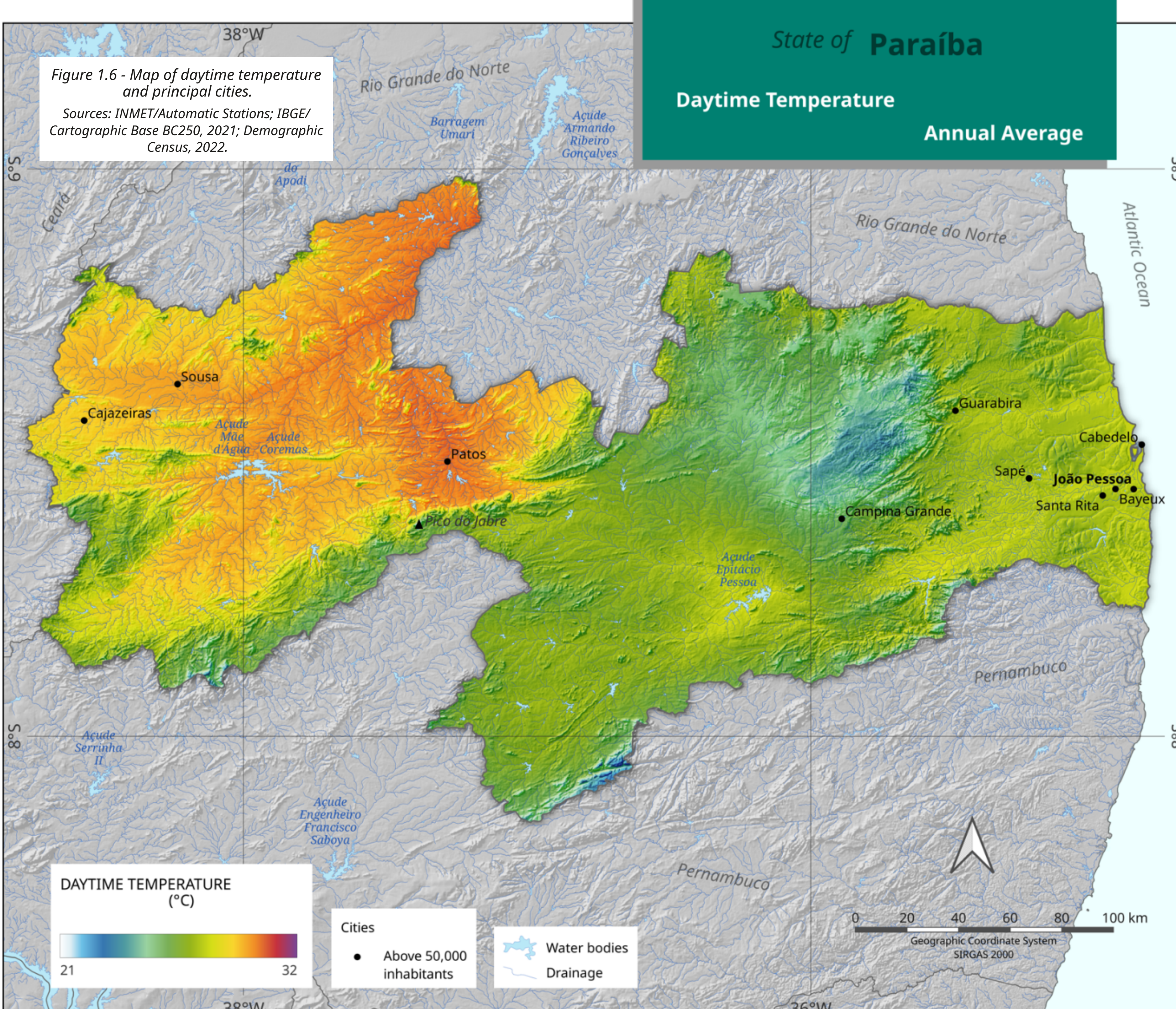


Figure 1.6 - Map of daytime temperature and principal cities.

Sources: INMET/Automatic Stations; IBGE/ Cartographic Base BC250, 2021; Demographic Census, 2022.

State of **Paraíba**

Water Resources

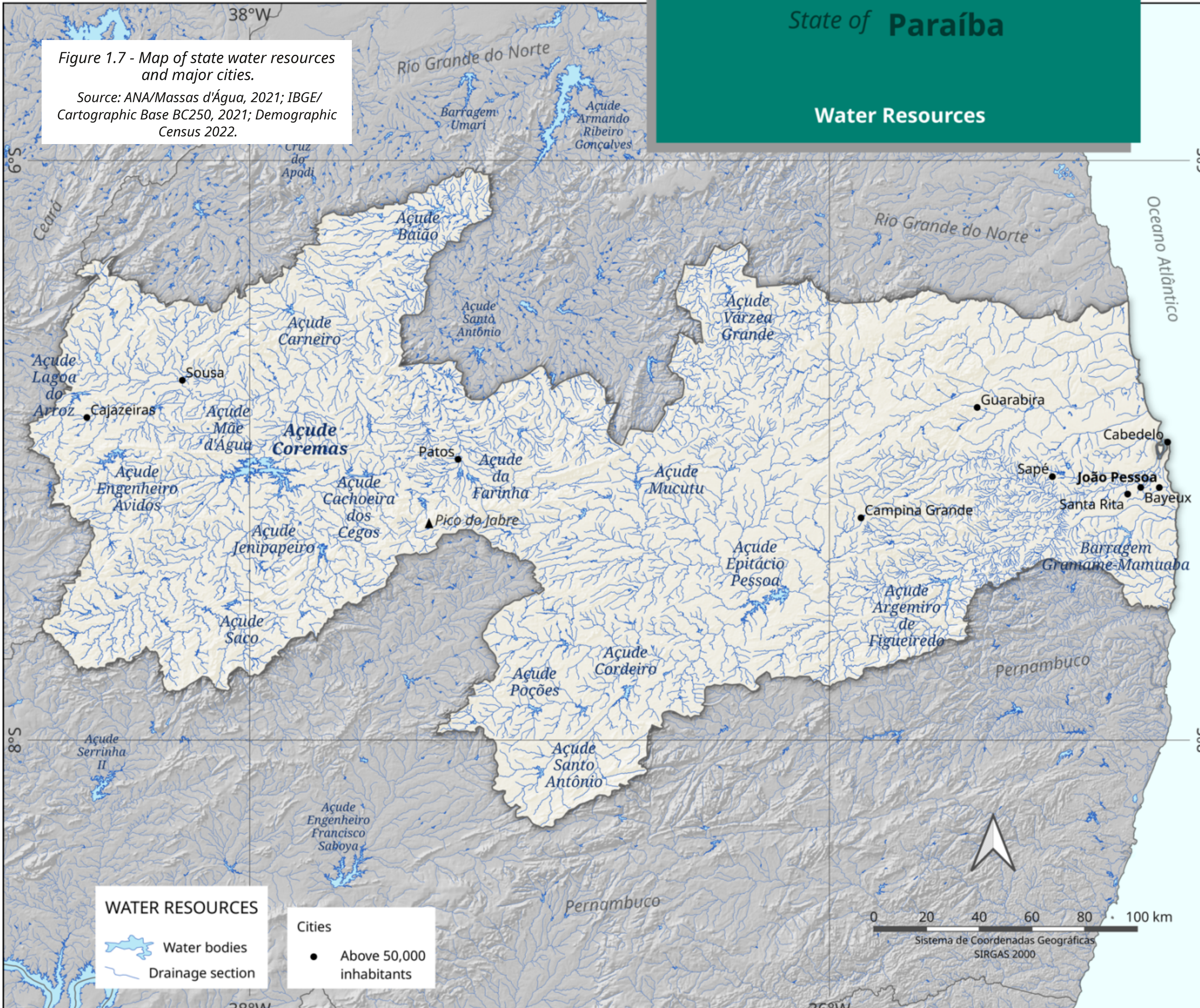


Figure 1.7 - Map of state water resources and major cities.

Source: ANA/Massas d'Água, 2021; IBGE/ Cartographic Base BC250, 2021; Demographic Census 2022.

Figure 1.8 shows the map with the location of conservation units.

Currently, in Paraíba, Conservation Units are protecting natural landscapes in the two existing biomes in the territory – Atlantic Forest and Caatinga – in addition to others in the marine ecosystem. Several activities can be developed in these protected territories, such as, for example, environmental education, scientific research, ecotourism, and sustainable extraction of renewable natural resources.

Conservation Units preserve critical natural heritage as endangered biodiversity. For instance, numerous Pau-brasil specimens (Paubrasilia echinata) are at the Ecological Station of the same name, which has one of this region's most important germplasm banks in the country. In addition, there are endemic birds (Mata do Pau-Ferro State Park), cave paintings (APA das Onças), and trace fossils from the Cretaceous period (Vale dos Dinossauros Natural Monument) also protected in the Paraíba's conservation units.

Another critical role of Conservation Units is to preserve the traditional knowledge of local communities. The Community Integration Project in the buffer zone of Areia Vermelha Marine State Park (PEMAV) supports women from the Cabedelo fishermen's colony with activities such as crafts produced by Renascer community shellfish gatherers.

Knowledge is a maxim that guides the management of Conservation Units. The belief in a sustainable future where ecosystems will be perpetuated for future generations is based on popular participation, the dissemination of scientific knowledge, and the experience of these spaces.

In addition to the Conservation Units, the State of Paraíba has lands designated for Indigenous populations, and Quilombola Communities, either regulated or under regulation, are presented in Figure 1.8 and Tables 1.2 and 1.3.

Demography

According to the IBGE Demographic Census carried out in 2022, the population of Paraíba was 3,974,495 inhabitants, registering a growth rate of 0.45% p.a. between 2010 and 2022. The state's demographic density is 70.4 inhab./km² (Figure 1.9). Population data by sex and urban/rural residence had not yet been published by the IBGE when this document was printed (July/2023). Updated values can be obtained from the 2022 Census page (http://censo2022.ibge.gov.br/panorama/).

Still considering the 2022 Census, the most populous cities in Paraíba are João Pessoa, the state capital, with about 834 thousand inhabitants; Campina Grande, with approximately 420 thousand inhabitants; Santa Rita, with approximately 150 thousand inhabitants; Patos, with about 105 thousand inhabitants, and Bayeux, with approximately 83 thousand inhabitants.

According to IPEA (2022), the Human Development Index (HDI) of the State of Paraíba has advanced in the last decade, from 0.66 in 2010 to 0.72 in 2017.

Economy

Data from the State Secretary of Planning, Budget, and Management indicate that Paraíba's Gross Domestic Product (GDP) was around R$ 70.3 billion. Figure 1.10 shows the evolution of GDP in Paraíba over the last two decades, with a growth of around 2.1 times between 2010 and 2020.

The economy of Paraíba is based on agricultural production, the leather industry, and tourism. The main agricultural products are sugar cane, pineapple, cassava, corn, beans, and herbaceous cotton (IBGE, 2022). The state has an estimated herd of 1.3 million head of cattle, raising pigs, sheep, and horses. In addition to leather goods, food, and textile products, sugar and alcohol are also industrialized.

Power System

According to ANEEL's Generation Information System (SIGA), Brazil's installed electricity generation capacity (supervised power) is around 189,871 MW, with photovoltaic solar responsible for 4.1% of centralized generation. Nevertheless, when

Table 1.1 - Conservation Units in Paraíba's territory. The numbering (Id) indicates the position on the map.
Source: MMA (Ministry of the Environment)/ICMBIO (Chico Mendes Institute for Biodiversity Conservation), 2021; SUDEMA, Municipalities of Cabedelo, Cacimba de Areia, Cajazeiras, João Pessoa and Mataraca.

Id	Conservation Unit	Area (ha)	Group	Level	Legal act	Municipality
12	Environmental Protection Area of Barra do Rio Mamanguape	14.917	Sustainable use	Federal	Decree no. S/N de 07/03/1998	Baía da Traição, Lucena, Marcação, Rio Tinto
-	Environmental Protection Area of da Praia de Jacarapé	-	Sustainable use	State	Law n° 11.422 de 28/08/2019	João Pessoa
18	Environmental Protection Area of Onças	36.000	Sustainable use	State	Decree no. 22.880 de 26/03/2002	São João do Tigre
3	Environmental Protection Area of Tambaba	11.500	Sustainable use	State	Decree no. 26.296 de 23/09/2005	Conde, Alhandra, Pitimbu
21	Environmental Protection Area of Naufrágio Queimado	42.446	Sustainable use	State	Decree n° 38.931 de 28/12/2018	João Pessoa
13	Environmental Protection Area of Roncador	6.113	Sustainable use	State	Decree no. 27.204 de 06/06/2006	Bananeiras, Pirpirituba
7	Environmental Protection Area of Cariri	18.560	Sustainable use	State	Decree no. 25.083 de 08/06/2004	Boa Vista, Cabaceiras, São João do Cariri
-	Environmental Protection Area Rosilda Cartaxo	-	-	Municipal	Law no. 1.647 de 27/09/2006	Cajazeiras
8	Area of Relevant Ecological Interest of Mata Goiamunduba	67	Sustainable use	State	Decree no. 23.833 de 29/12/2002	Bananeiras
2	Area of Relevant Ecological Interest of Manguezais da Foz do Rio Mamanguape	5.769	Sustainable use	Federal	Decree no. 91.890 de 05/11/1985	Marcação, Rio Tinto
14	Area of Relevant Ecological Interest of Barra do Rio Camaratuba	168	Sustainable use	Federal	Ordinary law no. 272/2008 de 04/12/2008	Baía da Traição, Mataraca
11	Ecological Station of Pau Brasil	82	Full protection	State	Decree no. 22.881 de 25/03/2002	Mamanguape
4	National Forest of Restinga de Cabedelo	117	Sustainable use	Federal	Decree no. S/N de 02/06/2004	João Pessoa, Cabedelo
5	Natural Monument of Vale dos Dinossauros	40	Full protection	State	Decree no. 23.832 de 27/12/2002	Sousa
-	Ecological Park of the District of Engenheiro Ávido	182	-	Municipal	Law no. 1.147/GP 97 de 29/08/1997	Cajazeiras
-	Municipal Ecological Park of Barra do Rio Camaratuba	-	-	Municipal	Law no. 001 de 13/02/1998	Mataraca
-	State Park of Mata do Xem-Xém	182	Full protection	State	Decree n° 21.262 de 28/08/2000	Bayeux
-	State Park of Pedra da Boca	157	Full protection	State	Decree n° 20.889 de 07/02/2000	Araruna
22	State Park of Serra da Santa Catarina	4.508	Full protection	State	Ano 2023	Aguiar, Nazarezinho, São José de Lagoa Tapada
19	State Park ofs Trilhas	851	Full protection	State	Decree no. 37.653 de 15/09/2017	João Pessoa
20	Marine State Park of Areia Vermelha	232	Full protection	State	Decree n° 21.263 de 07/02/2000	Cabedelo
9	State Park of Mata do Pau Ferro	607	Full protection	State	Decree no. 26.098 de 04/08/2005	Areia
-	Municipal Park of Cabedelo	50	-	Municipal	Decree no. 12 de 16/04/2003	Cabedelo

Continue

Continued from Table 1.1

Id	Conservation Unit	Area (ha)	Group	Level	Legal act	Municipality
-	Municipal Park Lauro Xavier	22	-	Municipal	Law no. 9.839 de 16/12/2002	João Pessoa
17	National Park of Serra do Teixeira	61.095	Full protection	Federal	Decree no. 11.552 de 05/06/2023	Água Branca, Cacimba de Areia, Catingueira, Imaculada, Juru, Mãe d'Água, Matureia, Olho d'Água, Santa Terezinha, Santana dos Garrotes, São José do Bonfim e Teixeira
15	Municipal Natural Park of Cuiá	43	Full protection	Municipal	Decree no. 7.517 de 17/04/2012	João Pessoa
1	Wildlife Refuge Mata do Buraquinho	518	Full protection	State	Decree no. 35.195 de 23/07/2014	João Pessoa
-	Environmental Reserve of the Municipality of Cacimba de Areia	-	-	Municipal	Law no. 256 de 17/12/2007	Cacimba de Areia
16	Biological Reserve Guaribas	4.052	Full protection	Federal	Decree no. 98.884 de 25/01/1990	Mamanguape, Rio Tinto
10	Extractive Reserve Acaú-Goiana	6.677	Sustainable use	Federal	Decree no. S/N de 26/09/2007	Caaporã, Pitimbu – PB Goiana – PE
6	Private Natural Heritage Reserve Armil	5	Sustainable use	Federal	Ordinance no. 195 de 14/03/2018	São Mamede
-	Private Natural Heritage Reserve Engenho Gargaú	1.059	Sustainable use	Federal	Ordinance no. 064 de 15/06/1994	Santa Rita
-	Private Natural Heritage Reserve Fazenda Almas	3.505	Sustainable use	Federal	Ordinance no. 1343 de 07/08/1990	São José dos Cordeiros
-	Private Natural Heritage Reserve Fazenda Cabeça de Boi	34	Sustainable use	State	Ordinance no. 30 de 29/06/2009	Pocinhos
-	Private Natural Heritage Reserve Fazenda Pacatuba	267	Sustainable use	Federal	Ordinance no. 110 de 29/12/1995	Sapé
-	Private Natural Heritage Reserve Fazenda Pedra d'Água	170	Sustainable use	Federal	Ordinance no. 60 de 16/07/1999	Solânea
-	Private Natural Heritage Reserve Fazenda Santa Clara	751	Sustainable use	Federal	Ordinance no. 29 de 28/02/2002	São João do Cariri
-	Private Natural Heritage Reserve Fazenda Tamanduá	325	Sustainable use	Federal	Ordinance no. 110 de 31/07/1998	Santa Teresinha
-	Private Natural Heritage Reserve Fazenda Várzea	391	Sustainable use	Federal	Ordinance no. 11 de 23/01/1998	Araruna
-	Private Natural Heritage Reserve Gurugy dos Paus Ferros	10	Sustainable use	State	Ordinance no. 002 de 22/02/2010	Conde
-	Private Natural Heritage Reserve Major Badú Loureiro	186	Sustainable use	Federal	Ordinance no. 109 de 04/09/2001	Catingueira

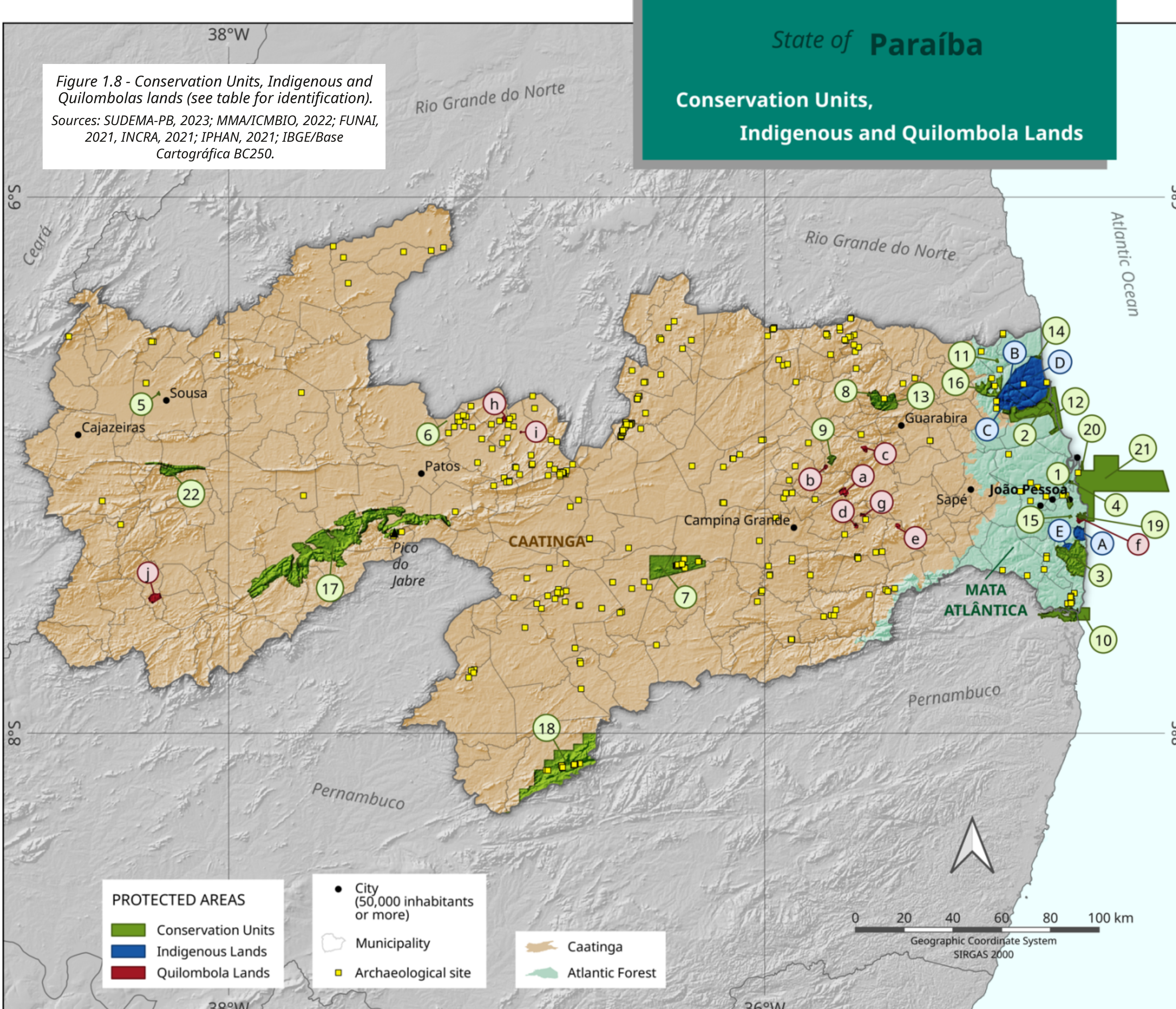


Figure 1.8 - Conservation Units, Indigenous and Quilombolas lands (see table for identification).

Sources: SUDEMA-PB, 2023; MMA/ICMBIO, 2022; FUNAI, 2021, INCRA, 2021; IPHAN, 2021; IBGE/Base Cartográfica BC250.

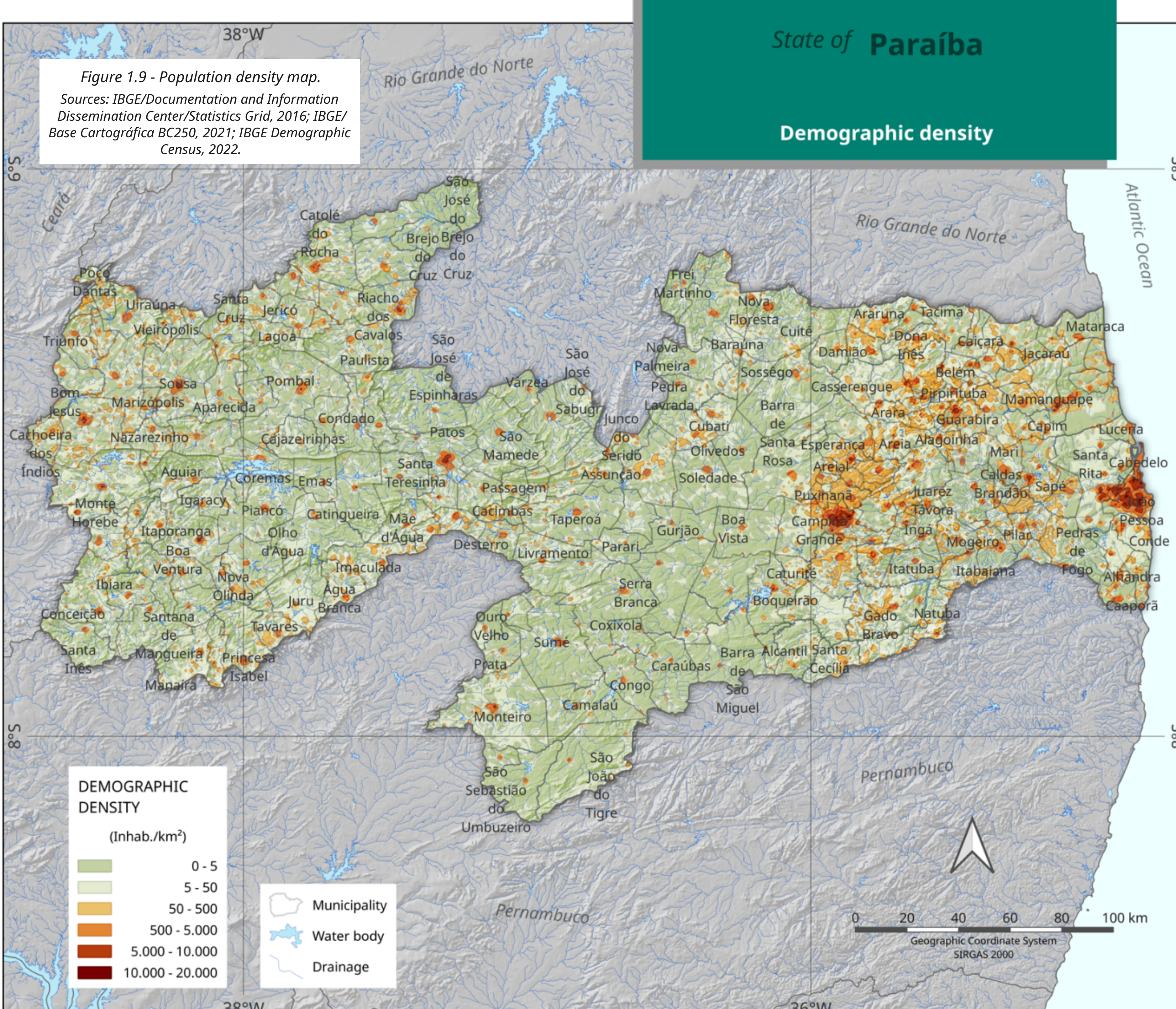


Figure 1.9 - Population density map.

Sources: IBGE/Documentation and Information Dissemination Center/Statistics Grid, 2016; IBGE/ Base Cartográfica BC250, 2021; IBGE Demographic Census, 2022.

considering the already existing potential in distributed generation (DG – 17,000 MW), the installed capacity in Brazil (centralized + DG) is 206,871 MW, with photovoltaic solar responsible for 11.8% of this total, which places it as the second largest renewable source in the country behind only the water source (ANEEL/SIGA, 2023; ANEEL/ Distributed Generation, 2023).

The share of photovoltaic solar energy stands out even more in Paraíba. The total installed electricity generation capacity is 1,733 MW (corresponding to 0.9% of the centralized power generation in Brazil), with photovoltaic solar responsible for 26.2% (454 MW). The total installed capacity in distributed power generation (supervised power) reaches 1,992 MW, with solar photovoltaics responsible for 35.7%. These numbers place PV technology as the primary energy source in Paraíba. (ANEEL/ SIGA, 2023; ANEEL/Distributed Generation, 2023). For the distributed power generation, the photovoltaic systems are concentrated mainly in the commercial and residential classes, with 40.9% and 40.8%, respectively, as shown in Figure 1.11.

Table 1.4 lists the top photovoltaic power plants operating in Paraíba – centralized generation (ANEEL/SIGA, 2023).

According to the National Energy Balance (BEN, 2022), Paraíba generated approximately 3,434 GWh in 2021, equivalent to 2.3% of the total produced in the Northeast region and 0.5% in Brazil. Renewable energy sources account for approximately 1680 Gwh (49%) of Paraíba's electricity mix. Ther-

Table 1.2 - Indigenous lands in the State of Paraíba. The letters (Id) indicate the position on the map.
Source: FUNAI (National Indian Foundation), 2021.

Id	Indigenous land	Area (ha)	Ethnicity	Municipality
A	Barra de Gramame		Tabajara	Conde
B	Jacaré de São Domingos	5037.1	Potiguara	Rio Tinto, Marcação
C	Monte-Mor	7628.7	Potiguara	Rio Tinto, Marcação
D	Potiguara	21283.8	Potiguara	Rio Tinto, Marcação, Baía da Traição
E	Vitória		Tabajara	Conde, Alhandra, Pitimbu

Table 1.3 - Quilombola lands in the State of Paraíba. The letters (Id) indicate the position on the map.
Source: Ministry of Agriculture, Livestock and Supply / INCRA (National Institute of Colonization and Agrarian Reform), 2021.

Id	Quilombola land	Area (ha)	Families	Municipality
a	Caiana dos Crioulos	67.6	98	Alagoa Grande, Matinhas e Massaranduba
b	Engenho Bonfim	12.2	21	Areia
c	Engenho Mundo Novo	32.2	37	Areia
d	Grilo	13.9	78	Riachão do Bacamarte
e	Matão	21.4	29	Mogeiro
f	Paratibe	26.8	114	João Pessoa
g	Pedra dÁagua	13.2		Ingá
h	Pitombeira	35.4	80	Várzea
i	Serra do Talhado	1.6	125	Santa Luzia
j	Vaca Morta	118.9	57	Diamante

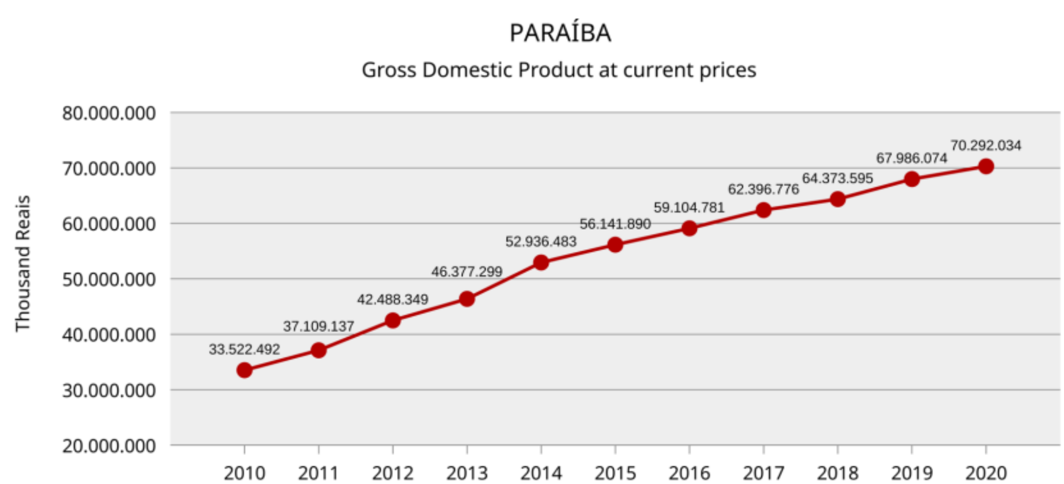


Figure 1.10 - Evolution of the Gross Domestic Product of the State of Paraíba.
Source: IBGE, in partnership with the State Statistical Agencies, State Government Secretariats, and the Manaus Free Trade Zone Superintendence - SUFRAMA.

Table 1.4 - Top photovoltaic power plants operating in Paraíba – centralized generation.
Source: ANEEL/SIGA, 2023.

Enterprise	Power output (MWp)	Municipality
Luzia 3	58,93	Santa Luzia
Luzia 2	39,29	Santa Luzia
Rio do Peixe II	36,01	São João do Rio do Peixe
Lagoa 1	32,89	São José da Lagoa Tapada
Lagoa 2	32,89	São José da Lagoa Tapada
Rio do Peixe I	32,74	São João do Rio do Peixe
Angico I	27,20	Condado
Malta	27,20	Malta
Coremas I	27,00	Coremas
Coremas III	27,00	Coremas
Coremas VII	27,00	Coremas
Coremas V	27,00	Coremas
Coremas II	27,00	Coremas
Coremas VIII	27,00	Coremas
Coremas IV	27,00	Coremas
Coremas VI	27,00	Pombal

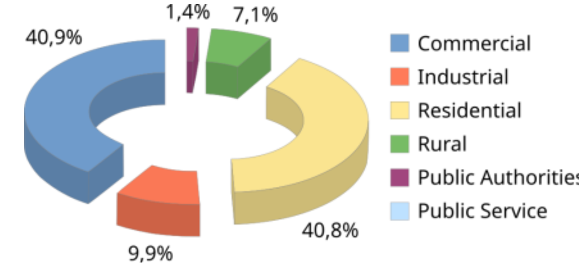


Figure 1.11 - Percentage of participation by consumption class of photovoltaic solar source in distributed power generation (DG).
Source: Adapted from ANEEL/Distributed Generation,

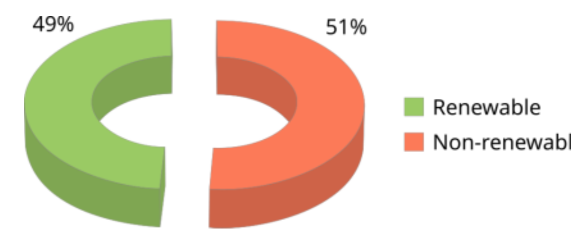


Figure 1.12 - Share of renewable energy resources in the Paraíba's electricity mix of Paraíba.
Adapted from ANEEL/BEN, 2022

moelectric power plants participate with 1750 Gwh (51%), as shown in Figure 1.12. The residential sector alone was responsible for the consumption of 2,346 GWh, or 68% of the total generated in the state.

Paraíba can assume a more significant role in power generation, considering the available potential of solar and wind energy resources.

Regarding the potential for photovoltaic solar generation, previous studies show that Paraíba is within the solar belt (Pereira et al., 2017) with high solar radiation at the surface. This Atlas details the spatial and temporal distribution of downward surface solar radiation in Paraíba, demonstrating that the state has enormous potential for growth in the solar energy market

The Wind Atlas of the State of Paraíba (https://mapaeolico.pb.gov.br/) indicates that more than 90% of the areas presenting annual mean wind speed higher than 7.0 m/s at 150 meters high are less than 40 km away from one of the substations.

Information on the electrical system serving the state of Paraíba was provided by the National Electric Energy Agency (ANEEL) and the Energy Research Company (EPE). It was used to prepare the scenarios for using the solar resource presented later in this document.

According to ANEEL and EPE, the transmission system in Paraíba consists of 500 kV and 230 kV lines, as illustrated in Figure 1.13.

According to the Distribution Company's Geographical Database (BDGD), the distribution system under ANEEL's responsibility is primarily made up of 69 kV lines currently operated under concession by Energisa Paraíba, which serves the entire state, as also shown in Figure 1.13.

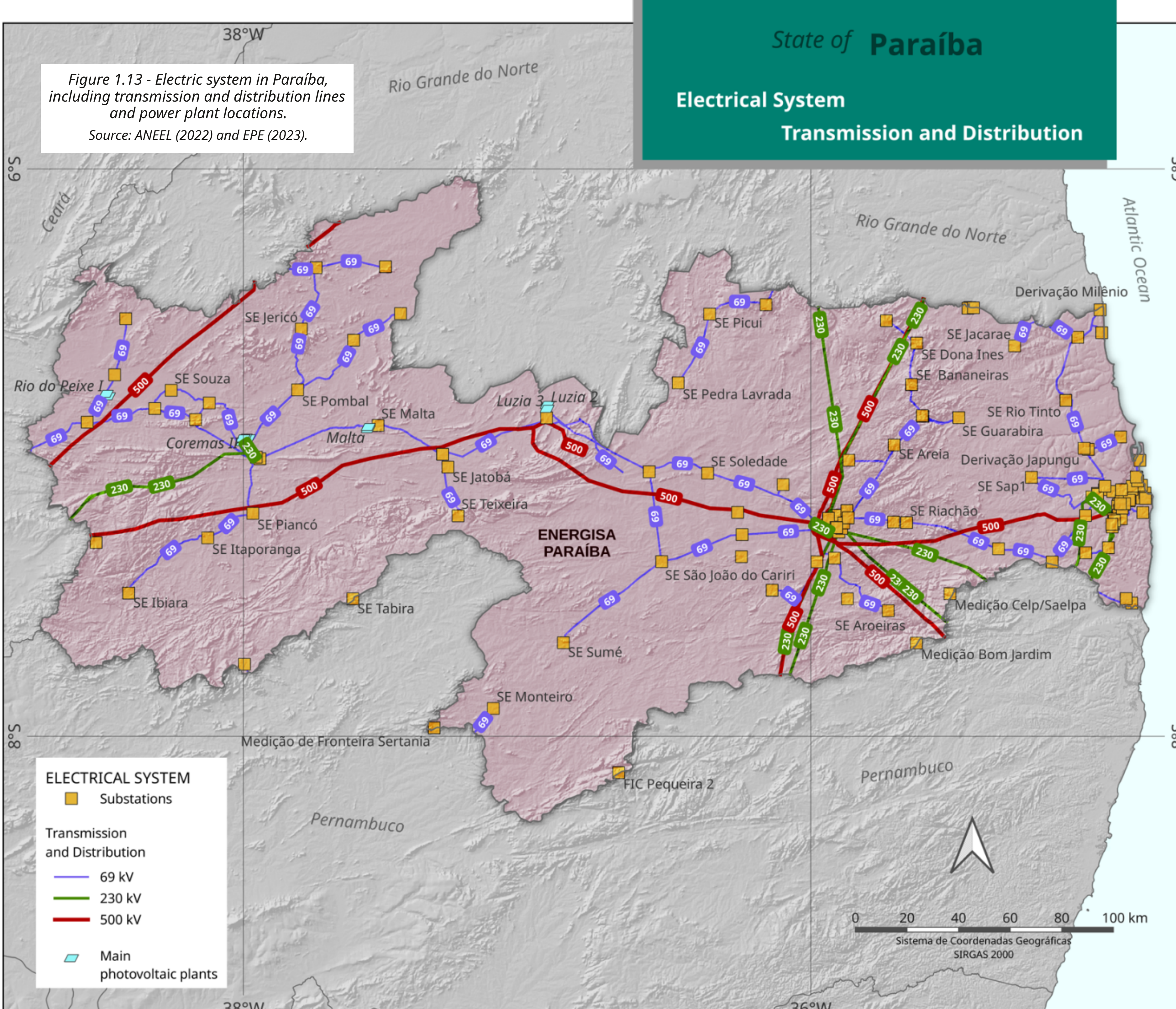


Figure 1.13 - Electric system in Paraíba, including transmission and distribution lines and power plant locations.

Source: ANEEL (2022) and EPE (2023).

Some photovoltaic plants in operation in Paraíba

Coremas Solar Complex, inaugurated in September 2020, in the municipality of Coremas, Paraíba (-6.9564°, -37.9937°). The complex comprises eight solar power plants with a generating capacity of 27 MWp (Megawatts-peak) each (Coremas I to VIII), including a substation and transmission line.

FUNDAMENTALS OF SOLAR ENERGY

Basic concepts of solar irradiation

Solar radiation is the energy source for electricity generation through two technologies already consolidated in the market: photovoltaic generation and heliothermic generation, also known as concentrated solar power or CSP. Solar energy also has applications in heat production to meet the demands of agricultural production, industrial processes, and water heating systems for buildings.

Solar energy is the result of the nuclear fusion of Hydrogen atoms, which represent about 75% of the Sun's composition, at an approximately constant rate for billions of years and with an instantaneous power of the order of 3.86 x 1026 W. Only a fraction of the solar energy emitted by the Sun reaches our planet Earth. The amount of energy reaching the top of the Earth's atmosphere has been measured since the early 1970s by different techniques and instruments and is known as the Solar Constant. The American Society for Testing and Materials established the value of 1366.1 ± 2.5 W/m² as a standard for the Solar Constant, whose value has been accepted worldwide as ASTM E490-00a (ASTM, 2019).

Among the various factors that influence the amount and variability of solar energy on the Earth's surface, the most important is the Earth's translational movement around the Sun in an elliptical orbit lasting 365 days, 5 hours, 48 minutes, and 48 seconds, and the rotation movement around a polar axis with an inclination of 23.45° concerning the plane of the solar orbit. These two movements combined define the daily (day/night) and the annual cycles associated with the seasons – summer, autumn, winter, and spring. Figure 2.1 illustrates these two main movements and their ephemeris.

Atmospheric components (gasses and particles present in the atmosphere) also play an important role in the attenuation of solar radiation due to interaction processes such as absorption and scattering of solar radiation. These radiative processes in the atmosphere determine the availability and variability of solar energy incident on the surface, which is used for electricity generation and other purposes.

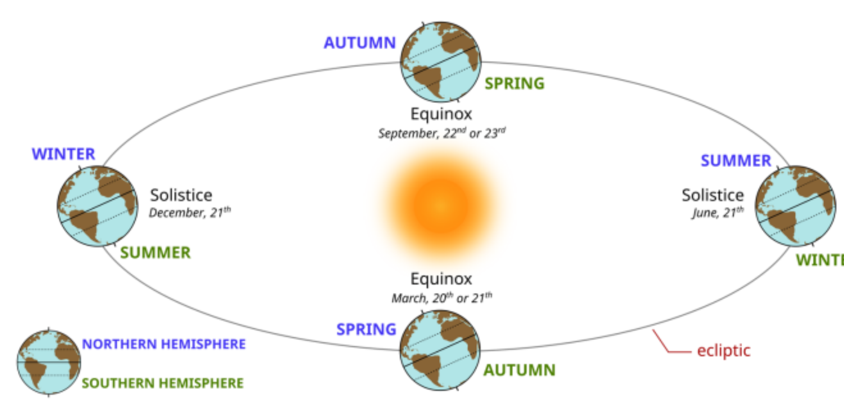


Figure 2.1 - Movement of the Earth around the Sun, highlighting the dates of the relevant ephemeris for the Southern Hemisphere.

Source: Martins and Pereira, 2019

Understanding solar radiation's daily and seasonal cycles requires defining a series of established concepts based on the relative position between the Sun and the Earth. Among these concepts are the fundamental notable angles illustrated in Figure 2.2: the zenith angle (θz), the altitude or elevation (α), and the solar azimuth angle (γs). The solar declination (δ), illustrated in Figure 2.3, is the angle between an imaginary line joining the Sun's and Earth's centers and the Earth's equatorial plane.

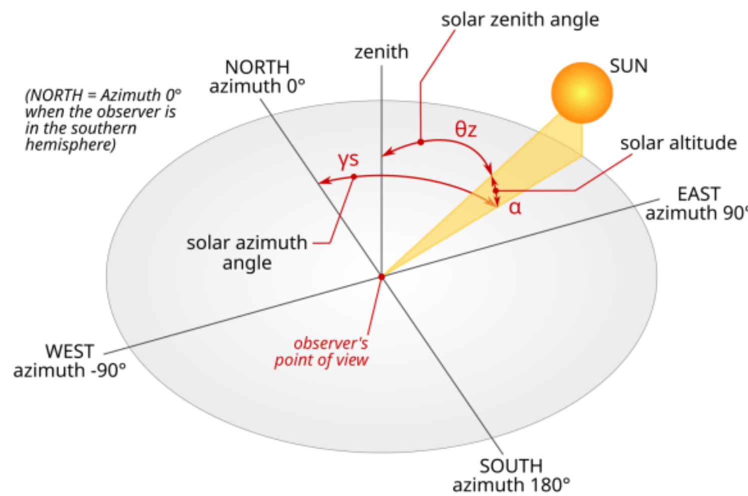


Figure 2.2 - Graphic representation of the primary angles that define the position of the Sun in the celestial vault.

Source: Martins and Pereira, 2019.

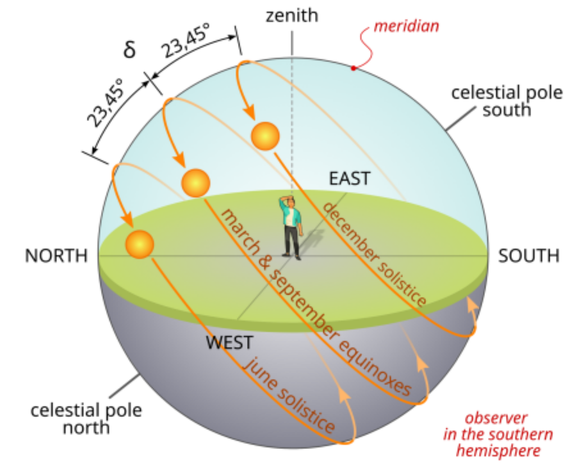


Figure 2.3 - Illustration of the declination angle (δ), which varies from 23.45° north to 23.45° south.

Source: Martins and Pereira, 2019.

Another fundamental concept is the photoperiod, which corresponds to the time interval for the passage of the Sun in the sky, from sunrise to sunset. It gives rise to the concept of twilight as defined by the ABTN standard (NBR-5123), which establishes standards for public lighting.

Components of incident solar irradiation

The Earth's atmosphere acts on the spectrum of incident solar radiation through scattering phenomena and selective absorption at specific wavelengths. Scattering occurs when a fraction of the incident radiation beam is re-radiated at longer wavelengths in random directions. The scattering process depends on the relationship between the atmospheric scatterer component's size distribution and the scattered radiation's wavelength. The scattering caused by atmospheric gases is described as Rayleigh scattering, while the scattering caused by particles suspended in the atmosphere and cloud droplets is described by the Mie scattering theory (Yamasoe & Corrêa, 2016).

Selective absorption of specific wavelengths of solar radiation occurs due to quantum phenomena of interaction between radiation and matter. The atmospheric components that most strongly contribute to the selective absorption of incident solar radiation in the ultraviolet range are ozone (O3), water vapor, and carbon dioxide (CO2) in the visible and near-infrared radiation ranges. As a result of these interactions of solar radiation with the atmosphere, the resulting solar spectrum that reaches the surface is strongly altered, as illustrated in Figure 2.4.

Solar irradiance represents the instantaneous flux of radiant energy incident on a surface per unit area, expressed in W/m² (Watt per square meter). **Solar irradiation** represents the amount of energy per unit area reaching the surface. Its unit of measurement in the International System (SI) is J/m² (Joule per square meter). However, the power generation industry most commonly uses the Wh/m² unit (Watt-hour per square meter) to express solar irradiation. This quantity is widely used in sizing photovoltaic systems.

Solar irradiance is classified into Global, Direct, and Diffuse components based on radiative scattering processes in the atmosphere. Solar irradiance can

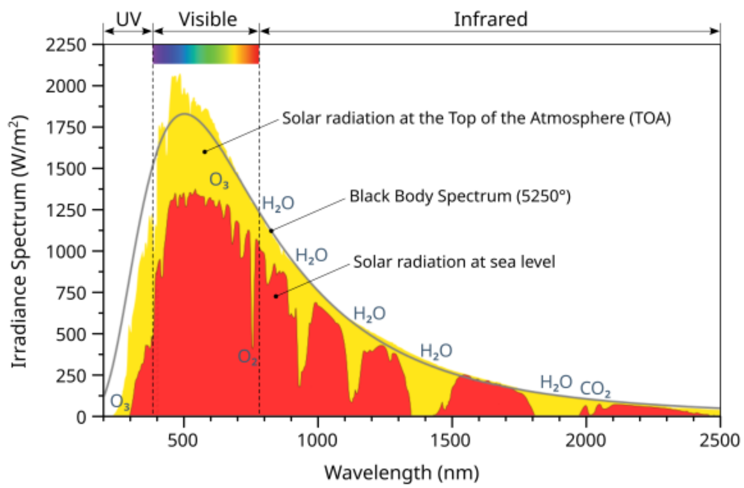


Figure 2.4 - The spectrum of solar radiation reaching the top of the atmosphere and the Earth's surface. The plot illustrates the absorption bands and the range of visible radiation.

also be determined considering the geometry and location of the surface on which the incidence occurs: Inclined Plane, Horizontal Plane, and Extrater-restrial. Based on these classifications, the definitions adopted in the Solar Energy Atlas of the state of Paraíba are presented below:

- *Extraterrestrial solar irradiance (G_0)*: the instantaneous flux of solar energy incident on an imaginary horizontal plane at the top of the atmosphere. It is also known as top-of-the-atmosphere irradiance or TOA;
- *Diffuse solar irradiance (Gdif or DHI)*: the instantaneous flux of solar energy incident on a horizontal plane located on the Earth's surface, resulting from the scattering of the direct solar beam by atmospheric constituents (molecules, particulate matter, clouds, etc.);
- *Direct normal solar irradiance (Gn or DNI)*: the instantaneous flux of solar energy coming directly from the Sun that falls on a plane located on the surface in the normal direction to the solar irradiation beam, without suffering any scattering during its course in the atmosphere;
- *Direct solar irradiance (Gdir)*: the amount of direct solar irradiance (Gn) incident perpendicularly to a horizontal plane located on the Earth's surface, being determined as the product between direct normal irradiance (Gn) and the cosine of the solar zenith angle (θz);
- *Global horizontal solar irradiance (G or GHI)*: the instantaneous flux of solar energy incident on a horizontal plane located on the Earth's surface, consisting of the sum of direct and diffuse solar irradiance, that is, G = Gdif + Gdir ou G = Gdif + Gn.cos(θz);
- *Tilted plane solar irradiance (GTIi)*: the instantaneous flux of solar energy per unit area, incident on an inclined plane concerning the Earth's surface. In general, this nomenclature is adopted to describe the solar irradiance in a plane with an inclination angle concerning the horizontal plane and facing the geographical North (or South) in the Southern (or Northern) Hemisphere.

The components of solar irradiance can be seen in the Figure 2.5.

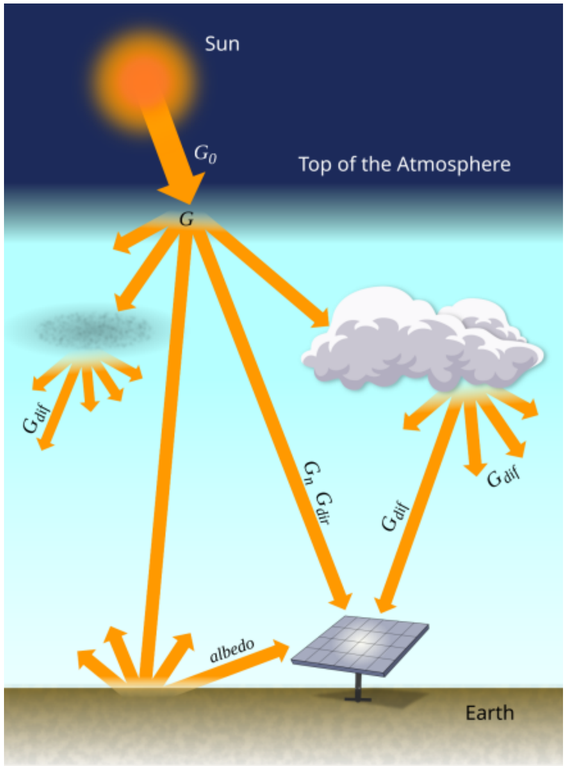


Figure 2.5 Components of solar radiation incident on a solar collector in an inclined plane.

Source: Brazilian Solar Energy Atlas - INPE, 2017.

Measurement of solar radiation

Several methods based on different physical processes are used to measure the solar energy incident on the surface, as shown in Table 2.1. Modern sensors, used to acquire solar radiation data, evaluate the physical parameters measured using an electrical signal and are generically called radiometers. ISO (International Organization for Standardization) and WMO (World Meteorological Organization) standards establish classifications and specifications for measuring solar irradiance (ISO, 1990; WMO, 2008).

Pyranometers are the most recent technology and widely used for global solar irradiance (GHI) measurements. These devices commonly use two types of sensors: the thermopile sensor (set of thermocouples) or the photodiode sensor.

In general, pyranometers are classified into three distinct classes:

- high quality (referred to as secondary standards);
- good quality (first-class instruments);
- moderate quality (second-class instruments).

Table 2.1 - Main physical processes used for acquiring solar radiation data.

Category	Measurement process	Sensors	Image
Indirect	Duration of sunlight (insolation)	Heliograph	
Mechanical	Bimetal	Actinograph	
Thermal	Transformation of shortwave radiant energy into longwave (thermopile)	Pyranometer Pyrheliometer Pyrgeometer	
Electric	Photoelectric effect	Luxmeter Photodiode Quantum Meter	
Optical	Conversion of UV radiation through fluorescent elements	GUV radiometer	
Molecular	Chemical reaction	Photographic film	

Thermopile pyranometers have a practically flat spectral response curve between 300 and 3000 nm (spectral range comprising visible radiation and part of ultraviolet and infrared radiation), which covers the entire solar radiation spectrum of interest, as shown in Figure 2.6. Nowadays, thermopile pyranometers are the most accurate type of radiometers (first class) for measuring solar radiation since the response curve of photodiode radiometers has a high spectral dependence and only partially covers the spectrum of incident solar radiation.

The direct methodology employs a pyrheliometer, a collimated pyranometer with a thermopile sensing element. A pyrheliometer must be coupled to a robotic system for tracking the solar disk, as shown in Figure 2.7 (a), to keep the sensor always illuminated by solar radiation beam throughout the day.

The indirect methodology uses a pair of pyranometers, one of which must be constantly shaded by using a ring (or a sphere attached to a solar tracker) to measure the diffuse component (DHI) of solar irradiance, as illustrated in Figure 2.7 (b). The direct solar irradiance (Gdir) is obtained by simple subtraction between the global radiation (GHI) and the diffuse component of solar radiation (DHI), and subsequent correction by the solar zenith angle.

Field measurements of solar irradiance are carried out by solarimetric stations with various configurations. However, to obtain data for solar energy projects, measure-

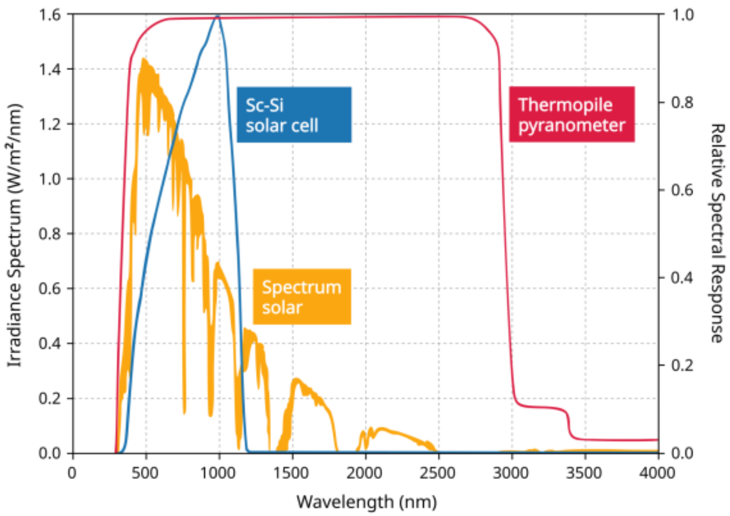


Figure 2.6 - Relative spectral responses of a sc-Si solar cell and a thermopile pyranometer.

Source: Neves, 2021.

ments of solar radiation are always accompanied by simultaneous measurements of meteorological variables, such as air temperature and wind speed, at the same data acquisition frequency.

There are two primary types of solarimetric stations: high-quality stations intended for research, development, and calibration of computational models used for surveying solar energy resources and automatic stations defined by EPE (EPE-DEE-RE-065/2013) for data registration and to meet the requirements established for participation in national energy auctions. According to the EPE regulation, the solarimetric station must have at least the following instruments:

- two pyranometers without spectral selectivity (second class instruments or better) according to ISO 9060:1990, for the measurement of global horizontal irradiation;
- one anemometer (for measuring wind speed);
- one hygrometer (for measuring the relative humidity of the air);
- one thermometer (for measuring the air temperature).

The stations destined for research and model development employ, in addition to pyranometers, pyrheliometers coupled to a solar tracker to acquire the direct normal solar irradiance and various other measurement instruments such as sky imaging cameras for evaluating cloudiness, spectrophotometers for studying the spectrum of solar radiation, solar photometers for analyzing the atmosphere composition (aerosols, water vapor), among others. Figure 2.8 illustrates these two types of solarimetric stations.

Uncertainties in solar radiation measurements result from the quality of installations, equipment, the location of measurements, and operational activities in the field. Table 2.2 presents, in a qualitative way, the relative relevance of the various installation, operation, and maintenance stages of a typical solarimetric station. For surveying solar energy resources for electric power generation, "first class" or "secondary standard" instruments should only be used if the project has sufficient long-term financial resources to support the operation and maintenance necessary to ensure the quality of measurements.

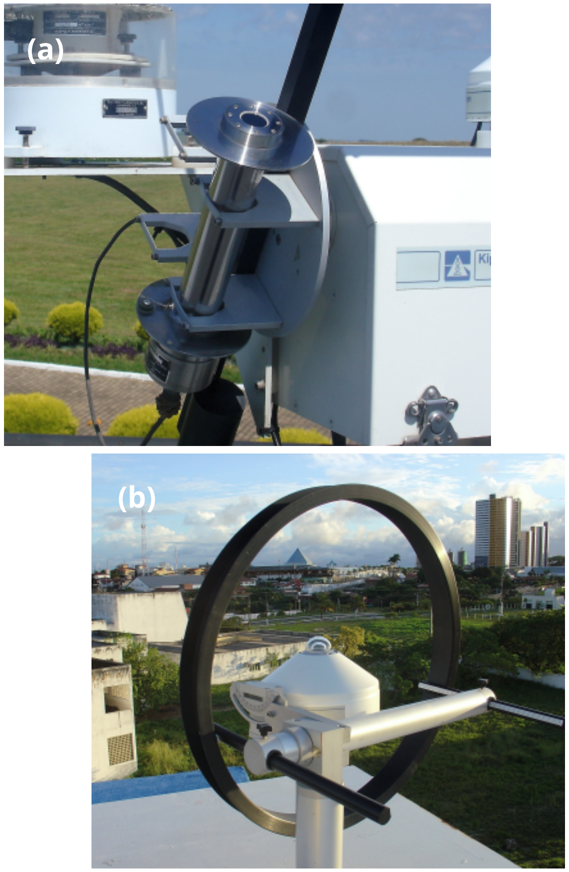


Figure 2.7 - Examples of processes for measuring direct solar radiation: (a) using the pyrheliometer and (b) using a pair of pyranometers, one of which is equipped with a shading ring (the second pyranometer does not appear in the image).

Generating electricity from solar energy

Two technologies are used to convert solar energy into electricity: photovoltaic conversion (or photovoltaic generation) and thermal conversion (or heliothermal generation). The first is based on the physical principle known as the photovoltaic effect, which is the production of an electric current in a semiconductor material exposed to electromagnetic radiation, such as the silicon cells present in photovoltaic modules.

Conversion depends on the semiconductor material used, which is characterized by the creation energy of free electron pairs and gaps (forbidden band energy). Thus, the choice of technology for the production of photovoltaic modules (mono- or poly-crystalline silicon, thin films or organic semiconductors) is linked to the spectral response and also to the incident solar spectrum. Figure 2.9 illustrates the photovoltaic effect on a semiconductor cell that makes up a photovoltaic panel. The conversion efficiency of solar radiation into electricity of the technologies available on the market is in the order of 18 to 24%.

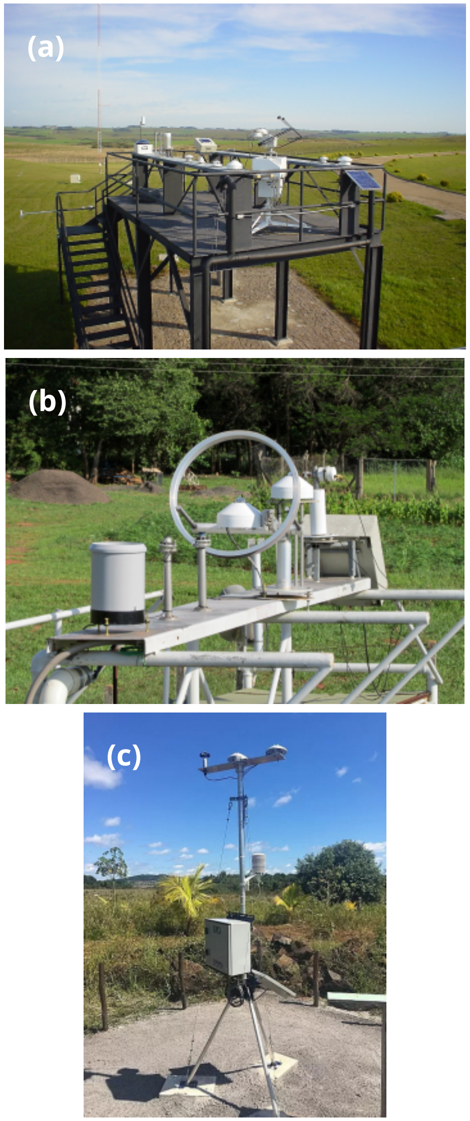


Figure 2.8 – Solarimetric platforms for data collection
(a, b) platform intended for research,
(c) platform meeting the EPE requirement (2021).

Uncertainties

The accuracy of a radiometer indicates how close the measurements taken are to the reference value (true value) and is related to systematic deviations, generally attributed to calibration problems. On the other hand, the uncertainty or precision is related to the spread of data concerning the average value. It is related to several instrumental factors or stages of data acquisition, such as maintenance, dirt in the pyranometer dome, structural instability of the platform, etc. The image opposite illustrates the concept of accuracy and precision in statistical terms. The center of the target represents the true value of the evaluated variable. The points represent the values observed for the same variable (Source: Martins and Pereira, 2019).

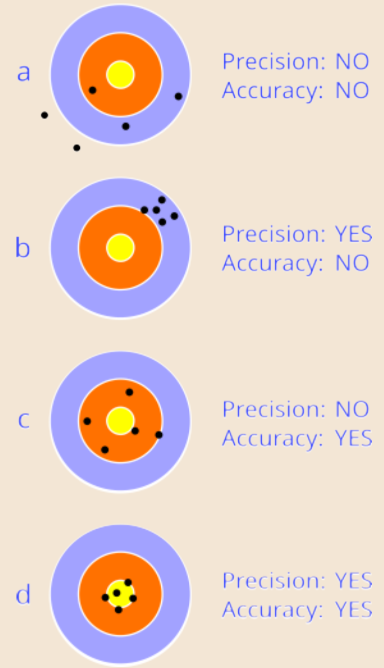


Table 2.2 - Relative relevance, in a qualitative way, of the various stages of installation, operation, and maintenance of a solarimetric station.

Stages	Relative Importance		
	Greater	Medium	Minor
Operation and maintenance	■		
Quality control	■		
Metadata generation and storage		■	
Choice of sensors		■	
Installation method		■	
Choice of location		■	
Sampling frequency		■	
Campaign period		■	
Sensor calibration			■
Data acquisition			■

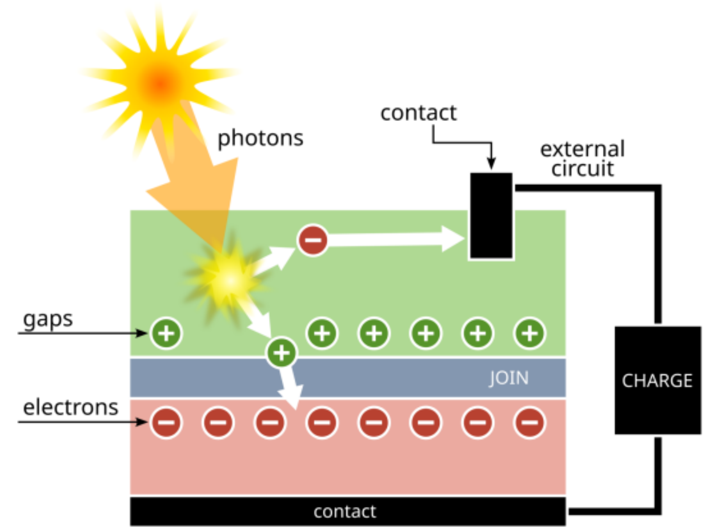


Figure 2.9 - Illustration of the photovoltaic effect on a photovoltaic cell.

Source: Neves, 2021.

Photovoltaic generation employs incident global irradiation, that is, both direct and diffuse components of solar radiation, including that due to surface albedo (reflection). Therefore, it occurs even on cloudy days but with lower productivity.

The operating temperature of the semiconductor cell also influences photovoltaic generation. Increasing temperature causes the reduction of photovoltaic conversion efficiency. Hence, the importance of temperature data at the location of the photovoltaic plant, as they influence the operating temperature of the photovoltaic module.

Thermosolar or heliothermic power generation (CSP – Concentrated Solar Power) uses mirrors (heliostats) that reflect sunlight to concentrate the solar beam for thermal conversion. The solar beam heats a working fluid, generating water vapor that moves the turbines, driving the electricity generator. There are several typologies of solar thermal generation, using linear parabolic mirrors or systems of several flat mirrors in an arrangement in order to generate heat at a single point. Figure 2.10 illustrates the main typologies of solar thermal generation most used. Thermal solar generation uses only the direct component of incident solar radiation and, therefore, can only be applied in regions with low cloudiness and high incidence of direct normal solar radiation, such as in arid regions. However, it has the advantage of generating electricity even after sunset, as long as it has storage systems for the heat generated during the day.

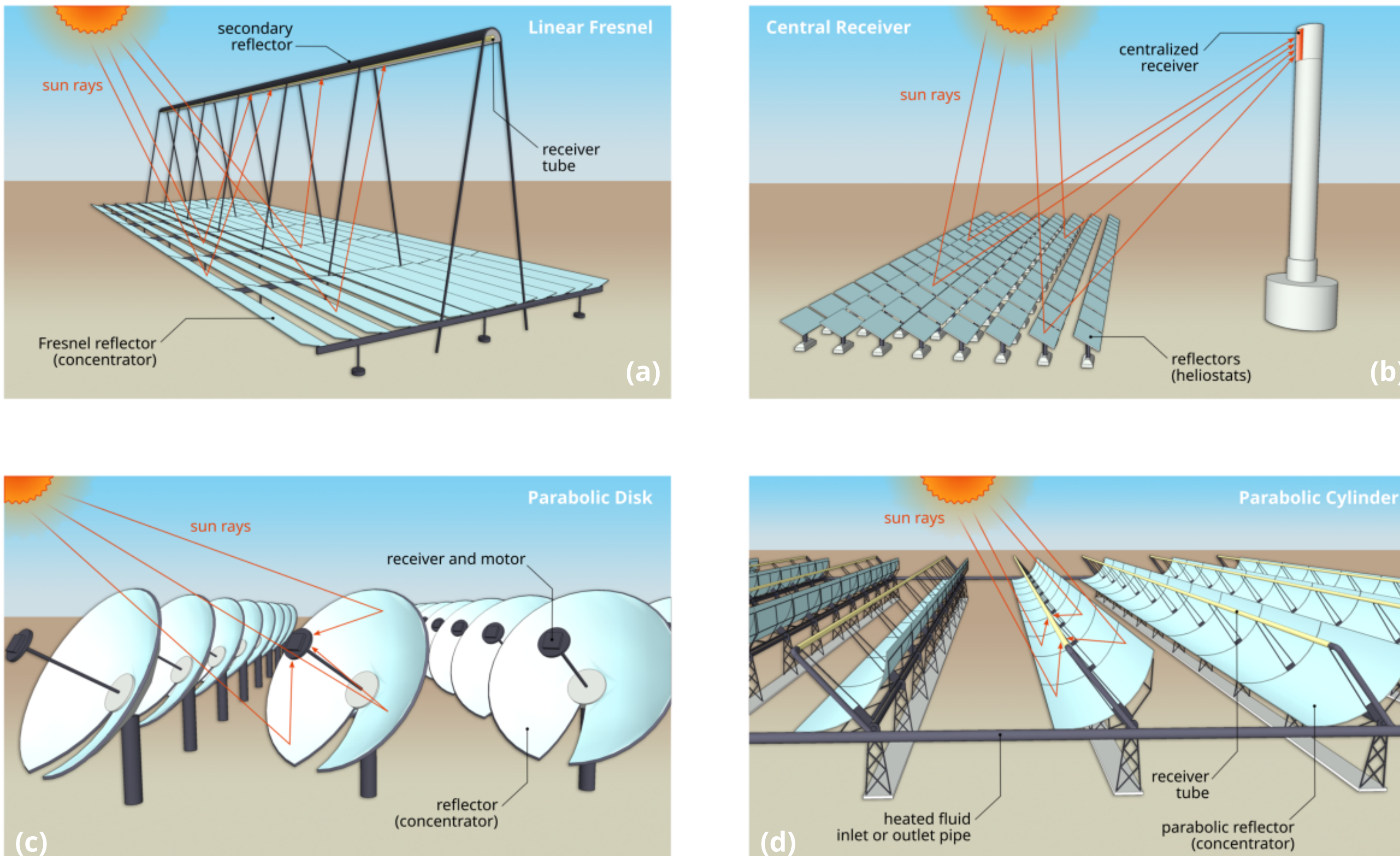


Figure 2.10 - (a) heliothermic generation system (a) by Fresnel lens technology (b) employing a tower system; (c) employing parabolic disk; (d) employing parabolic cylinder.

METHODOLOGY

The elaboration of the Solarimetric Atlas of Paraíba adopted an innovative methodology that combines the use of a radiative transfer numerical model, reanalysis database, and data observed by remote sensing of the atmosphere (Martins & Pereira, 2006; Martins et al., 2008; Costa et al., 2016; Pereira et al., 2017). As a result of research carried out over the last few decades, the spectral model of radiative transfer in the atmosphere, BRASIL-SR, used in the elaboration of this Atlas, employs physical properties of the atmosphere - air temperature, relative humidity, optical thickness of aerosols, concentration of atmospheric gases, cloudiness – to estimate the vertical profile of the leading gases and particles present in the atmosphere based on consolidated techniques in the scientific literature. Data related to land cover and use (albedo and altitude) are also essential for simulating the physical processes of attenuation and scattering of solar radiation and obtaining solar irradiance incident on the surface and reflected back to the sky (Casagrande et al., 2021). Information on atmospheric cloudiness, the main factor modulating the downward solar radiation on the surface, is obtained from images from geostationary satellites in the GOES family.

The values of incident solar irradiance on the surface provided by the BRASIL-SR model for each satellite image are numerically integrated to determine the daily totals for a period of 10 years starting in 2012. The uncertainties associated with the methodology are assessed using statistical metrics, such as bias or systematic deviations, the root-mean-square error, and Pearson's correlation, determined by comparing the estimated and observed values at the surface measuring stations.

The database made available in this Atlas includes the annual and monthly averages of the daily total of the following components of surface solar irradiation:

- Total daily global solar irradiation on the horizontal plane (GHI);
- Daily total of global solar irradiation on a 10° tilted plane relative to the horizontal plane (GTI_{10});
- Daily total of diffuse solar irradiation on the horizontal plane (DHI);
- Daily total of normal direct solar irradiation (DNI), i.e., solar energy incident on a surface perpendicular to the solar radiation beam.

BRASIL-SR Model Description

The solar irradiation values produced by the BRASIL-SR model have been adopted as a reference for the Brazilian territory by government institutions and energy sector entrepreneurs (CRESESB, 2022; SOLERGO, 2022).

Figure 3.1 presents the model operation flow. The BRASIL-SR spectral model uses 37 spectral intervals distributed between 200 nm to 3700 nm. Solar spectral data at the top of the atmosphere (TOA) follow Gueymard (2004).

The vertical profiles of air temperature, atmospheric pressure, and atmospheric gas concentration follow Anderson et al. (1986), and they are available for five standard

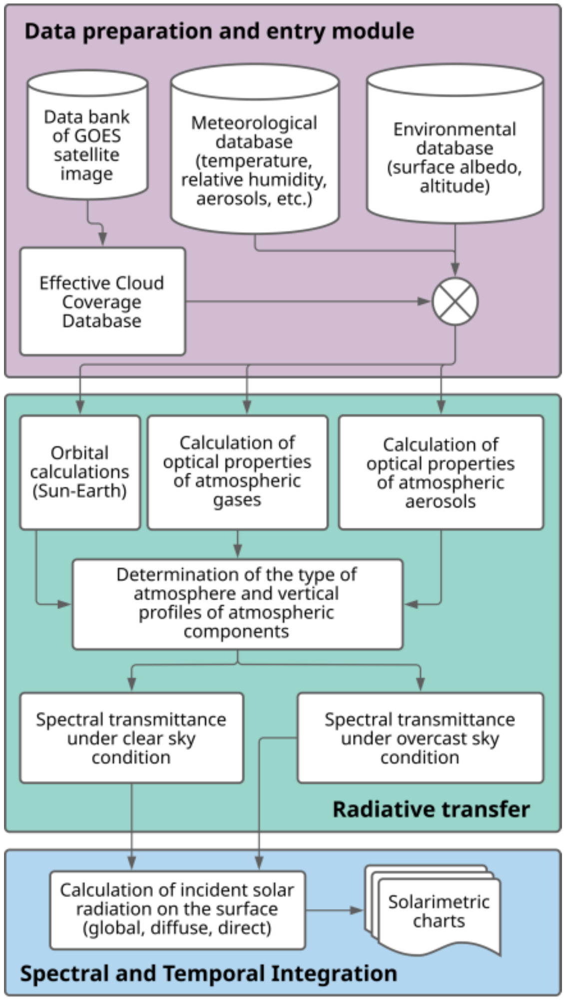


Figure 3.1 - Block diagram of the methodology used in the Solar Atlas of Paraíba.

atmospheres selected based on the surface temperature. The absorption coefficients of solar radiation by water vapor, O_3, CO_2, and O_2 gases are calculated based on methods proposed by Wiscombe (1977), Schreier (2019), and Gordon (2017).

The model surface boundary condition is established based on the surface spectral albedo for direct and diffuse radiation. Albedo information was determined as described by Schaaf et al. (2002) using the derived BRDF kernel parameters for the MODIS sensor on the ACQUA and TERRA satellites. BRDF kernel parameters are linearly interpolated for the 37 spectral wavelengths used by the model.

The optical depth database of atmospheric aerosols for the 550 nm wavelength is interpolated for the remaining 36 wavelengths of spectral ranges using the Angström exponent as an input parameter (Casagrande et al., 2021). The optical depth of aerosols is distributed vertically in each grid cell, assuming a fixed optical depth of 0.0216 for heights between 5 km and 50 km. Below 5 km height, an exponential decay of the optical depth with altitude is assumed. The selection of the other aerosol optical properties (single scattering albedo and asymmetry factor) is based on the predominant biome in each grid cell, as described in Darbyshire et al. (2018).

The BRASIL-SR model assumes that the clouds are distributed in two atmospheric layers of the vertical profile of the atmosphere. The optical properties of Stratocumulus clouds were used for the Atlas. The methodology assumes that under a completely overcast sky, there is no incidence of direct irradiation on the surface.

Input Data

To properly utilize the BRASIL-SR radiative transfer model, one must gather a collection of meteorological and environmental data to numerically parameterize the radiative interactive processes in the atmosphere. This topic provides a brief overview of the necessary steps for organizing this data, which will automate the input data reading process and enable the model to run smoothly. This procedure resulted in the ten years of surface incident solar irradiation data that comprise this Solar Energy Atlas of the State of Paraíba. All the databases used were obtained from renowned institutions and are widely used in various areas, including agribusiness and energy (Casagrande et al., 2021).

Cloud cover

Cloudiness is the main factor in attenuating the solar radiation incident on the surface. Therefore, providing the BRASIL-SR model with quality information on the cloudiness present in a given location is essential for obtaining reliable and representative estimates of solar irradiation (estimates with low uncertainty). Quality data on cloud cover over large areas is obtained by analyzing satellite images in the visible spectral range taken by geostationary satellites. The equation determines the effective dimensionless cloud cover index (C_{eff}) for each pixel (digital image element)

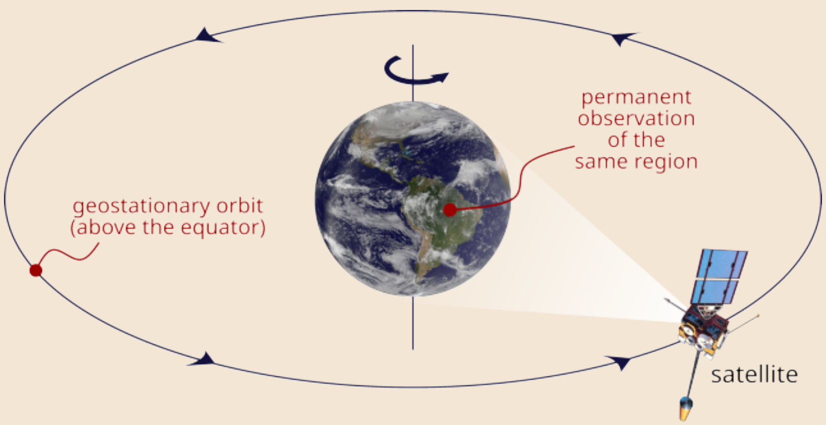
$$C_{eff} = \frac{L - L_{clear}}{L_{cloudy} - L_{clear}}$$

where L represents the radiance value observed by the satellite for a specific pixel in the image. L_{clear} and L_{cloudy} represent the radiance values observed by the satellite for the same pixel when it is in clear sky and sky covered by clouds, respectively. The values of L_{clear} and L_{cloudy} are determined from statistical analysis of satellite images obtained in similar situations of the geometry of pixel illumination by the Sun, i.e., approximately the same solar zenith angle.

The effective cloud cover index was determined based on the images from the geostationary satellite GOES 13 (already decommissioned) between 2012 and 2017 and GOES 16 for the remaining period between 2018 and 2021. The images in the visible channel (wavelength 0.64 µm) from the GOES 13 satellite have a spatial resolution of 4 km. Its time resolution (interval of acquisition of each image) was 30 minutes.

The GOES 16 satellite replaced GOES 13 and is the first of the new generation of satellites in the GOES family, with improvements in the spatial and time

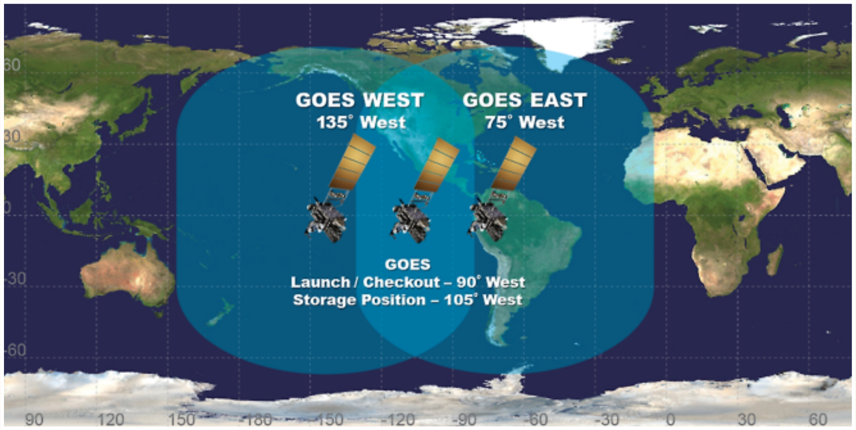
Geostationary satellites



Geostationary satellites are used to provide a continuous Earth observation service over a large area. The GOES (Geostationary Operational Environmental Satellite) family of satellites has a geosynchronous orbit in the equatorial plane and with the same orbital period as the planet's rotation period. The geostationary orbit is a type of geosynchronous orbit with an additional feature. It remains stationary relative to a single point on the planet's surface. The satellites are positioned approximately 36,000 km above the Earth's surface.

NOAA/NASA (National Oceanic and Atmospheric Administration / National Aeronautics and Space Administration) operates the GOES family of satellites which have the best geometry for observing Brazilian territory as they remain positioned over the equator at the 75˚ West meridian.

The figure below illustrates the coverage areas of the GOES geostationary satellites over the Americas.



resolution of the data made available thanks to the ABI imager. Images in the visible channel (wavelength 0.64 μm), with a spatial resolution of 1.0 km and a 10-minute resolution, were used to create the Atlas. Table 3.1 summarizes the technical specifications of the two satellites. Figure 3.2 illustrates visible channel images obtained by the GOES 13 and 16 satellites.

Temperature, relative humidity and precipitable water

The BRASIL-SR model uses air temperature, relative humidity, and precipitable water values to establish the vertical profiles of atmospheric constituents. The air temperature values are fundamental to establishing the vertical profiles of the constituent gases of the atmosphere (Martins, 2001). Solar radiation interacts strongly with precipitable water, attenuating the solar irradiation incident on the surface. Its data is used to correct the water vapor profile in the atmospheric column. To produce the Atlas, the data for three meteorological variables available in the ERA-5 reanalysis database were also interpolated based on the nearest neighbor pixel method to the spatial resolution of the GOES satellite images. The ERA-5 reanalysis is available from the Copernicus Climate Change Service. (https://climate.copernicus.eu/).

Ozone

Ozone is the atmospheric constituent responsible for the attenuation of solar radiation in the ultraviolet spectral range. The database from the Copernicus Climate Change Service provided the ozone concentration in the atmospheric column to parameterize the radiative processes associated with UV spectral band. This database has a spatial resolution equal to 1°. Therefore, it is necessary to adjust the base to the spatial resolution presented by the satellite images. The vertical profile followed the standard atmosphere selected as a function of surface air temperature.

Albedo

Albedo or reflection coefficient is the ratio between the radiation reflected by the surface and the radiation incident on it. It is

Table 3.1 - Temporal frequency of image collection over the time adopted for elaborating the Solarimetric Atlas of Paraíba.

Satellite	Time Series Extension	Time resolution	Spatial resolution
GOES -13	April 2003 to December 2017	Two images per hour	4 km
GOES -16	January 2018 to December 2021	Six images per hour	1 km

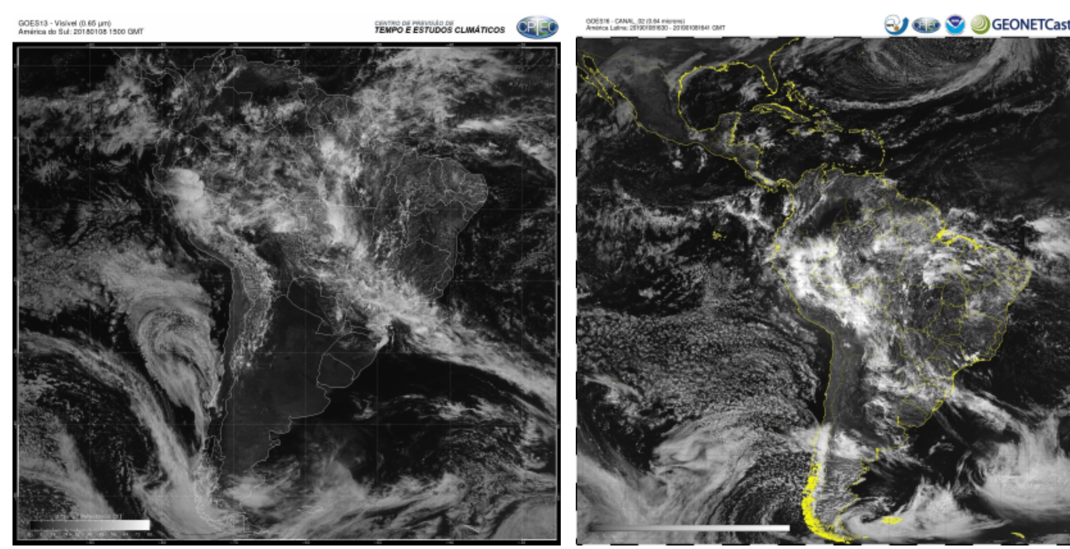


Figure 3.2 - Images in the visible channel of the satellites GOES 13 (left) and GOES 16 (right) in rectangular projection. Source: DISSM/INPE.

dimensionless and is usually measured on a scale from zero to one. The bidirectional reflectance distribution function (BDRF) provides the reflectance of a target as a function of the illumination and viewing geometries, for example. The changes in reflectance and albedo of a given surface are related to its lighting geometry and surface type, being different for different wavelengths. The methodology to represent surface albedo variability uses the bidirectional reflectance distribution functions (FDRB), combining parameters such as isotropic scattering, scattering on horizontally homogeneous surfaces, and optical scattering geometric. Following these principles, the BRASIL-SR model uses ground spectral albedo data to calculate direct and diffuse solar irradiation by using parameters of the FDRB functions and polynomial formulas with coefficients independent of the wavelength. Monthly climatological values in seven wavelength bands were linearly interpolated for the 37 wavelength intervals adopted in the BRASIL-SR model. The database used for this processing is available for public access at http://tds.webservice-energy.org.

Altitude and Biomes

The model also uses topographic altitude data for correction and parameterization of some of the atmospheric variables and the biome map to select the set of optical properties of aerosols defined from the prevailing biome of each grid point. The altitude database for the Brazilian territory is the GTOPO30, from the Earth Resources Observation and Science (EROS) Data Center/United States Geological Survey (USGS). This database is available in grid format with an arc resolution of 30 sec (approximately 1 km) and vertical discretization of 100 m. Biome data come from the Brazilian Institute of Geography and Statistics (IBGE), with a map scale 1:250,000 (Figure 3.3). As with the other input data, the values are interpolated to the pixel size of the satellite images.

Computational processing

The BRASIL-SR model was run for a limited area domain, as illustrated in Figure 3.4, covering a region beyond the borders of the Paraíba state territory, with a rectangular grid in the horizontal resolution of 0.04° x 0.04° (~16 km²). This domain comprises latitudes between 9.46° south and 5.54° south and longitudes between 40.46° west and 34.62° west. The entire set of meteorological and environmental data used as input to the model was organized for the domain illustrated in Figure 3.4, including satellite images, air temperature, relative humidity, and optical thickness of aerosols.

The domain area was defined based on the location of meteorological stations with solarimetric data to assess the uncertainties in the estimates of surface solar

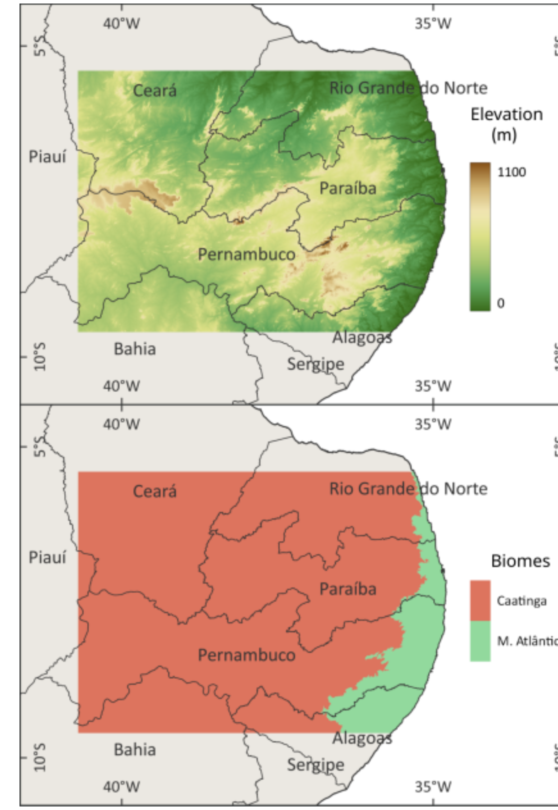


Figure 3.3 - Relief maps (above) and biomes (below) used in the BRASIL-SR model.

Source: EROS/USGS and IBGE.

irradiation produced by the model. Solarimetric data observed in the territory of Paraíba and neighboring states were selected to ensure the representativeness of the state's border areas and enable a rigorous evaluation of the BRASIL-SR model performance throughout the entire state area. The observed database includes a set of public meteorological stations managed by the National Institute of Meteorology (INMET), National Institute of Space Research (INPE), Federal Institute of Pernambuco (IFPE), and a private data

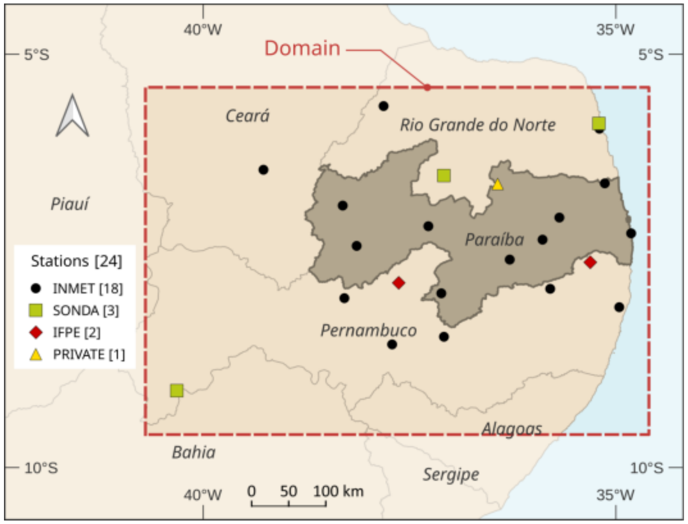


Figure 3.4 - The red dashed area represents the target area configuration of the BRASIL-SR model to obtain estimates of the daily total of incident solar irradiation on the surface. The dots indicate the location of the measuring stations

collection station kindly provided by *Casa dos Ventos*.

The elaboration of the solar resource mapping presented in this document had a high computational demand due to the extension of the Paraíba territory, the amount of information stored in the meteorological and environmental databases, and the satellite images used to feed the model. The model was run for a period of 120 months (10 years) so that the computational demand met the following steps:

i. Pre-processing and storage of satellite images for the domain area;

ii. Determination of cloud cover for each stored satellite image;

iii. Transfer and processing of meteorological and environmental data to the rectangular grid of the target domain;

iv. Running the model with the input database prepared and stored in the previous steps;

v. Post-processing of model estimates and determination of monthly and annual average values of daily solar irradiation totals in Paraíba.

These listed steps were processed in a cloud computational system using the Amazon Elastic Compute Cloud (Amazon EC2) service (AWS). For greater computational efficiency, a T3a-type instance was chosen - an expandable general-purpose instance designed for applications facing temporary CPU usage peaks. The contracted infrastructure had eight virtual CPUs (AMD EPYC 7000 series processors at 2.5 GHz) and 32 GB of RAM memory, connected to a general-purpose SSD (solid-state storage drive) with a capacity of 100 GB for fast loading operating system and libraries, as well as an input/output-optimized HDD (hard disk) with a capacity of 1TB for storing the model's input and output data.

All computational packages supporting the model (including open-access scientific libraries such as NetCDF and HDF5) were recompiled to optimize their performance for the processors available in the instance. The compilers of the Intel OneAPI package (version 2022.1.0) ensured compatibility with the BRASIL-SR model and maximum application performance.

The final volume of the input database (calculated after pre-processing, which resizes the data to the domain grid and compresses the files) was approximately 27 GB. The processing took approximately 576 machine hours using the eight cores full-time, not including rounds for testing, evaluating and adjusting model settings, or downloading and pre-processing input data. At the end of the runs, 297 GB of model output data were generated, of which 283 GB comprise high-resolution data (0.01° x 0.01°).

Validation and uncertainty analysis

Atmospheric or satellite models are valuable tools for mapping solar resources at high resolution. However, uncertainties must be quantified, as they represent risks in a solar project. The validation of the modeling used for this Atlas consisted of comparing the estimates of daily totals of solar irradiation in its global horizontal (GHI) and direct normal (DNI) components, provided by the satellite model, with a database of observed data collected at surface measurement. These data sets were not used to adjust the BRASIL-SR model results statistically, ensuring that the errors represent the entire state of Paraíba.

The validation procedure used data from 24 solarimetric stations belonging to meteorological centers, research and teaching institutions, and private entrepreneurs to guarantee total coverage and spatial representativeness of the state of Paraíba and its surroundings. After a quality control process, described in a later chapter, 24 stations with reliable global solar irradiance measurements were selected, 4 of which have direct irradiance data records:

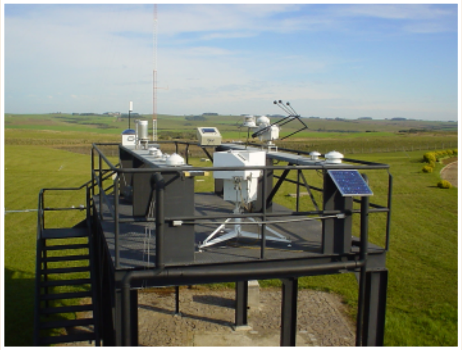
- 18 (eighteen) automatic weather stations operated by the National Institute of Meteorology (INMET) containing hourly records of horizontal global solar irradiation. Data are made available through the portal of INMET and have public access <https://portal.inmet.gov.br/>;
- 2 (two) solarimetric stations belonging to the Pernambuco Solarimetric Network, operated by the Federal Institute of Pernambuco (IFPE). The data, of public access, can be accessed on the portal of the Pernambuco Solarimetric Network <https://redesolpe.com.br/>;
- 3 (three) solarimetric stations belonging to the SONDA Network operated by the National Institute for Space Research (INPE) and located in Petrolina/PE, Caicó/RN, and Natal/RN, with records every minute of global horizontal, diffuse horizontal and horizontal solar irradiance normal direct (except Natal/RN). All stations have publicly accessible data through the portal of the SONDA Network <http://sonda.ccst.inpe.br/>;
- 1 (one) standard EPE solarimetric station located in the Campina Grande mesoregion, State of Paraíba, belonging to private developers.

Solarimetric stations

INMET's automatic weather stations meet the standard of the Global Observing System/World Meteorological Organization (GOS/WMO) world meteorological observation system and have several sensors measuring atmospheric pressure, air temperature, relative humidity, precipitation, solar radiation, wind direction, and speed, among others. Each station has a second-class pyranometer (ISO 9060:2018). These stations operate autonomously and generally have limitations regarding preventive maintenance and cleaning of the pyranometer domes, which leads to a higher percentage of data being excluded during the quality control procedure. However, it is the most comprehensive base of solarimetric measurements available in the country.

Example of standard INMET station.

The SONDA Network focuses on collecting and disseminating environmental data to promote the country's expansion of solar and wind energy sources. Its solarimetric stations follow the Baseline Surface Radiation Network (BSRN) standards and use first-class radiometric sensors following the requirements of the ISO 9060:2018 standard. SONDA stations have a wider range of sensors, typically comprising solar trackers measuring solar irradiance's direct normal (DNI) and diffuse (DHI) components. They may also include pyrgeometers, PAR sensors, all-sky cameras, solar photometers, and spectroradiometers.



BSRN standard station example.

The database available at *Casa dos Ventos* came from a station that meets the EPE standard (DEE-RE-065/2013). The standard EPE stations have at least two pyranometers of the second class "Spectrally Flat" or higher, following the ISO 9060:2018 standard, ensuring redundancy for measuring horizontal global irradiation, in addition to measuring relative humidity, air temperature, and wind speed.

Example of a standard EPE station.

The Pernambuco Solarimetric Network includes stations operating in different campuses of the Federal Institute of Pernambuco. Only data collected at stations near the border of Paraíba and equipped with a solar tracker were used in this Atlas, which allows the measurement of direct normal (DNI) and diffuse (DHI) components of solar irradiance.

Quality control

It is common for solarimetric measurements to have flaws and data quality problems over the years. In such context, the quality control of the observed data is required before they can be used to assess the uncertainties in solar irradiance estimates by computer models. In addition to the accumulation of dirt in radiometers, which is quite common, calibration regularity, signal conversion errors, and interference caused by obstacles are some of the most frequent problems.

The quality control met the criteria recommended internationally by the BSRN (Baseline Surface Radiation Network) combined with other technical-scientific documents (Gueymard, 2014; WMO no. 8, 2018). The algorithm was divided into four gradually more rigorous stages in addition to a prior consistency analysis. As the automated qualification process is subject to failures, a visual inspection was also carried out for final approval of the measurements. Figure 3.5 graphically illustrates, in a block diagram, this procedure. At the same time, Table 3.2 shows the total percentage of approved data for the GHI and DNI variables.

Statistical Metrics

Comparisons between model data and surface measurements were performed for each station individually and for the entire available data set. Conventional statistical metrics defined by Mean Error (***bias***) and Root Mean Squared Error (***REQM***) were used. The ***bias*** indicates the model's tendency to overestimate (positive values) or underestimate (negative values) the solar potential at the location, meanwhile the ***REQM*** is a measure of the spread between the measured data and the data estimated by the model so that the smaller the ***REQM*** values, the better the model performance. Pearson's correlation (***r***) is a test that measures the statistical relationship between the irradiation estimated by the model and the values observed at surface stations. A linear association is expected between these two sets of values, so the ***r*** values must be close to 1.0 (one). Equations 1, 2, and 3 detail these indices.

$$bias = \frac{1}{N}\sum_{i=1}^{n}(x_i - y_i) \quad \text{(Eq. 1)}$$

$$REQM = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - y_i)^2} \quad \text{(Eq. 2)}$$

$$r = \frac{\sum_{i=1}^{n}[(x_i - \bar{x}_i)(y_i - \bar{y}_i)]}{\sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \bar{x}_i)^2} \cdot \sqrt{\frac{1}{N}\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}} \quad \text{(Eq. 3)}$$

where y_i is the observed value of the variable at the i^{th} instant of time, x_i is the value of the same variable estimated by the model corresponding to the same instant of time as the observed value, and N is the number of records of the variable being validated.

High values of ***bias*** and ***REQM*** obtained for some locations are related to modeling and surface measurement uncertainties. Problems related to radiometers soiling, calibration, and even shading effects due to improper location of the measuring station

Table 3.2 - Total percentage of approved data for the GHI and DNI variables after the qualification process, considering the total number of evaluated stations.

Variable	Length of time series (in days)	Number of approved days	Approved percentage
GHI	49250	35048	71,2%
DNI	11750	7347	62,5%

are challenging to detect and often need to be noticed by the quality control method applied to the observed data and even by visual inspection. Therefore, assessing and quantifying these issues whenever possible over a large set of measurement stations is advisable to reduce the impact of measurement uncertainties.

Tables 3.3 and 3.4 summarize the validation metrics obtained for the GHI and DNI for all stations selected in the mapped domain.

Percentual ***bias*** and ***REQM*** were evaluted based on the mean value of observations at measurement sites used in the validation process.

The percentiles provide information on the fraction of observations (or deviations) that are below their value, calculated on a monthly basis. Thus, for example, the 25th Percentile, or P_{25}, represents the upper limit of 25% of the records present in the statistical analysis, and so on.

The deviations of each station have the same weight in the determination of the percentiles and in the final averages. The mean refers to the arithmetic mean of all 24 stations employed in the validation process that passed quality control. There is no weighting by data period.

Comparison between solarimetric bases

Several solarimetric databases are available, regionally, nationally, and globally, originating from different methods such as interpolation between surface stations, mesoscale or global dynamic modeling (reanalysis), and satellite models. The database of the Solar Energy Atlas of the State of Paraíba (Paraíba, 2022) was developed and validated using the BRASIL-SR satellite model, the same tool widely disseminated through the Brazilian Atlas of Solar Energy (Brasil, 2017). It should be noted, however, that these databases have

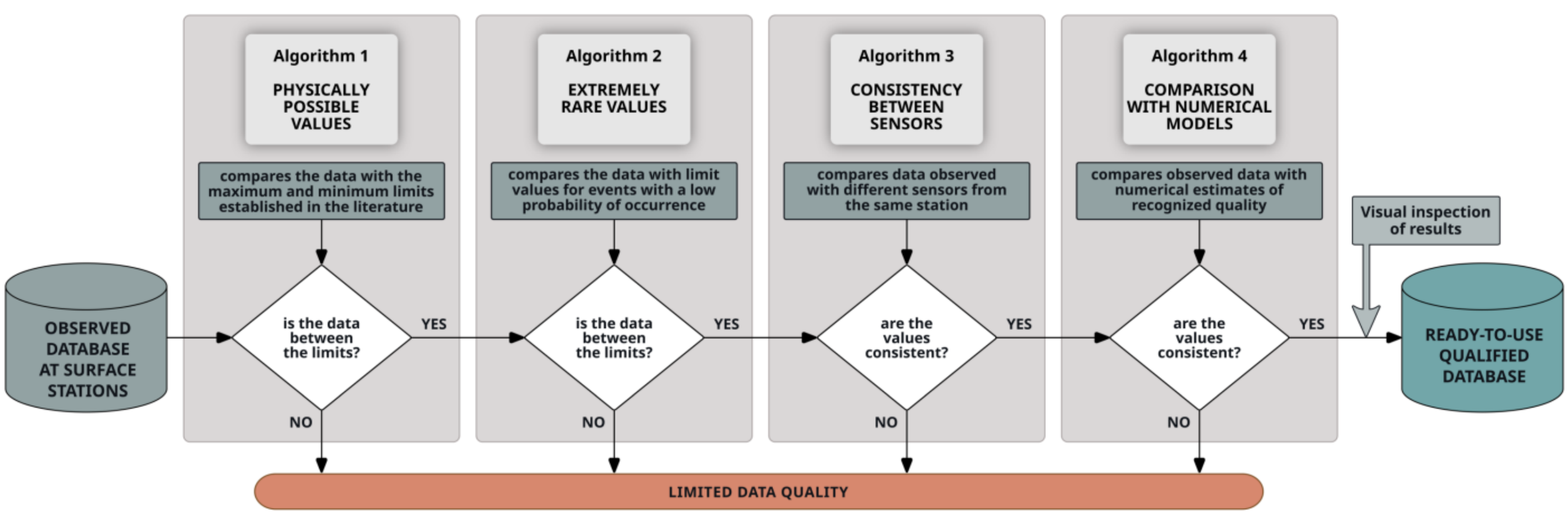


Figure 3.5 - Flowchart of the quality control process of solarimetric data used in this Atlas.

GHI Metrics	Observed Average (Wh/m²)	Bias (Wh/m²)	Bias (%)	REQM (Wh/m²)	REQM (%)	Correlation (r)
Maximum	6096	386	7,1%	454	8,8%	0,98
Average	5551	105	2,0%	284	5,2%	0,96
Minimum	4973	-281	-4,7%	178	3,1%	0,75
P75	5785	256	4,6%	339	6,1%	0,98
P50	5522	109	2,0%	255	4,7%	0,97
P25	5354	4	0,0%	226	3,8%	0,95

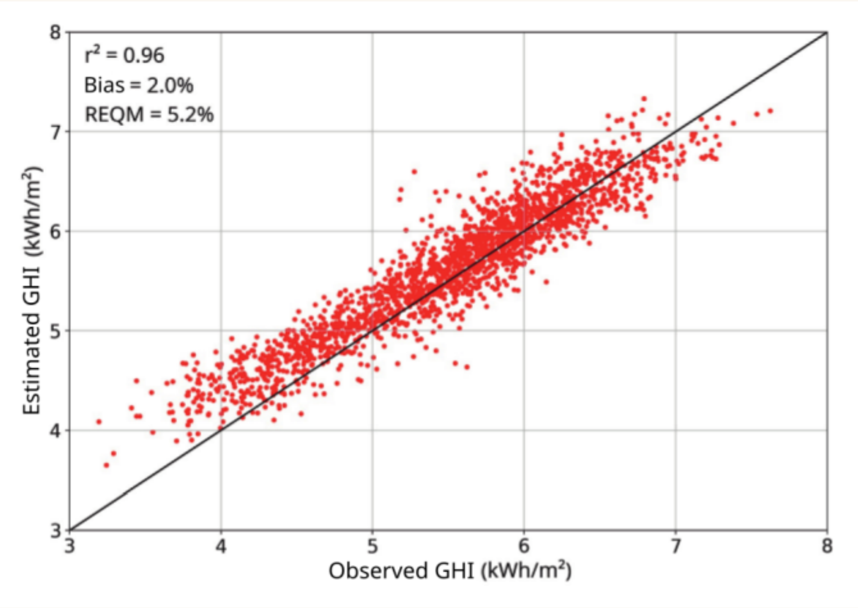
Table 3.3 - Validation metrics of model outputs for daily total horizontal global irradiation.

Table 3.4 - Validation metrics of model outputs for daily totals of normal direct irradiation.

DNI Metrics	Observed Average (Wh/m²)	Bias (Wh/m²)	Bias (%)	REQM (Wh/m²)	REQM (%)	Correlation (r)
Average	5391	140	3,6%	590	11,5%	0,91
P50	5459	220	4,0%	554	11,0%	0,93

Scatter diagram

The illustration on the side shows a scatter diagram between the monthly averages of observed (abscissa) and estimated (ordinate) daily GHI totals for all the stations analyzed. There is a high linear correlation (> 0.95) and an average relative bias of 2%. The relative REQM is 5.2%. These metrics are compatible with the uncertainties of satellite estimation models. The small positive bias is appropriate because it has to be taken into account that part of the measurements may be slightly underestimated due to soiling of the domes as a result of infrequent maintenance.



different characteristics, as highlighted in Table 3.5.

Version 2.0 of the BRASIL-SR model brought critical improvements in clear-sky algorithms, surface reflectance functions, and the detection of sparse cloudiness on dry days. Furthermore, parameters for cloud transmittance were explicitly adjusted for the region of interest. To illustrate performance differences and show the importance of regionalized solar modeling, Figure 3.6 compares the results of this Atlas (Atlas PB) with those of the Brazilian Atlas of Solar Energy database (Atlas BR) for a subset of high-reliability measurements. It can be seen from Figure 3.6 that the average bias for the Atlas PB was -0.09 kWh/m² against -0.18 kWh/m² for the Atlas BR. Such low uncertainties are due to the improved version of the BRASIL-SR model and state-specific parameterization adjustments. This made the bias correction unnecessary, as the uncertainty of the estimates was close to the uncertainties of the field measurements themselves. Therefore, this Atlas presents higher reliability for solar radiation estimates for the State of Paraíba.

Table 3.5 - Main differences between the databases generated for the Paraíba Solarimetric Energy Atlas (2023) and the Brazilian Solar Energy Atlas (2017).

	Atlas Brazil 2017	Atlas Paraíba 2023
Period	1999 a 2015	2012 a 2021
Model / Version	BRASIL-SR 1.2	BRASIL-SR 2.0
Spatial resolution	4 km	4 km / 1 km
Bias correction	Yes	No
Stations used	493 stations	24 stations

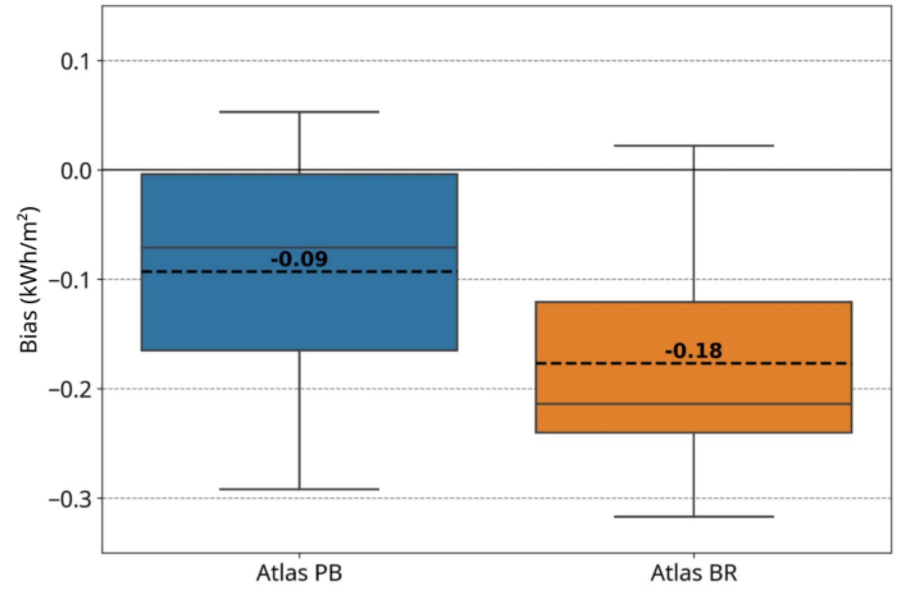


Figure 3.6 - Bias differences between the solarimetric bases of Brazil-2017 (Atlas BR) and Paraíba-2023 (Atlas PB) for the subset of high-reliability measurements. The maximum and minimum limits, the median (solid line), and the interquartile range (boxes) are shown. Means (dashed line) follow the value labels.

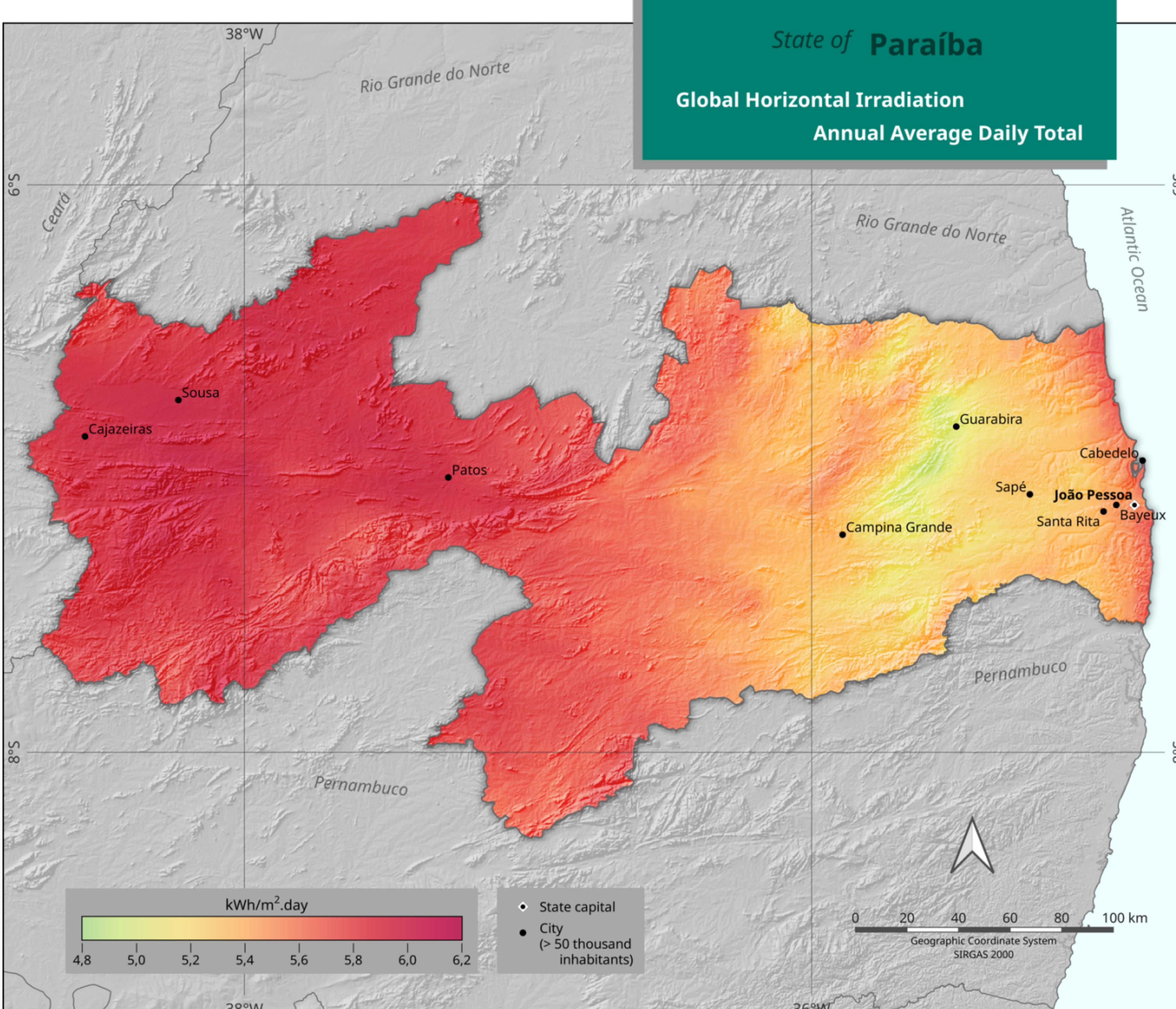
SOLARIMETRIC MAPS

The following pages present the solarimetric maps obtained from simulations of the BRASIL-SR model between January 2012 and December 2021. Each of the surface solar irradiation components is presented by a map of the annual average of the daily totals, followed by twelve maps with monthly average values of the daily totals. The sequence of presentation of the charts follows global irradiation in the horizontal plane (GHI), global irradiation in the inclined plane at 10° relative to the horizontal plane (GTI_{10}), direct irradiation normal to the surface (DNI), and diffuse irradiation in the horizontal plane (DHI).

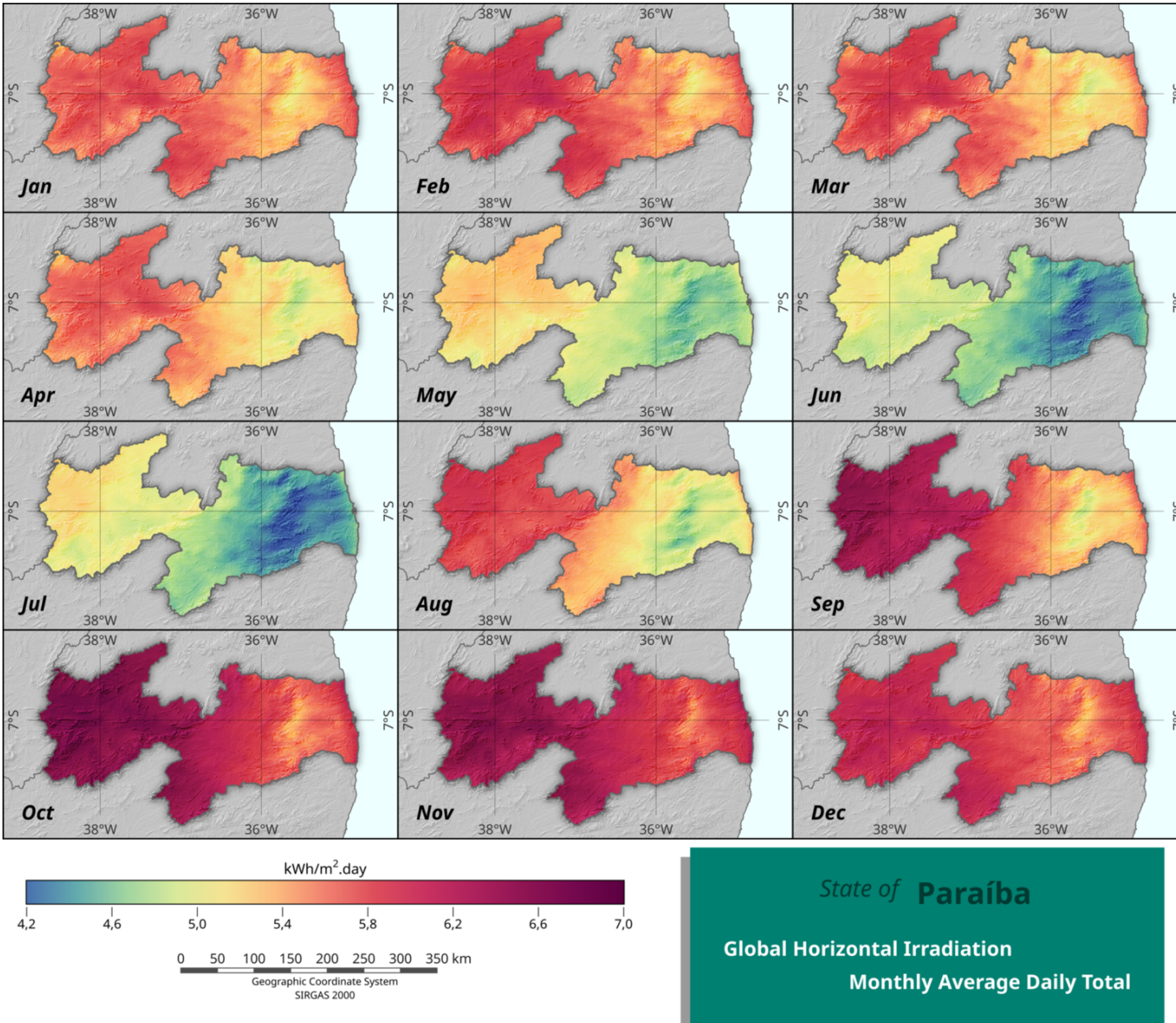
The maps highlight a higher incidence of solar irradiation in the west of Paraíba, with average values for GHI of up to 6.2 kWh/m^2 per day. The Brejo Paraibano, located between the Immediate Regions of Campina Grande and Guarabira (see Figure 1.1), had the lowest incidence of solar irradiation (with GHI values of approximately 5 kWh/m^2.day) but still higher than the average determined in previous studies (Pereira et al., 2017) for GHI solar irradiation in the Brazilian territory (about 4.8 kWh/m^2.day).

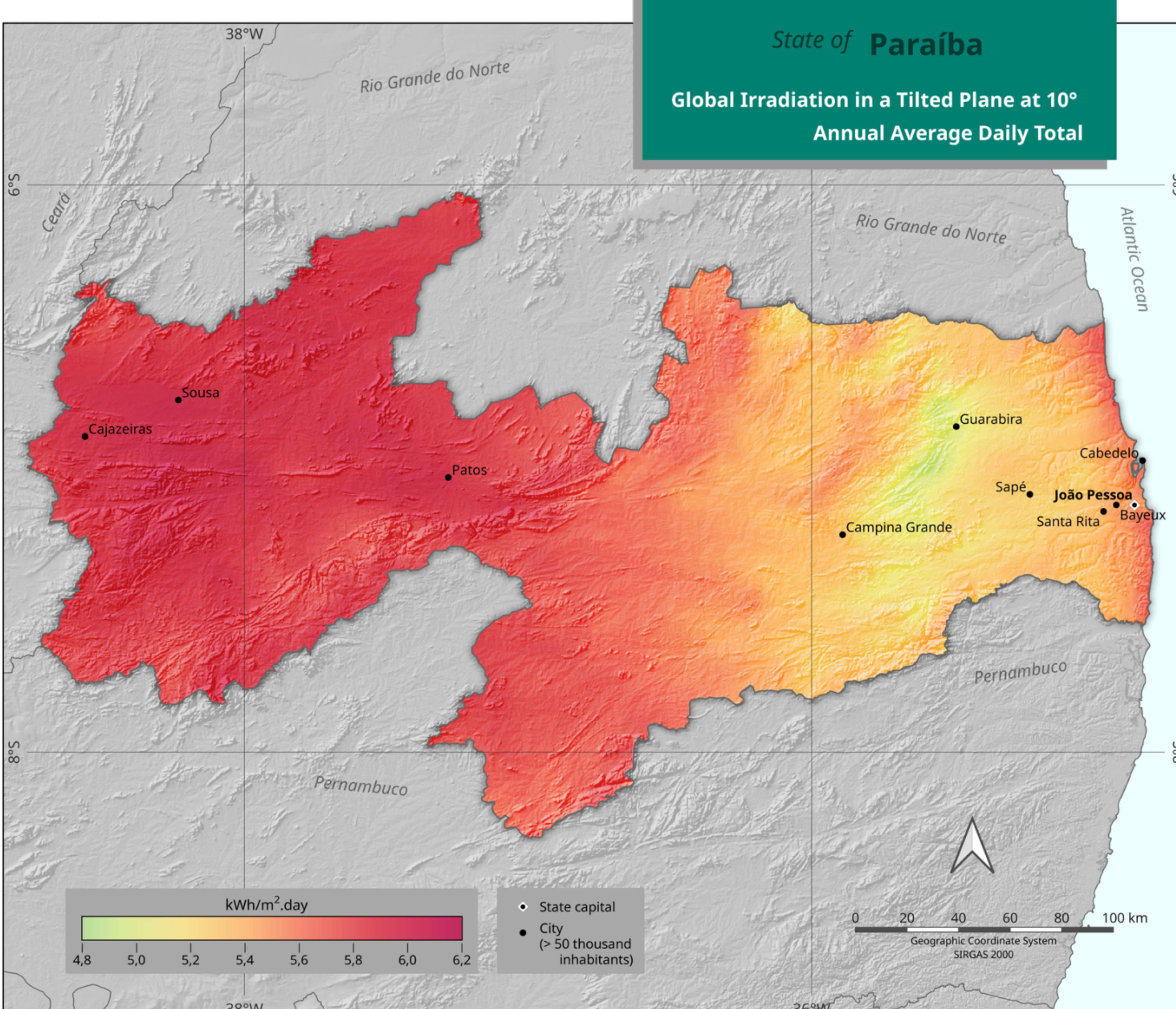
The maps also make it possible to identify the seasonal variability of the solar irradiation incidence in Paraíba. The solar energy resource grows from July, reaching maximum values in November, when the GHI component on the surface reaches values of up to 7 kWh/m^2 .day. The minimum incidence of solar energy in the territory of Paraíba occurs in June, when the highest GHI values observed in the west of the state are around 5.5 kWh/m^2. It is important to remember the information presented in the second chapter of this Atlas on the seasonal precipitation cycle in the state - where the rainy season occurs mainly between February and June, depending on the region of the state.

The solarimetric charts were elaborated with a spatial resolution of around 16 km^2, allowing a spatial detailing of the information about the surface solar irradiation in the region. The solar energy maps are crucial for energy entrepreneurs and stakeholders who need information about the solar energy potential in the Paraíba territory. Access to this information is available on the Web Tool provided by the Secretariat of Infrastructure and Water Resources of the State of Paraíba, where, in addition to checking annual and monthly values of the solar resource, the user can perform basic simulations and find out about the estimated potential for generating electricity using solar energy at points or even in areas of interest. However, it is important to note that the Web Tool should not be used for designing and sizing solar power systems. For this, it is necessary to prepare an executive project carried out by qualified professionals in order to meet the specific technical requirements associated with the characteristics of the installation site (possible shading, lighting geometry, support infrastructure for photovoltaic modules, etc.) and established in regulations published by the energy concessionaire.

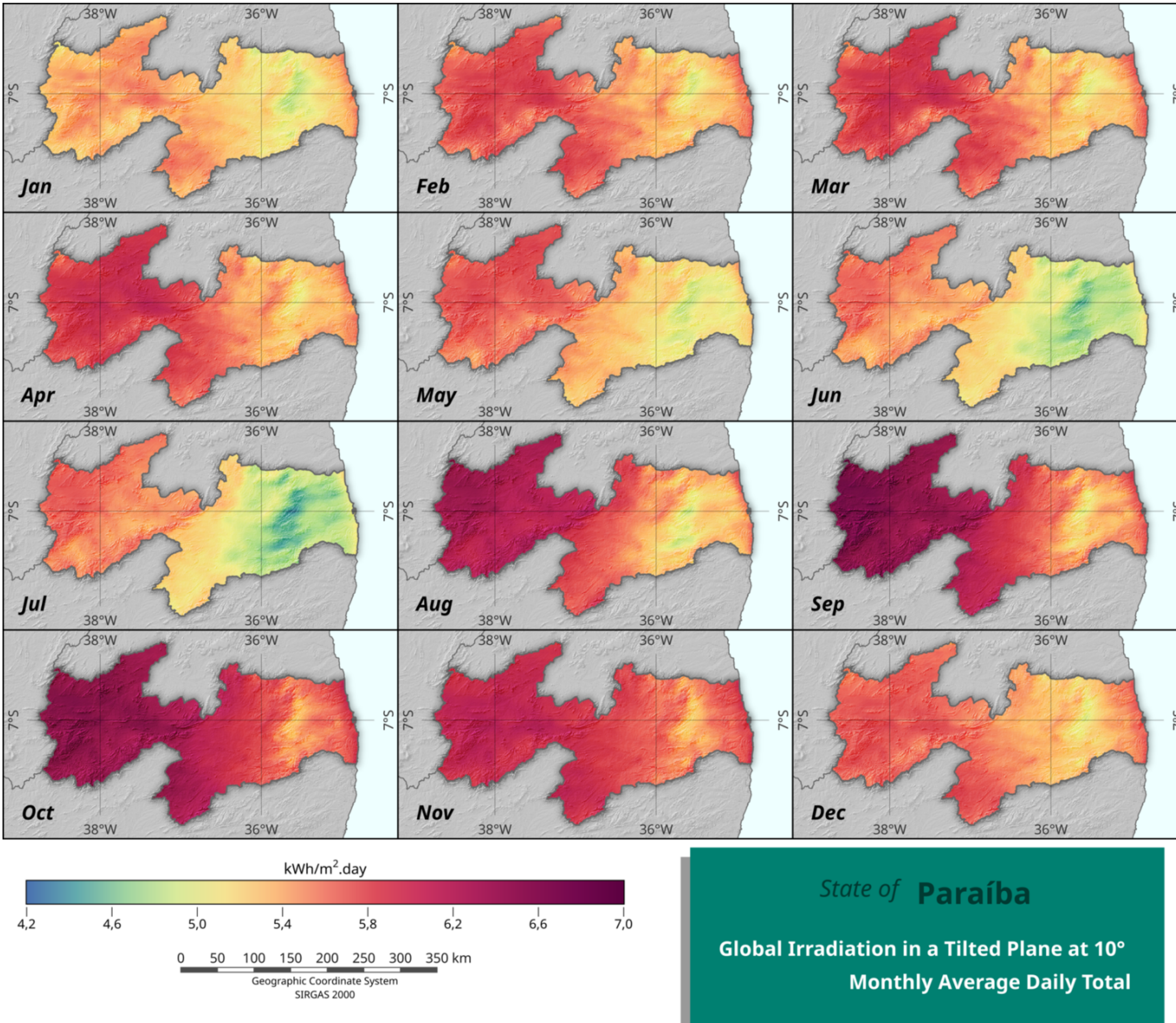


State of Paraíba
Global Horizontal Irradiation
Annual Average Daily Total
38°W
6°S
8°S
36°W
Rio Grande do Norte
Ceará
Rio Grande do Norte
Atlantic Ocean
Pernambuco
Pernambuco
Sousa
Cajazeiras
Patos
Guarabira
Cabedelo
Sapé
João Pessoa
Bayeux
Santa Rita
Campina Grande
kWh/m².day
4,8
5,0
5,2
5,4
5,6
5,8
6,0
6,2
State capital
City
(> 50 thousand inhabitants)
0
20
40
60
80
100 km
Geographic Coordinate System
SIRGAS 2000


Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
38°W
36°W
7°S
kWh/m².day
4,2
4,6
5,0
5,4
5,8
6,2
6,6
7,0
0 50 100 150 200 250 300 350 km
Geographic Coordinate System
SIRGAS 2000
State of Paraíba
Global Horizontal Irradiation
Monthly Average Daily Total



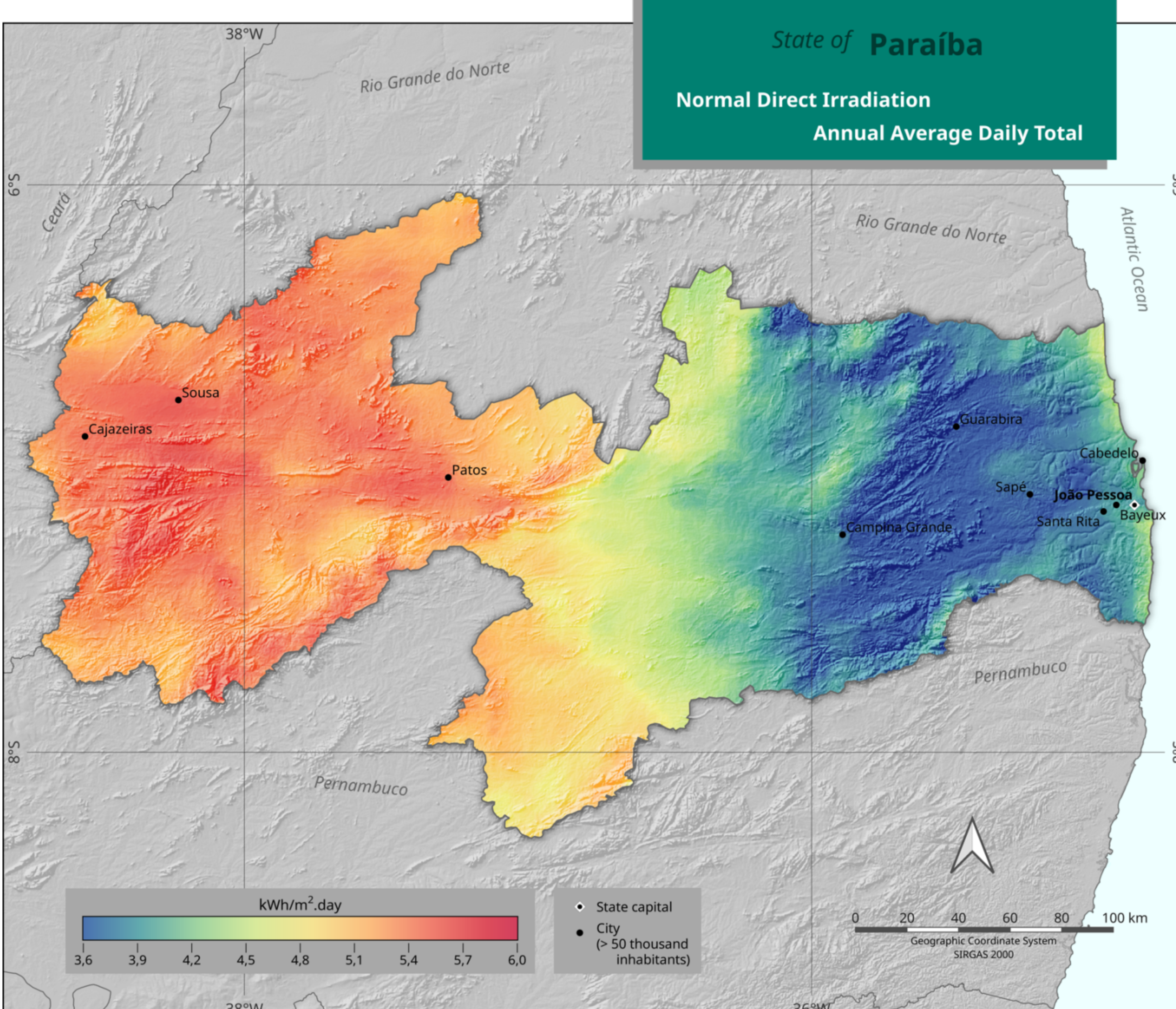
State of Paraíba
Global Irradiation in a Tilted Plane at 10°
Annual Average Daily Total
38°W
36°W
6°S
8°S
Rio Grande do Norte
Ceará
Pernambuco
Atlantic Ocean
Sousa
Cajazeiras
Patos
Guarabira
Cabedelo
Sapé
João Pessoa
Santa Rita
Bayeux
Campina Grande
kWh/m².day
4,8
5,0
5,2
5,4
5,6
5,8
6,0
6,2
State capital
City
(> 50 thousand inhabitants)
0
20
40
60
80
100 km
Geographic Coordinate System
SIRGAS 2000

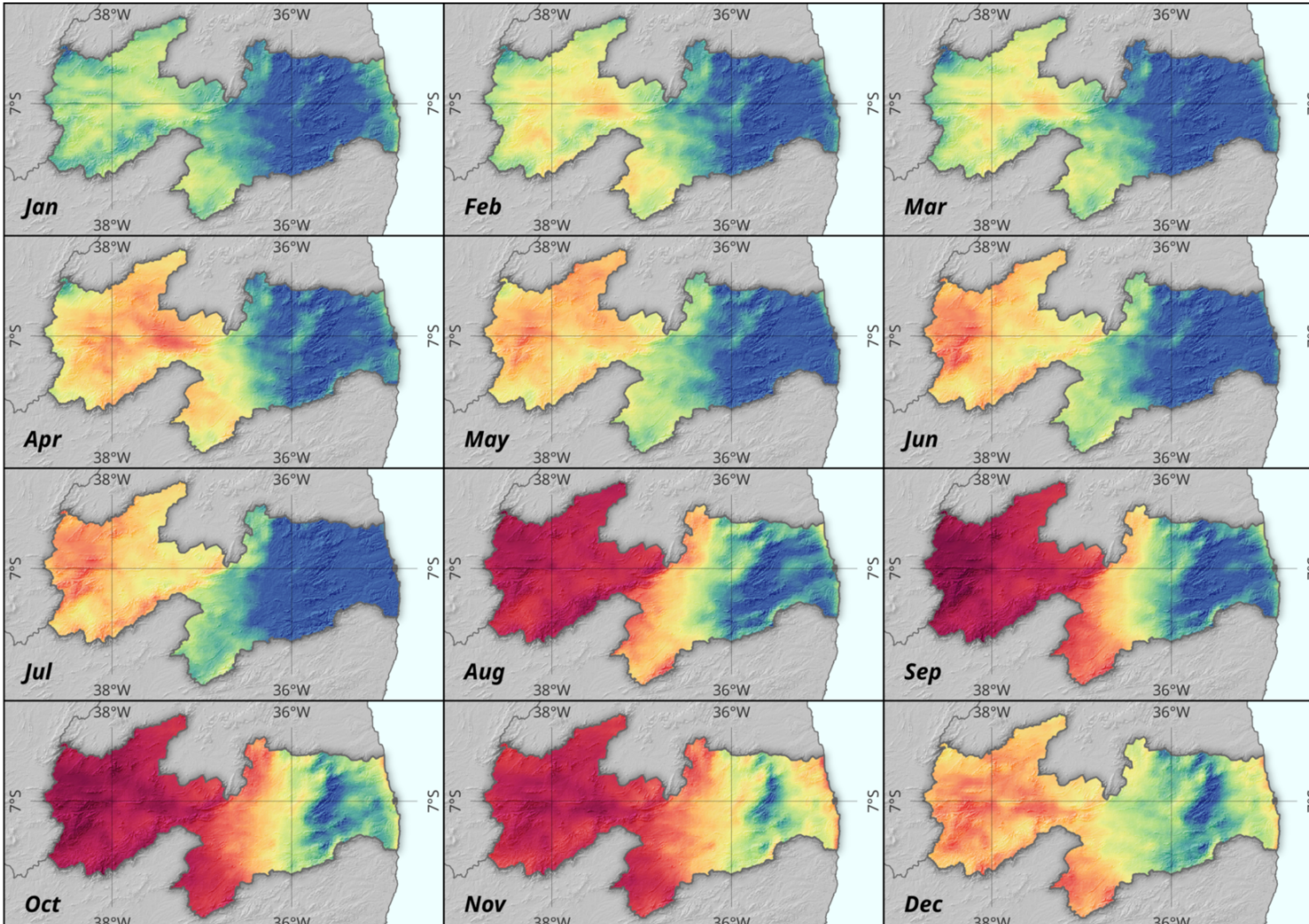

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
38°W
36°W
7°S
kWh/m2.day
4,2
4,6
5,0
5,4
5,8
6,2
6,6
7,0
0 50 100 150 200 250 300 350 km
Geographic Coordinate System
SIRGAS 2000
State of Paraíba
Global Irradiation in a Tilted Plane at 10°
Monthly Average Daily Total

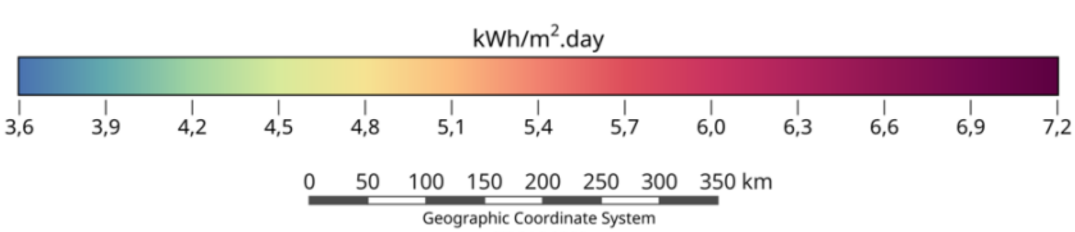
State of Paraíba

Normal Direct Irradiation

Annual Average Daily Total



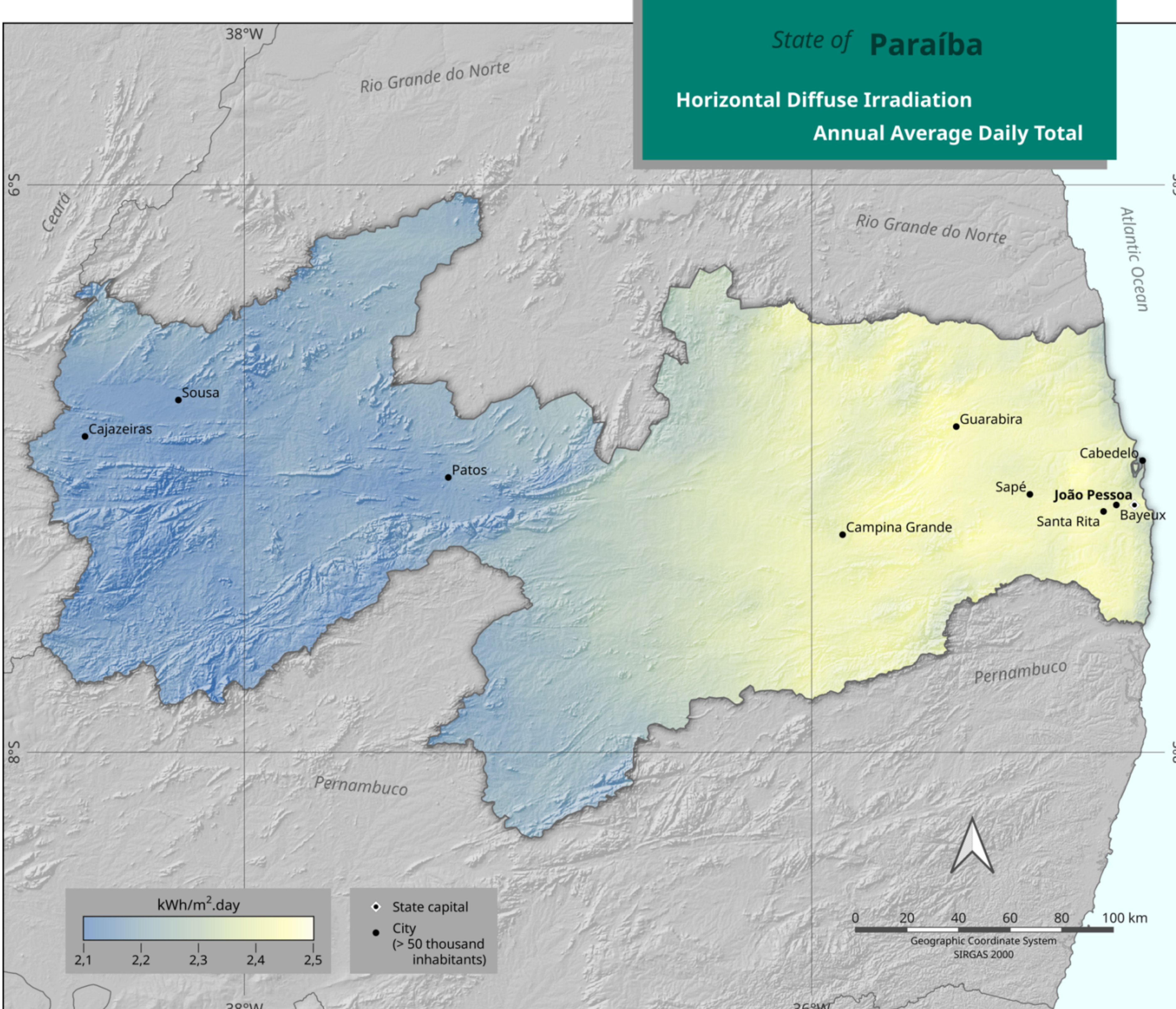


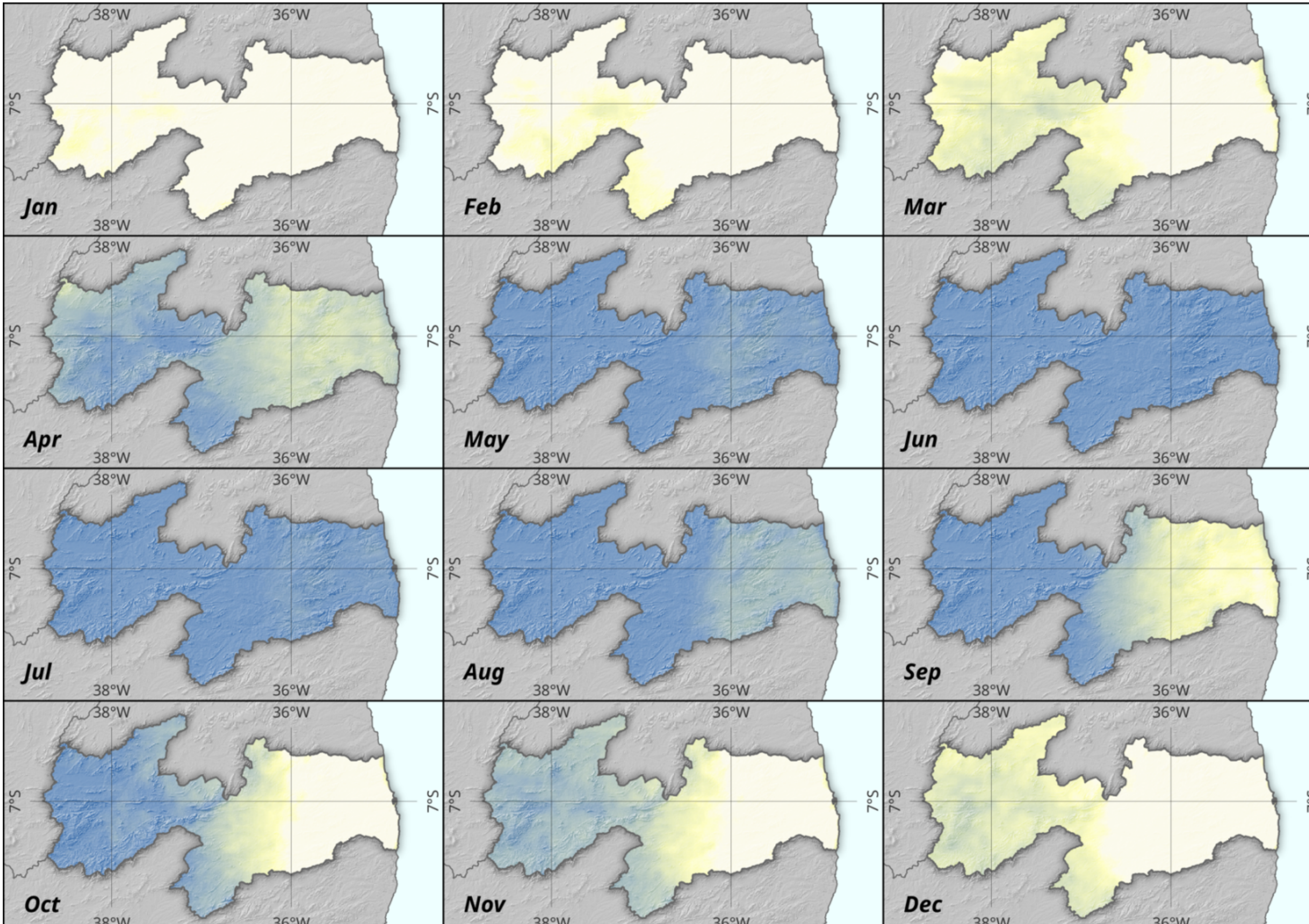


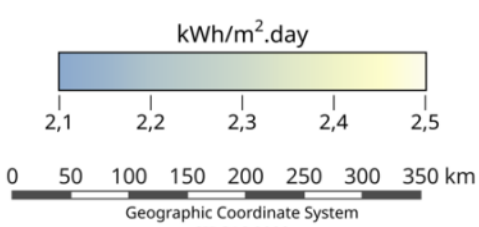
State of **Paraíba**

Normal Direct Irradiation

Monthly Average Daily Total


State of Paraíba
Horizontal Diffuse Irradiation
Annual Average Daily Total
38°W
36°W
6°S
8°S
Rio Grande do Norte
Rio Grande do Norte
Ceará
Pernambuco
Pernambuco
Atlantic Ocean
Sousa
Cajazeiras
Patos
Guarabira
Cabedelo
Sapé
João Pessoa
Santa Rita
Bayeux
Campina Grande
kWh/m2.day
2,1
2,2
2,3
2,4
2,5
State capital
City
(> 50 thousand inhabitants)
0
20
40
60
80
100 km
Geographic Coordinate System
SIRGAS 2000





State of **Paraíba**

Horizontal Diffuse Irradiation

Monthly Average Daily Total

PHOTOVOLTAIC POWER POTENTIAL

In this topic, an analysis of the potential application of photovoltaic solar energy systems in the state of Paraíba is presented.

Theoretical potential

Theoretical potential is understood as the available potential for photovoltaic solar generation, assuming that the modules would be installed in ideal conditions for photovoltaic generation, i.e., modules oriented to geographic north with an inclination of 10° relative to the horizontal plane and without shading.

The calculation of the theoretical potential used the Global Irradiation database on the 10° Inclined Plane (GTI_{10}), assuming the use of the entire area of the state of Paraíba for solar generation – with an occupancy rate of 100%. For this analysis, none of spatial restriction was assumed; therefore, protected and flooded areas were not excluded in this calculation.

Optical and electrical losses in energy generation and transmission were also not considered, as technological development and improvement are projected into the future. This premise is equivalent to assuming a Performance Rate of the photovoltaic system equal to 100%.

In addition to the assumptions described above, the calculation assumed:

- the whole area of the State of Paraíba of 56,467.242 km^2 (IBGE, 2022);
- the average value of Global Irradiation Inclined at 10° (GTI_{10}) in the territory of Paraíba was determined at 5.73 kWh/ m^2.day;
- the use of photovoltaic modules with the most widespread technology currently available on the market – monocrystalline silicon, bifacial with a power of 650 Wp, with an approximate area of 3.1 m^2 and efficiency of 21%.

Once these assumptions were established, the theoretical potential obtained is approximately **12 TWp**, generating around **70 TWh/day** or **25,550 TWh/year**. To illustrate, an area with only 0.02% of the State of Paraíba would be enough, in theory, to generate an amount of electricity equivalent to the energy consumption of the entire state in 2021, which was 5,881 GWh.

Technical potential

As in determining the theoretical potential, the evaluation of the technical potential of photovoltaic generation assumes the ideal conditions for power generation: modules oriented to the geographical north with an inclination of 10° in relation to the horizontal plane and without shading. In addition, the following assumptions are assumed:

- previously calculated theoretical potential;
- exclusion of areas with environmental and geographic restrictions: water supply pipeline, permanent preservation areas (50 meters margin for watercourses), water bodies (100 meters margin), transposition channels (50 meters margin), urban areas (500 meter margin), slopes greater than 5 degrees, highways (100 meter margin), railways

(100 meter margin), indigenous lands, quilombola lands, conservation units;

- optical and electrical losses in the photovoltaic system were considered using a performance ratio equal to 75%;
- occupancy rate with photovoltaic modules equal to 44 MWp/km^2, typical value observed in centralized photovoltaic plants operating in the Brazilian territory.

Considering these assumptions, the technical potential was determined at approximately **1.54 TWp**, capable of generating around **6.88 TWh/day** or **2,512 TWh/year**.

Economic potential - I

This economic scenario for photovoltaic energy potential assumes, as a starting point, the previously determined technical potential, adding a restriction for the distance between the place of interest for generation and the next point of connection to the National Interconnected System (SIN):

- maximum distance equal to or less than 30 km from the grid connection point (69 kV lines or superior).

Thus, the result obtained for economic potential I is approximately **1.46 TWp**, capable of generating around **6.51 TWh/day** or **2,375 TWh/year**.

Economic potential - II

The second scenario of economic potential has as assumptions those considered in the previous scenarios, plus the following restriction:

- maximum distance from the grid connection point (69 kV lines or superior) equal to or less than 10 km.

Thus, economic potential II results in approximately **907 GWp**, generating around **4.05 TWh/day** or **1,479 TWh/year**. To get an idea of this economic potential, just 0.14% of the state's area would be enough to generate an amount of electricity equal to the consumption recorded in 2021 by Paraíba, about 5,881 GWh.

Economic potential – III

The third scenario adopted for the economic potential of solar resources in the state of Paraíba aims to evaluate the use of solar energy in distributed generation systems installed on the roofs of buildings in urban areas. To this end, the following assumptions were adopted:

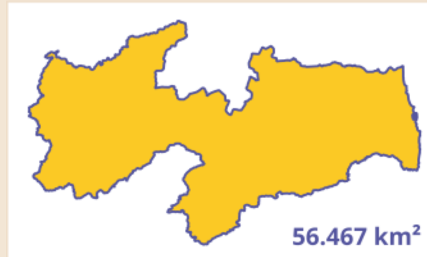
- guidelines indicated in Technical Note DEA/EPE 19/14 - Insertion of Distributed Photovoltaic Generation in Brazil – Conditions and Impacts;
- information on the number and type of residences (house or apartment) was obtained from the 2010 IBGE CENSUS for urban areas (source: https://sidra.ibge.gov.br/); when this document was prepared, detailed data from the 2022 Census were not yet available;
- average roof area of 85 m^2 for houses and 15 m^2 per apartment was assumed;
- the total number of households in an urban area in the State of Paraíba of 829,761 was adopted based on IBGE data (2022);
- utilization factor of 30% of the final area found for photovoltaic systems connected to the grid;
- database of Global Irradiation in the Inclined Plane at 10° (GTI_{10})
- generation system based on Mono-PERC photovoltaic modules with an approximate power of 650Wp, an approximate area of 3.1 m^2, and an efficiency of 21%

Considering these assumptions, the economic potential III is estimated at approximately **4.16 GWp**, capable of generating around **17.87 GWh/day** or **6.52 TWh/year**, that is, greater than the electricity demand of the state, being possible to export the surplus to the National Interconnected System (SIN).

Figure 5.1 presents the concept of distributed generation.

Photovoltaic power potential

THEORETICAL POTENTIAL
25.550 TWh/ano



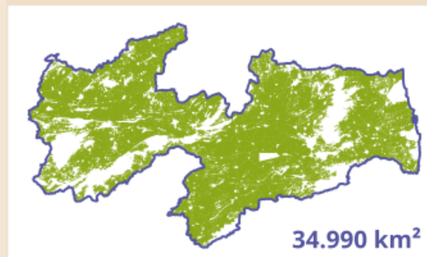
Irradiation data on a tilted plane at 10°;

Photovoltaic modules in ideal conditions;

Performance rate = 100%;

Total area of the state of Paraíba considered (occupancy rate = 100%).

TECHNICAL POTENTIAL
2.512 TWh/ano

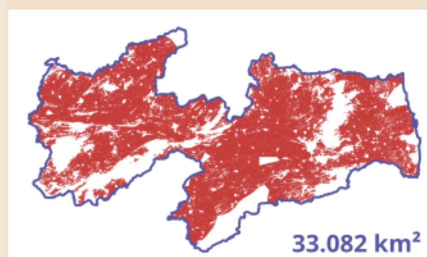


Theoretical potential, excluded the following items:

Areas with a slope above 5 degrees;

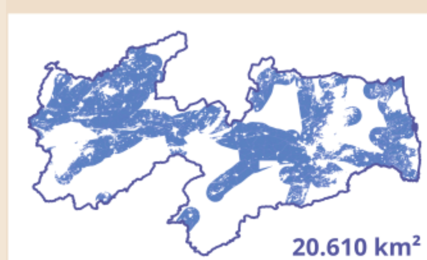
Pipelines, permanent preservation areas, water bodies, transposition channels, urban areas, highways, railroads, indigenous lands, quilombola lands and conservation units.

ECONOMIC POTENTIAL I
2.375 TWh/ano



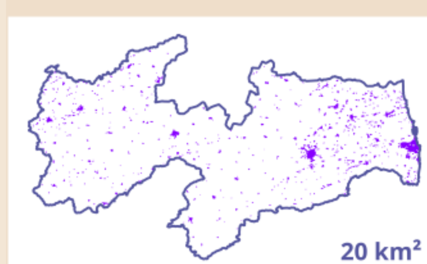
Using the technical potential, areas more than 30 km from transmission and distribution lines are also excluded.

ECONOMIC POTENTIAL II
1.479 TWh/ano



Economic potential I is used, also excluding areas more than 10 km from transmission and distribution lines.

ECONOMIC POTENTIAL III
6,52 TWh/ano



Distributed generation systems installed on the roofs of buildings in urban areas;

Adoption of DEA/EPE Technical Note 19/14;

Average roof areas of 85 m^2 for houses and 15 m^2 for apartments.

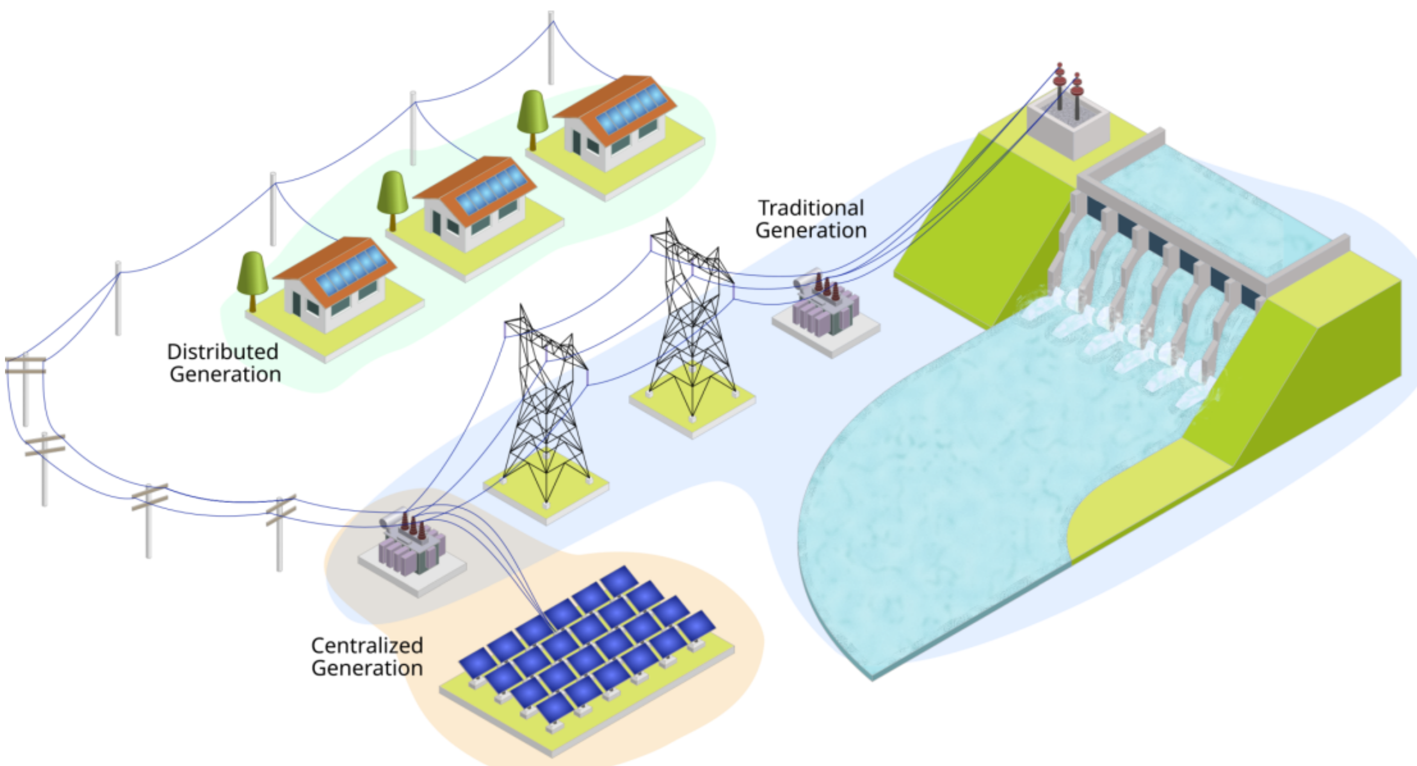


Figure 5.1 - Photovoltaic installations in homes, industries, buildings, and rural areas.

OTHER RELEVANT ASPECTS

Solar thermal energy (or thermosolar)

The thermal use of solar radiation has been done since antiquity by human society once its relatively simple and efficient way of converting solar radiation for various applications, from water heating, dehydration, cooking food, input for industrial processes, and even for generating electricity, more recently.

Water heating

Brazilian commercial, public, and residential buildings are responsible for much of the country's electricity consumption. In particular, the residential electric shower has the greatest impact on domestic electricity consumption. An alternative to reduce domestic electricity consumption is the use of solar water heaters. Figure 6.1 illustrates the operation of a residential solar heater.

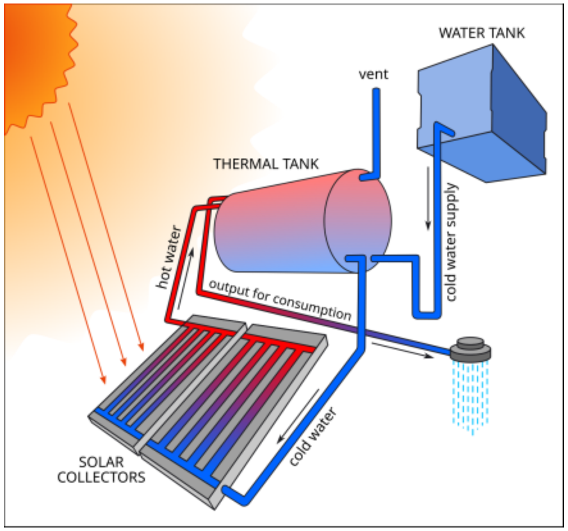


Figure 6.1. Scheme of a low-cost system for domestic water heating using solar heat.

The climate of the State of Paraíba is not subject to large temperature variations throughout the year compared to the southern and southeastern states. However, it can benefit from using solar thermal energy in industrial processes that require heated water. The textile industry and agro-industries, such as dairy products and fruit processing sheds, are some examples of sectors that could reduce electricity (or firewood) consumption from solar thermal heating for their industrial processes.

Electricity generation

Solar thermal energy can also be used to generate electricity. Heliothermal plants or CSP (Concentrated Solar Power) are being proposed and built on an experimental and even commercial basis to provide high energy stability to the grid. This technology consists of mirrors distributed in a spatial arrangement that act as concentrators in a central tower configuration or parabolic troughs/Fresnel mirrors in a linear configuration (Figure 2.10, quoted above, illustrates these systems). In both cases, the heat from solar radiation vaporizes a fluid that moves conventional turbines coupled to generators. Heliothermic solar power plants with central towers still face obstacles to their use in Brazil due to the variability of solar radiation in places with greater insolation associated to the characteristics of the tropical atmosphere. In addition, the high implementation and operation costs make it difficult for this technology to be competitive in the country. On the other hand, hybrid solutions that combine a linear solar concentrator with another complementary heat source (such as biomass) have been gaining attention and may become important alternatives to compose the Brazilian generating complex in the future.

Complementarities (hybrid generation)

Solar power plants are not dispatchable due to their dependence on fluctuations in weather conditions and consequent variability of incident solar irradiation. Therefore, hybrid solar-wind plants have emerged as an alternative to reduce the variability of the electricity generation park and reduce costs through infrastructure sharing. The states of northeastern Brazil stands out for the abundance of these two energy sources. Furthermore, considering that the SIN is powered mainly by hydroelectric power plants and, therefore, is subject to a strong dependence on the water regime, it can benefit from the growth of energy generated by the solar source. As a rule, dry periods are characterized by less cloudiness and higher solar irradiation levels at the surface. As several studies have already shown, periods of more intense winds (trade winds) are also characterized by less precipitation in the northeast region. Thus, the complementarity between hydro-solar-wind sources (Figure 6.2) is an important opportunity to maximize the use of renewable energies with safety and low environmental impact.

Green hydrogen

The hydrogen production from renewable energy sources, known as green hydrogen, emerges as a new energy vector for decarbonizing energy matrices worldwide. In addition to the already traditional markets, such as the ammonia and fertilizer manufacturing industry, In the refining process and other uses, new markets for green hydrogen can be developed in the segments of transport,

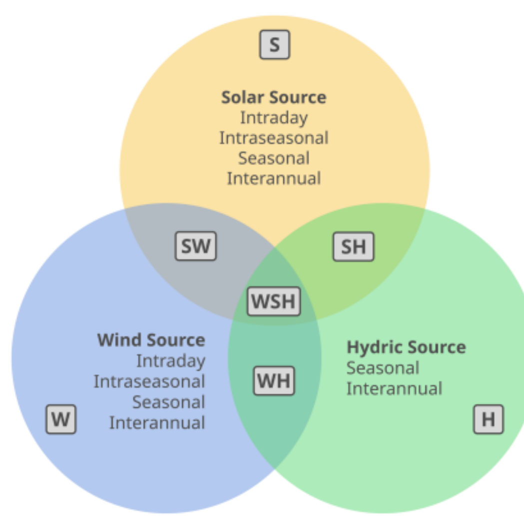


Figure 6.2 - Diagram explaining possible complementarities between renewable sources and respective scales of variability.

Source: André Gonçalves, 2017.

electricity generation, energy storage, and several industrial processes. Climate neutrality and energy security goals have led solid economies in countries in Europe and Asia to launch significant investments to promote a clean energy transition based on green hydrogen. However, many of these countries have less potential for renewable energy than Brazil, disfavoring its local production and opening up a promising market for the export of this commodity by Brazil. Remarkably, the northeastern Brazilian states have high levels of solar irradiation throughout the year, with very low interannual and decadal variability, and such conditions could be ideal for the development of green hydrogen production plants. However, producing green hydrogen through the electrolysis of water requires more than 18 liters of fresh water to produce one kilogram of hydrogen, considering the current state of technology. This represents a challenge for Brazilian states where water resources are scarcer, strictly where the highest levels of solar irradiation occur. Figure 6.3 presents the green hydrogen production scheme.

Solar energy and emissions mitigation

Solar energy generation plays an essential role in the paradigm of modern, sustainable economic growth with low environmental impact. As an emission-free source during electricity generation, solar energy can reduce CO_2 emissions from the electricity generation sector, since each MWh of energy generated using the solar source avoids between 534 and 1143 kg of CO_2 equivalent emitted to the atmosphere in thermoelectric plants fed with fossil fuels.

The diversification and electrification of the Brazilian energy matrix represent an environmental and economic opportunity if carried out on predominantly renewable bases. In this context, solar energy stands out among low-carbon technologies in at least three key aspects:

- economic competitiveness, as it is currently the cheapest form of electricity generation;
- scalability, as it can serve from small isolated consumers to large centralized plants;
- abundance, as the solar resource is widely distributed at economically viable levels throughout the territory.

The rapid evolution of storage systems, with batteries, thermal storage, or the future use of green hydrogen, adds to the gains promoted by solar energy. It will allow boosting the decarbonization of more difficult sectors, such as transport and cement and steel industries. Therefore, solar energy represents one of the main alternatives for the country's strategic positioning in the green hydrogen market, which can make Brazil one of the most competitive countries in the world in the long term.

Technology, economy, and job creation

According to data from the Associação Brasileira de Energia Solar Fotovoltaica (ABSOLAR), the use of technologies for harnessing solar energy has already generated more than 390,000 jobs between 2012 and 2020, with the largest share coming from the distributed generation segment, due to the substantial expansion of this sector. The generation of direct jobs occurs mainly in the installation of photovoltaic systems and it has a positive impact on advancing secondary vocational

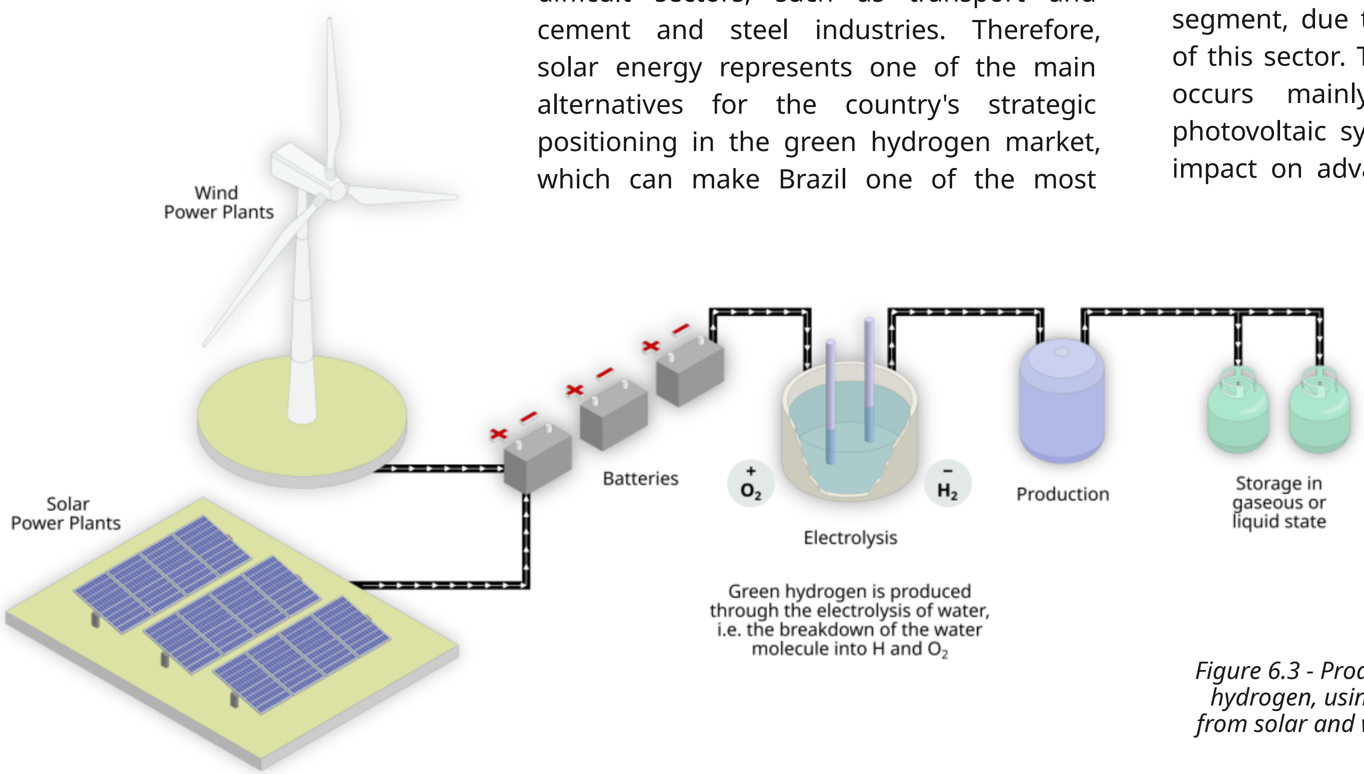


Figure 6.3 - Production process of green hydrogen, using the electrical energy from solar and wind renewable sources.

education, as illustrated in Figure 6.4. Indirect jobs are associated with the steel, aluminum, copper, and concrete chain due to the materials used in the facilities.

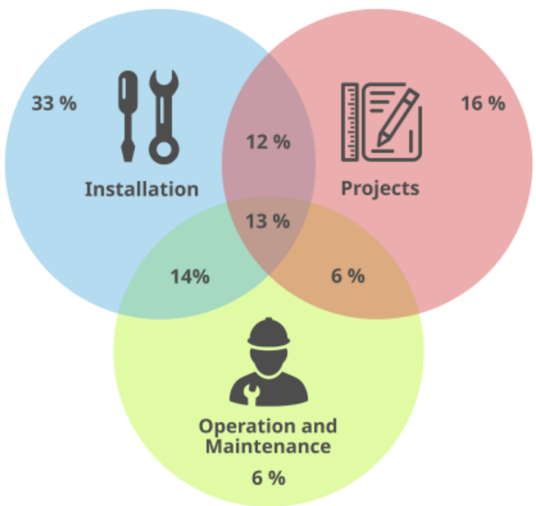


Figure 6.4 - Performance profile of direct jobs the solar energy sector generates.

Source: ABSOLAR.

Climate variability of solar potential

Four important representative cities of the State of Paraíba were selected to study climate variability, as shown in Figure 6.5.

The solar resource has high daily variability due to the diurnal cycle and moderate intraseasonal variability. In the State of Paraíba, where the annual average of global irradiation is 5.71 kWh/m², daily totals of solar irradiation can vary from 2.0 kWh/m² to 8.0 kWh/m², daily totals can vary from 2.0 kWh/m² to 8.0 kWh/m², depending on the variability of weather systems. However, the solar resource has low variability over the years for the State of Paraíba. Hence, the variation between a year of high and another year with low solar radiation is typically less than 5.0% of the mean climatological value, as shown in Figure 6.6. This variability is lower than the seasonal variability shown by the extremes of the box plots. These data demonstrate the higher interannual stability of solar generation compared to other renewable sources available in the region, such as wind power and hydroelectricity. As for trends, future climate scenarios indicate a slight reduction (from 1% to 2%) in the solar potential in the mesoregions of Sertão Paraibano, Borborema, and Agreste Paraibano until the middle of the century, although there is still significant uncertainty about these impacts.

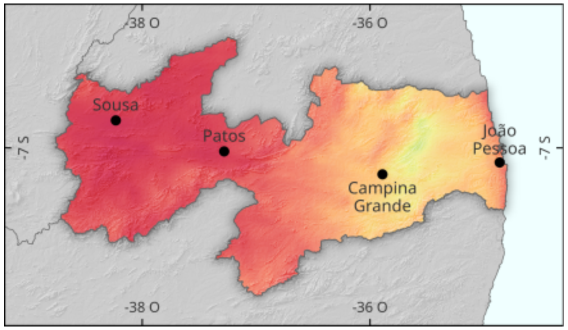


Figure 6.5 - Representative locations for generating variability graphs: João Pessoa, Campina Grande, Patos, and Sousa.

Observing the variation of solar irradiation in the four locations, it is clear that the solar energy resource showed a positive variation in the years 2015 and 2016 in all locations. On the other hand, the solar energy resource presented values below the average in the four locations in 2018, with a reduction of up to 3.5% concerning the average of the 10 years.

Figure 6.7 shows the daily variability for each component of solar irradiation in Paraíba, estimated by the standard deviation (σ) of total daily irradiation over the years. In principle, the standard deviation can be helpful in estimating how different the days are around the mean (μ), so that μ +/- σ contains 68.2% of the days, μ +/- 2σ contains 95,6% of days, and so on, assuming approximately Gaussian distributions.

It can be seen from the maps that the highest GHI variability (over 600 Wh/m²) occurs in the southwest portion of the intermediate region of Campina Grande (near the municipality of Monteiro) and also in small portions of the intermediate regions of João Pessoa (near to the coast) and Patos. On the other hand, the DNI shows greater variability northwest of the intermediate region of Souza-Cajazeiras, reaching values above 800 Wh/m². The global irradiation on the inclined plane (GTI) presents a variability 20% lower than the GHI, reaching maximum values in the range of 500 Wh/m². DHI shows low variability throughout the state, with absolute values in the 150 – 300 Wh/m² range.

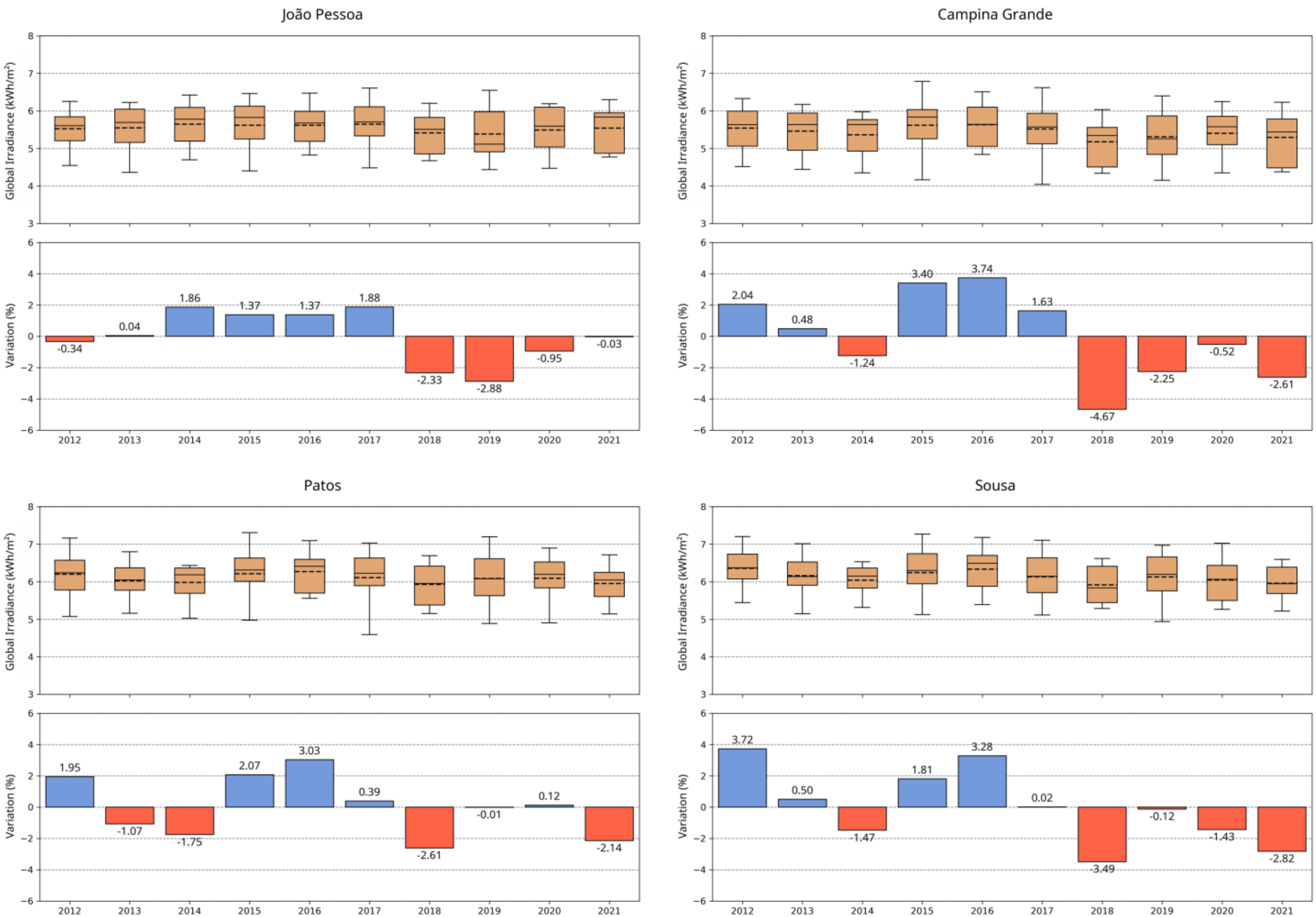


Figure 6.6 - Graphs of the climatic variability of the solar resource in four representative locations: João Pessoa, Campina Grande, Patos and Sousa. The box plot (top) shows seasonal variability through the distribution of monthly averages throughout the year. The annual average is shown as a dashed line. The variation graph (bottom) shows the variation of the annual averages around the long-term (climatological) average.

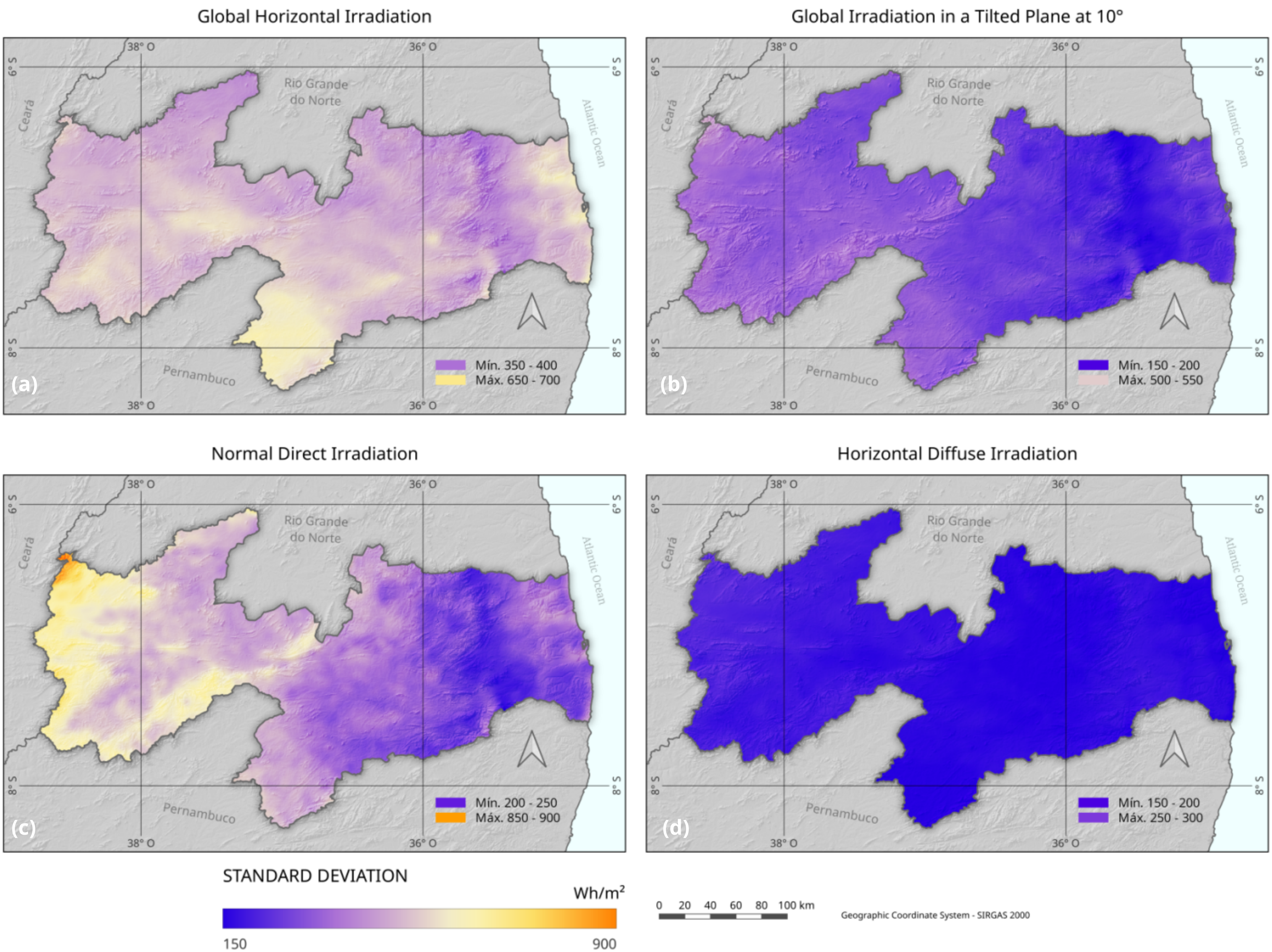


Figure 6.7 - Standard deviation (σ) of total daily irradiation (a) global horizontal; (b) global slope; (c) normal direct and (d) horizontal diffuse, obtained over the years 2012 to 2021.

FINAL CONSIDERATIONS

The oil crisis of the 1970s, with high prices imposed by the OPEC countries, showed the fragility of countries due to their great dependence on this resource, which has since led to a search for alternative sources of oil that can meet demands.

In even more recent decades, the world has been faced with a new and even more challenging paradigm: the need to find alternative and renewable sources of energy, not only because of the price of and dependence on fossil fuels, but now because of their burning and the emission of CO_2 into the atmosphere, which contributes significantly to the rise in global temperatures and climate change on the planet.

Within this context, the solar source, and especially solar photovoltaics, has proved to be extremely reliable and a great ally in the fight against climate change, with worldwide installed capacity rising in just over twenty years from 1 GWp in 1999 to over 1 TWp.

The situation in Brazil has been no different. Over the last 30 years, important research and publications have been developed that have supported and continue to contribute to the application of this source on Brazilian soil, especially those developed by INPE, such as the publication of the Brazilian Atlas of Solar Energy, 1st and 2nd editions, which already indicated the excellent solar potential throughout Brazil, especially in the northeast region.

The state of Paraíba, perceptive to these changes, has taken another important step in its rich history by delivering the Paraíba Solarimetric Atlas and its Interactive Web Tool to society in order to promote and disseminate the use of this technology and thus contribute to a cleaner and more renewable energy matrix. The Interactive Tool allows queries and simulations to be made for any location in the state. Access to this information will enable more assertive investments to be made in the state, benefiting both the government and society by generating jobs and income.

ANNEX - LEGISLATION APPLIED TO THE ENERGY SECTOR

The Brazilian legislation applied to the energy sector has been continuously evolving to keep up with the scientific and technological advances, the environmental agendas associated with climate change, and the preservation, conservation, and recovery of the environment. This is aimed at providing broad access to energy, quality of life, and health for the Brazilian population.

Regarding the compliance with environmental legislation, CONAMA Resolution 237/1997 allows environmental agencies to establish simplified procedures for the environmental licensing of projects with little potential for environmental impact. Also, CONAMA Resolution 279/2001 (and its amendments) establishes a simplified procedure for licensing enterprises with minor environmental impact, including generation from solar resources.

Tables A.1, A.2, A.3, and A.4 present a brief list of documents that regulate, standardize, and guide installations to harness our solar energy resources. This chapter is not intended to exhaust this subject since solar generation is a sector in continuous evolution and with rapid growth in the Brazilian energy matrix.

The technical note "Environmental legislation of interest to the electricity sector", published by Eletrobrás in September 2022, is an important source of information that presents a complete approach to the Brazilian legal system applied to the energy sector. Another important source of consultation is the Technical Note "Survey of legislation for environmental licensing of electricity generation projects using the solar resource", prepared jointly by Eletrobrás and EPE and published in May 2022 (DGOA 017/2022 NT-EPE-DEA -SMA-019/2022). Both documents are listed in the chapter of references in this Atlas.

Table A.1 includes the ABNT standards, and Table A.2 the ANEEL resolutions related to power generation from solar energy resource. Technical and scientific articles that address aspects of technical and environmental legislation (Table A.3), both nationally and regionally, are also available for public access in support of new studies, taking into account the growth of the sector and the interest of entrepreneurs, decision-makers and civil society (Hoffmann et al., 2019; Luna et al., 2019; Silva et al., 2019; Pereira, 2019; Viana & Basso, 2021; Severo et al. al., 2022). Finally, Table A.4 lists the federal and state legislation applied to the sector.

Table A.1 - Norms directed to electricity generation plants from solar energy resource.

Document	Issue date	Description
ABNT NBR 10.899/2020	Aug, 18th 2020	Standardizes the terminology and specifies the technical terms related to photovoltaic systems for converting solar radiant energy into electrical energy.
ABNT NBR 16.690/2019	Sep, 03rd 2019	Establishes the design requirements for electrical installations of photovoltaic arrays, including provisions for conductors, electrical protection devices, switching devices, grounding, and equipotentialization of the photovoltaic array.
ABNT NBR 16.274/2014	Apr, 06th 2014	It establishes the minimum information and documentation that must be compiled after installing a grid-connected PV system. It also describes the documentation, commissioning tests, and inspection criteria necessary to assess the installation's safety and the system's correct operation.

Table A.2 - Ordinances and normative resolutions aimed at generating electricity by solar source.

Document	Issue date	Description
Normative Resolution ANEEL no. 1059/2023	Feb, 07th 2023	Improves the rules for the connection and billing of distributed microgeneration and mini-generation plants, as well as the rules of the Electric Energy Compensation System; amends Normative Resolutions No. 920, of February 23, 2021, 956, of December 7, 2021, 1,000, of December 7, 2021, 1009, of March 22, 2022, and other provisions.
Law no. 14.300/2022	Jan 06th 2022	Establishes the legal framework for microgeneration and distributed mini generation, the Electric Energy Compensation System (SCEE) and the Social Renewable Energy Program (PERS); amends Laws No. 10,848, of March 15, 2004, and 9,427, of December 26, 1996; and take other measures.
Ordinance MME no. 538/2015	Dec, 15th 2015	Creates the Distributed Electricity Generation Development Program - ProGD, with the following objectives: I - promote the expansion of distributed generation of electric energy based on renewable sources and cogeneration; II – encourage the deployment of distributed generation in a) public buildings, such as schools, universities, and hospitals, and b) commercial, industrial, and residential buildings.
Normative Resolution ANEEL no. 687/2015	Nov, 24th 2015	Amends Normative Resolution No. 482 of April 17, 2012, and Modules 1 and 3 of the Distribution Procedures – PRODIST.
Normative Resolution ANEEL no. 482/2015	Apr, 17th 2012	Establishes the general conditions for the access of distributed microgeneration and mini-generation to the electric energy distribution systems, the electric energy compensation system, and other measures.

Table A.3 - Technical and scientific articles addressing technical and environmental legislation at various levels.

Document	Issue date	Description
Joint Technical Note Eletrobrás /EPE DGOA 017/2022 NT-EPE-DEA-SMA-019/2022	Dec, 2022	Survey of environmental licensing legislation for solar power generation projects: situation in 2022.
Technical Note on Floating Photovoltaics EPE-DEE-NT-016/2020-r0	Feb, 19th 2020	Introduces the technology of floating solar systems, as well as discusses its potential advantages and challenges, considering the particularities of Brazil. Socio-environmental, legal, and competitiveness aspects are also addressed.
Technical Note Expansion of Generation Associated to wind-photovoltaic plants Considerations for calculating the physical guarantee of energy EPE-DEE-NT-084/2020-r0	Dec, 16th 2020	The document presents a proposed methodology for estimating the curtailment in the Physical Guarantee of energy, aiming to support the definition by the MME to be considered in these innovative arrangements.
Mapping Refinement Study of the Potential Roof Area of Residential Buildings in Brazil	2020	Proposes a methodology for mapping the potential roof area of residential buildings in Brazil for photovoltaic energy use.
Technical Note Photovoltaic Projects in Energy Auctions Characteristics of the projects participating in the auctions from 2013 to 2018 EPE-DEE-NT-091/2018-r0	Oct, 17th 2018	Proposes the dissemination of information on solar source projects, discussing some trends and the most relevant aspects. The document presents the technical qualification of the projects traded in the A-4 auctions of 2017 and 2018, in addition to an analysis of the evolution of the projects over the six years of participation in the Regulated Market Energy Auctions.
TECHNICAL NOTE DEA/EPE 19/14 Insertion of Distributed Photovoltaic Generation in Brazil - Conditions and Impacts		Given different conditions, it aims to understand the dynamics of photovoltaic distributed generation over the ten-year horizon. For this, specific objectives were established to compose the study: - Identify the main advances obtained and possible barriers; - Survey the technical potential of residential photovoltaic generation; - Leveraging distributed generation from small solar photovoltaic sources; - Identify and evaluate, qualitatively and quantitatively, the impacts for the various agents involved.

Table A.4 - Laws, decrees, ordinances, and norms regulating energy generation activity.

Document	Issue date	Description
Federal Law 14.300	Jan, 6th 2022	Social Renewable (PERS); amends Laws No. 10,848, of March 15, 2004, and 9,427, of December 26, 1996; and takes other measures. Establishes the legal framework for micro generation and distributed mini generation, the Electric Energy Compensation System (SCEE) and the Social Renewable Energy Program (PERS); amends Laws No. 10,848, of March 15, 2004, and 9,427, of December 26, 1996; and takes other measures.
Federal Law 8.874/2016	Oct, 13th 2006	Regulates the conditions for approving projects considered a priority in infrastructure or research-intensive production, economic development, and innovation for article 2 of Law 12,431/2011 and revokes Decree 7,603/2011. Priority is given to projects that provide relevant environmental or social benefits, such as projects based on renewable technologies for solar energy generation.
Regulation IBAMA 78/2021	Jan, 13th 2021	Establishes environmental sensitivity parameters (Annexes IV.A to IV.O) and risk classification of economic activities associated with release acts under the responsibility of IBAMA (Federal Environmental Licensing) related to electric power transmission systems (Annex IV.D); generation from solar resource (Annex IV.G); in indigenous lands (Annex IX.L); suppression of vegetation and capture, collection, handling and transport of fauna (Annex IV.O).
Regulation MMA 326/2020	Jul, 24th 2020	Establishes the Environmental Agenda in Public Administration Program - A3P Program and establishes its guidelines. The A3P Program aims to promote socio-environmental responsibility, the adoption of sustainability procedures and socio-environmental criteria in public sector activities, including the use of solar energy when it implies energy savings and little or no environmental impact (Art. 2, I, II, IV, V and VI).
Administrative Rule SUDEMA 101/2017 (Estado da Paraíba)	Apr, 11th 2017	Exemption from environmental licensing in the state of Paraíba for activities that fit as being of micro or small size and with small polluting potential, including photovoltaic solar microgeneration, as defined in the Joint Technical Note Eletrobrás/EPE - NT Eletrobrás DGOA 003/2021 / NT-EPE-DEA-SMA-006-2021 Classification: Public 30.

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