German-Brazilian Energy Partnership

Agrivoltaic systems in Brazil

Techno-economic feasibility and potential study

Legal Information

Publisher:
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Last updated:
June/2024

Publication:
November/2025

This study was prepared by GIZ on behalf of the German Federal Ministry of Economic Affairs and Energy (BMWE) as part of the German-Brazilian Energy Partnership. The findings and opinions expressed are solely those of the authors and do not represent the position of the partner or stakeholders of Germany's climate and energy partnerships.

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Summary

List of figures

List of tables

1. Introduction

Brazil is a continental territory of environmental richness, comprising an exuberant and diverse fauna and flora as the home of more than 5 million km2 of the Amazon rainforest (IBGE, 2021) and many other local biomes, such as the Cerrado, Pantanal, Caatinga and Atlantic Forest. This diversity and richness are reflected in Brazilian culture and identity, and they stand for the unquestionable promise of future research on exploiting biodiversity conservation for the good of all.

On the other hand, Brazil is also one of the most unequal and exclusionary societies, accounting with a rural structure centered on the large-scale agribusiness industry and diffuse patterns of urbanization where many Brazilians live apart from rights of adequate access to resources, infrastructure, and common services (BRANDÃO, 2016). In this context, for many of its residents, Brazil is a place of food insecurity and energy poverty, phenomena that affect more intensely rural populations and marginalized groups living in vulnerable communities.

Despite being one of the largest food producers in the world, having a large-scale agriculture as the basis of its economy, Brazil is back on the UN Hunger Map since 2022 (FAO, 2022). More than 60 million Brazilians face some level of food insecurity, with the most severe levels affecting the population in the Northern and Northeastern regions and rural areas (REDE PENSSAN, 2022). Monocultures and the agribusiness industry are also main drivers of the Amazon deforestation and of the increased use of pesticides in Brazil. Since 2019 the widespread use of pesticides in Brazil is growing at a fast pace (NUNES et al., 2021). Notably, the current Brazilian agricultural business model does not consider the country`s richness and biodiversity.

Another challenge faced by Brazilian rural areas and vulnerable groups is the poor access to reliable and sustainable energy services. Energy is an essential component of all social economic systems, taking an essential role in the global sustainable development. The lack of access to and the poor quality of energy services are factors that lead to social exclusion processes and impede the development of communities with these characteristics (GUZOWSKI; MARTIN; ZABALOY, 2021) Despite its excellent solar radiation resources (INPE, 2017), in Brazil energy poverty affects mainly isolated communities in rural areas and densely populated urban areas marked especially by poverty and low infrastructure (GUZOWSKI; MARTIN; ZABALOY, 2021). In numbers, 11% of Brazilian households, approximately 8 million consumer units, still live in conditions of energy poverty, and in rural areas this number reaches 16% (approximately 11.6 million consumer units) (BEZERRA et al., 2022; IBGE, 2019a).

Solar photovoltaic (PV) technology is considered one of the key solutions to fight climate change, and it has grown significantly in the last decade. According to the report Snapshot of Global PV Markets 2023 issued by the International Energy Agency (IEA), PV installed capacity has reached almost 1,2 TW by the end of 2022 (IEA, 2023). However, unlike wind power and fossil fuels, solar PV power plants require considerable space, making it challenging to find suitable locations for large PV installations (HERMANN et al., 2022). To address this issue, one solution involves integrating PV systems into various human activity areas, including buildings – Building Integrated Photovoltaics (BIPV), lakes - Floating PV, and agricultural land use – Agrivoltaics (HERMANN et al., 2022).

In this context, the double use of land for agriculture and solar power generation has the potential to become a powerful tool to overcome the above-mentioned challenges. AgriPV systems generate renewable electricity without taking land area for food production (TROMMSDORFF et al., 2022). This technology has also a promising potential to become a resilient tool to face climate change. AgriPV systems can offer soil protection against excessive solar radiation, heat, and drought (FRAUNHOFER INSTITUTE, 2022). In this context, agrivoltaic systems can benefit grazing activities by creating a cooler microclimate and providing for livestock shelter from sun, wind, and predators. One example that supports that the shade provided by agrivoltaics might benefit animal welfare is a study where researchers noted that lambs spent over 90% of daylight hours within the boundaries of the shade provided by trees (PENT et al., 2021).

This report aims to present detailed information regarding the agrivoltaic technology, including historical, regulatory, and current applications globally, systems designs and applications. It also includes a country-specific overview presenting existing agrivoltaic systems in Brazil, the potential of the technology considering the country's regional diversity, potential benefits and drawbacks and recommendations for the development of the technology in the Brazilian context.

2. Agrivoltaic technology: concept, history and applications

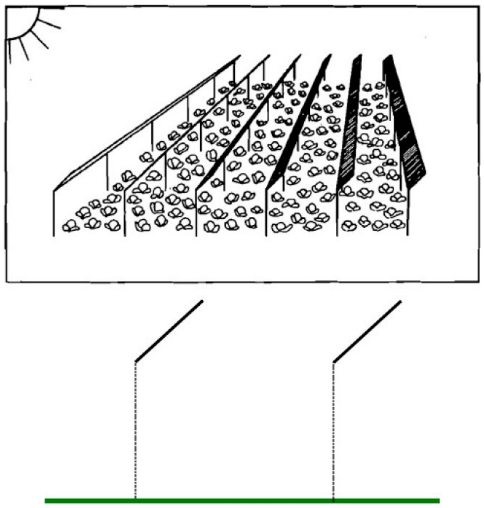
This chapter will cover a general overview of agrivoltaic systems (Agri-PV) including historical and current applications globally. Also, it will contain an explanation of the different configurations of agrivoltaic systems, including the various system designs and component technologies that are currently on the market.

2.1 Concept and brief history

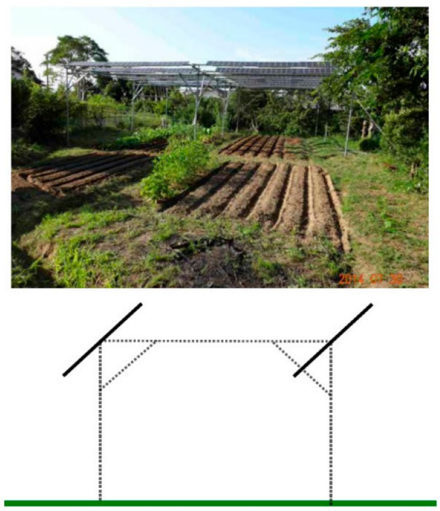
An agrivoltaic system can be defined as a technology that aims to simultaneously use land for agricultural purposes and photovoltaic (PV) energy generation (GOETZBERGER & ZASTROW, 1982) . Agrivoltaics can increase the efficiency of land use, feature adapted support structures and can be implemented in association with various crops. Agrivoltaics are growing rapidly, but standard definitions and designs are still lacking in many states and countries. The systems can be referred to by various terms, such as "dual use", "co-location", "Agri-PV", "Agro-PV", "agrovoltaics", "agri-solar", "solar sharing" or "pollinator-friendly solar", depending on the region and specific applications around the world (MACKNICK et al., 2022) . In this document, the term "Agrivoltaic" was selected due to its widespread usage and because it is used in the key references utilized for this study, such as the publication "Agrivoltaics: Opportunities for Agriculture and the Energy Transition" by Fraunhofer Institute for Solar Energy Systems in Germany (2022).

The agrivoltaic technology was first mentioned academically in 1981 by Professor Adolf Goetzberger, the founder of the Fraunhofer Institute for Solar Energy Systems in Germany, and his colleague Armin Zastrow in a publication at the Solar Energy journal (GOETZBERGER & ZASTROW, 1982). The article entitled "On the coexistence of solar energy conversion and plant cultivation" served as the initial step in creating the concept of agrivoltaic systems. However, this concept remained largely forgotten for many years until the first system was created in 2004, constructed in Japan by Akira Nagashima, who referred to the model as "solar sharing" (TOLEDO; SCOGNAMIGLIO, 2021). Both mentioned agrivoltaic models are shown in **Figure 1**.

Figure 1 - First agrivoltaic models. © Goetzberger e Zastrow (a), A. Nagashima (b)



(**a**) Conceptualization designed by Goetzberger and Zastrow (1981)



(**b**) First model developed by Akira Nagashima in Japan (2004)

Source: Toledo (2021)

Since then, agrivoltaic systems have been growing rapidly in Europe, Asia, and the United States (HERMANN; SCHÖNBERGER, 2022). These systems exist on various scales, from small setups for family agriculture to large-scale installations exceeding 700 MW in China, for example.

Within the international context, there is significant potential for small-scale agrivoltaic systems, which can provide remarkable social benefits to the involved families. Countries like Japan, Italy, and South Korea, which have limited land availability considering their populations, are already investing in agrivoltaic systems to diversify the income sources within the agricultural sector (HERMANN; SCHÖNBERGER, 2022).

Germany is one of the pioneering countries in the development of the agrivoltaic technology (Figure 2 and Figure 3). On the research level, the country hosts several projects that provide data for the continuous improvement of the technology. Additionally, Germany stands out in creating technical guidelines for agrivoltaic systems. The Fraunhofer Institute for Solar Energy Systems (ISE) and the University of Hohenheim collaborated with the German Institute for Standardization (DIN) and other partners to develop the DIN SPEC 91434[1] standard. Published in May 2021, this document titled "Agri-photovoltaic systems – Requirements for primary agricultural use" aims to establish a testing method for agrivoltaic systems. It aims to provide standardized agrivoltaic measurement procedures for reporting and documentation to legislative bodies, financiers, approval authorities, as well as for post-testing stages and certification by experts and certification organizations.

Figure 2 - Agrivoltaic system wiht organic fruit at nachtwey, Germany

Source: Hermann et al. (2022)

Figure 3 - Agrivoltaic system wiht organic fruit at nachtwey (2), Germany

Source: Hermann et al. (2022)

Considering the context of climate change, population growth, and increasing electricity demand, the photovoltaic technology is expected to continue expanding and gaining more participance in the global energy mix. However, there is also a rising need for food production, leading to competition for land and space, particularly in densely populated areas. As conventional photovoltaic systems can occupy significant land areas, agrivoltaic technology emerges as a crucial alternative for the efficient use of land in densely populated countries (TOLEDO; SCOGNAMIGLIO, 2021).

The combined use of land for food production and energy generation offers several advantages for both purposes beyond land efficiency (HERMANN; SCHÖNBERGER, 2022) such as:

- Reduction in the need or optimization of irrigation: Agrivoltaic systems can reduce irrigation requirements due to the reduction of evapotranspiration and there is also a possibility of collecting rainwater for irrigation purposes.
- Reduction in wind erosion: The presence of photovoltaic mounting structures can act as protection or shielding for the crops, reducing the impact of wind erosion.
- Reduction of pesticide and anti-fungi spraying due to enhanced plant protection.
- Utilization of PV mounting structure for crop protection: The structures supporting the photovoltaic panels can provide additional protection for the crops, such as shade or protection from extreme weather events, and they can be used to install protective nets or sheets.
- Optimization of light availability for crops: Some agrivoltaic systems use solar tracking technology to optimize the availability of light for the crops, enhancing their growth conditions.

1 https://www.en-standard.eu/din-spec-91434-agri-photovoltaic-systems-requirements-for-primary-agricultural-use/

- Improved module efficiency through better convective cooling: Agrivoltaic systems can lead to better cooling of photovoltaic modules, which can result in increased energy generation efficiency.
- Higher efficiency of bifacial modules due to increased height above ground and adjacent module lines: The design and setup of agrivoltaic systems can improve the efficiency of bifacial modules, which can harvest sunlight from both sides.

Besides the technical benefits that might boost energy generation and food production, agrivoltaic technology can also generate economic and social advantages for farmers. These systems bring greater energy autonomy to farming families (Figure 4) and offer the potential for income diversification through the sale of surplus electricity. In Japan and South Korea, for example, the implementation of agrivoltaic projects has been driven by a focus on social benefits for farmers and rural communities. In Japan, the technology was introduced to address the challenges of rural depopulation and declining agricultural income, particularly after the Fukushima catastrophe led to contaminated agricultural crop yields. In Korea, policymakers aim to create an agrivoltaic pension scheme, recognizing the demographic shift in the aging farming sector, where many farmers are retiring and facing reduced income (SCHINDELE et al., 2020).

Figure 4 - A farmer harvesting rice under an agrivoltaic system with rice cultivation in the village of Gidong, South Korea.

Source: Hanwha Solutions (JAE-HYUK; COUNTY, 2022)

In the case of the above-mentioned countries, by integrating solar dual-use, farmers can generate additional income by selling solar electricity, while preserving the cropland beneath agrivoltaic installations for potential future agricultural use. Both Japan and South Korea have designed their regulations to encourage local participation, ensuring a decentralized and equal distribution of agrivoltaic projects (SCHINDELE et al., 2020). In South Korea, for example, the government plans to install, by 2030, 100,000 agrivoltaic systems on farms to ensure retirement security for farmers, providing them with a monthly income of approximately 1,000 US dollars through electricity sales (HERMANN; SCHÖNBERGER, 2022). Unlike in France, where agrivoltaic projects tend to be relatively large, and China, where there are no size limits, Japan and South Korea's focus on smaller-scale projects benefits local farmers and communities, fostering economic resilience and sustainable land use (SCHINDELE et al., 2020).

To ensure the benefits of adopting agrivoltaic technology, it is essential that all stages of planning, design, and installation of the systems are carried out properly. In Brazil, the technology is still in the pilot implementation phase, and in the coming years, it is crucial to conduct further studies on the suitability of the technology to local climatic conditions and crops. Additionally, these studies and insights gained from pilot projects are fundamental for developing guidelines and/or national regulation frameworks that will steer the development of agrivoltaic systems.

The lack of guidelines or national regulation is a relevant issue and giving incentives without it generated consequences in France in the last decade. According to a report from the Fraunhofer ISE (2020), as clear criteria had not been defined for agrivoltaic systems in the first round of tenders in France, the participation of agricultural production ended up being very low or even non-existent in some projects. This outcome led to certain resistance towards agrivoltaics in the country, especially within the agricultural sector (Fraunhofer ISE, 2020). Consequently, in 2021, standards for the installation of these systems were developed and published by the French Environment and Energy Management Agency (ADEME), which now serves as a guidance for current and future projects (ADEME et al., 2021).

Another challenge for the technology is the lack of trained professionals to plan and install projects in the Brazilian market. The technology is still new for PV companies and even educational institutions, with limited training opportunities available for energy professionals. Additionally, knowledge of PV systems alone is not sufficient for the development of a successful agrivoltaic project. As indicated in technical guide documents such as "Agri-photovoltaic systems – Requirements for primary agricultural use"[2] (DIN SPEC 91434) from Germany and "Guidelines for The Design, Construction, and Operation of Agrovoltaic Plants"[3] from Italy, the presence of multidisciplinary teams is crucial for planning, maintenance, and monitoring of these systems.

2 https://www.en-standard.eu/din-spec-91434-agri-photovoltaic-systems-requirements-for-primary-agricultural-use/

3 https://www.pv-magazine.com/2022/07/05/italy-publishes-new-national-guidelines-for-agrovoltaic-plants/

2.2 Applications and technologies

According to Macknick et al. (2022), agrivoltaic systems can be categorized into two main configurations: (1) elevated systems with crop production below the PV array, and (2) lower systems with crops grown between rows of PV modules. Therefore, agrivoltaic systems also exhibit versatility, with options ranging from lower setups, allowing for crop cultivation between rows of modules, to taller structures exceeding 5 meters in height, which enable passage of agricultural machinery beneath the PV arrays. These structures can be either fixed or equipped with single or dual-axis tracking systems to optimize energy generation.

In terms of applications (Figure 5), according to Macknick et al. (2022), the primary categories include:

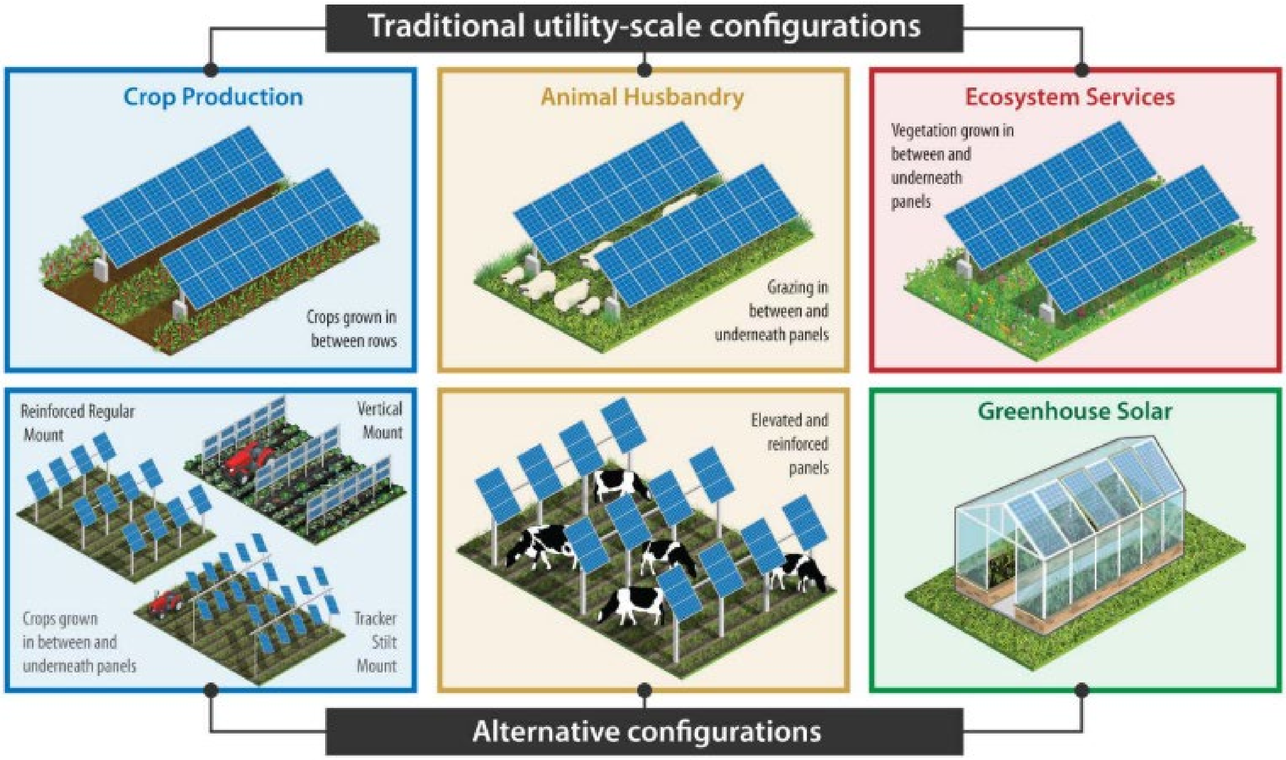
(1) Crop and food production: cultivation below or between rows of PV modules;

(2) Livestock production: grazing below or in the vicinity of the systems, providing thermal comfort through shading;

(3) Provision of ecosystem services through vegetation management: creating habitats for pollinators, soil formation, biodiversity maintenance, and carbon sequestration;

(4) Solar greenhouses: PV modules installed above greenhouses, utilizing the greenhouse structure for module installation and offering partial shading.

Figure 5 - Types of agrivoltaics systems that have been deployed commercially



Source: Macknick (2022)

Furthermore, some configurations are designed for specific applications, such as vertical bifacial modules or structures arranged to facilitate rainwater collection (Figure 6). The vertical systems are more cost-effective compared to overhead agrivoltaics, due to the lower substructure, but also offers fewer light management options. One advantage of the vertical interspace systems could be a reduction in wind speed, which has a positive effect reducing evaporation of the crops (HERMANN; SCHÖNBERGER, 2022). The vertical agrivoltaics can replace agricultural fences and protect grazing areas (Figure 7).

One other interesting application of vertical agrivoltaics is in association with greenhouses, leveraging greenhouse albedo to increase electricity output (Figure 8). This piolot project was installed in farm in Colorado – USA and the design and simulation was developed by the enterprise Sandbox Solar, with their software SPADE Agrivoltaic. The project's peak energy generation periods are at 9 a.m. and 4 p.m., generating more energy in the times where solar generation is usually lower (WEAVER, 2023).

Figure 6 - Concept design for a rainwater harvesting system with storage tank

Source: Hermann (2022)

Figure 7 - Bifacial solar modules fence for livestock enclosure

Source: Next2Sun (2023)

Figure 8 - Vertical PV system associated with greenhouses

Source: SandboxSolar (2023)

Another experimental application refers to **mobile solar PV panels**. In April 2022, a Dutch consortium consisting of Npk Design, L'orèl Consultancy, and LTO Noord announced the creation of a mobile agrivoltaics system called the H2arvester4. This system comprises 168 solar panels and an irrigation system, which can provide water to the surrounding areas.

Regarding photovoltaic module technologies, a wide range of options can be applied. Certain technologies, particularly those with **transparency or a transparent backsheet**, offer advantages by allowing more light through the module (Figure 9), which can significantly benefit agricultural cultivation. Also, **bifacial PV modules** can make use of increased albedo values (HERMANN; SCHÖNBERGER, 2022).

Figure 9 - Agrivoltaic research site featuring monofacial, translucent, and bifacial solar panels

Source: Macknick (2022)

Notably, specialized PV module models have been developed specifically for agrivoltaic applications, including **thin-film tubular modules** (Figure 10) and **modules with increased cell spacing**. Companies such as the German Tubesolar and Grip Parity and the Austrian DAS Energy are actively working with these technologies. Moreover, some companies, like BYD, are considering the possibility of domestic module manufacturing to cater specifically to agrivoltaic requirements. The tubular modules are installed horizontally and promise spatially uniform light and water permeability. These benefits are particularly important in agricultural production with no artificial irrigation (HERMANN; SCHÖNBERGER, 2022).

4 https://www.h2arvester.nl/?lang=en

Figure 10 - Tubesolar system

Source: Tubesolar (2023)

Such adaptability in applications and innovative technologies contribute to the continued growth and implementation of agrivoltaic technologies worldwide.

2.3 Business Models

Agrivoltaic systems incur higher costs compared to conventional photovoltaic systems, as they require adapted structures to combine cultivation and energy generation. According to the NREL Report "Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops", costs for elevated reinforced agrivoltaic systems can be up to 52% higher than a conventional fixed PV system (FIGURE 11) (Horowitz et al., 2020).

The agrivoltaic systems can be completely funded by the farmers themselves, who are also beneficiaries of the system, but other stakeholders can also be involved in the business model, covering four main areas: (1) Land ownership; (2) Agricultural land management; (3) Photovoltaic system ownership/investment; and (4) Photovoltaic system operation (HERMANN; SCHÖNBERGER, 2022).

Figure 11 - Typycal PV installed costs compared to different Agrivoltaic configuration costs

Source: Horowitz et al., 2020

According to Hermann and Schönberger (2022), besides the four different areas, there are also four main business models:

- **Basic case "everything from a single-entity model":** The first would be the simplest one, where all four areas may be responsibility of the same actor, typically a farming business. One advantage is that costs of project planning and the complexity of contract negotiations are lower.
- **External land ownership:** In this business model the land is leased from an external stakeholder and the other three areas are in the hands of the farming business. This situation required a long-term land lease agreement, as in the case of ground-mounted PV projects.
- **External PV investment:** For large PV systems an external investment for the PV systems is more common than small systems. This business model has the potential for economies of scale and optimization thanks to greater division of labor.
- **Shared responsibilities:** In this model there is a mix of players involved in the agrivoltaic system. The ownership of the land, the ownership of the PV system and the operation of the farm and PV system are responsibility of different parties, which might add complexity to the project.

Thus, the systems can be self-funded and individually owned or can operate through partial land leasing for the installation of the system by a third-party investor, for example. The different configurations of the business models for agrivoltaics, with the different actors and functions are displayed in TABLE 1.

Table 1 - Configurations of different agrivoltaic business models

Business model	Function			
	Providing land	Agricultural management	Providing the PV system	Operating the PV system
1. Base case	Farm			
2. External land ownership	Land owners	Farm		
3. External PV investment	Farm		PV investors	Farm
4. Cultivation and operation only	Land owners	Farm	PV investors	Farm
5. Cultivation only	Land owners	Farm	PV investors	PV operators

Source: Hermann and Schönberger (2022) based on Schindele et al. (2019)

Furthermore, there are several projects developed through cooperative models, where both the investment and the benefits of energy generation can be shared among the participating farmers in the cooperative. Some examples include:

- The Community solar park5 in Aasen, Germany, built with vertical modules in partnership with the energy cooperative Solverde Bürgerkraftwerke Energiegenossenschaft in 2020 (HERMANN; SCHÖNBERGER, 2022);
- The Gidong Village Power Plant6 in South Korea, which has a partnership with a social cooperative of local residents for "solar sharing," mostly comprising elderly individuals who are no longer able to work in the fields (JAE-HYUK; COUNTY, 2022);
- Enerjisa's7 project in partnership with the agricultural cooperative Komşuköy in Turkey - the country's first agrivoltaic pilot (TODOROVIĆ, 2023);
- The project by the Agricultural Cooperative CCampo in Santarém – PA, Brazil. This pilot-scale project was conducted with the support of DGRV, OCB, and the Solar Energy Research Laboratory at UFSC.

5 https://www.renewable-energy-industry.com/news/press-releases/pm-6456-start-of-construction-of-an-innovated-agro-photovoltaic-open-space-plant-in-donaueschingen-aasen-germany-

6 https://www.koreatimes.co.kr/www/tech/2023/03/129_335503.html

7 https://balkangreenenergynews.com/enerjisa-launches-first-agrivoltaic-pilot-project-in-turkey/

3. State of the art for agrivoltaic systems worldwide

Agrivoltaic technology has increased considerably in the last decade and has benefited from government support programs worldwide. In 2012, Japan launched the first supporting scheme on agrivoltaics systems, and then, other countries like China, South Korea, France, and Germany followed (DEPARTMENT OF ENERGY - USA, 2022). Policies, regulations and technical guidelines regarding these systems are of great importance in order to foster a sustainable development of the sector.

This section gathers information about the context of regulations and technical guidelines regarding agrivoltaic systems in various countries. This content will help build a framework on international best practices which will help create a national scenario for the technology.

3.1 Germany

Germany is a country that stands out for its advancements in agrivoltaic technology. According to the report "Agrivoltaics: Opportunities for Agriculture and the Energy Transition—A Guideline for Germany" by Fraunhofer ISE (2022), it was estimated in 2022 that there were 14 GWp of "overhead agrivoltaics" installed worldwide, with 1.7 GWp of these located in Germany.

The German government aims to significantly increase its solar electricity capacity from 60 GWp to 215 GWp by 2030. To achieve this, they plan to utilize rooftops and ground-based installations, and agrivoltaics is seen as a potential alternative, offering benefits like additional income for farmers and enhanced climate resilience. To incentivize investment in agrivoltaics, the Government has granted eligibility for guaranteed grid access and Feed-In-Tariffs under the Renewable Energies Act (EEG). Additionally, agrivoltaic projects will receive a "technology bonus" for each kilowatt-hour (kWh) generated, enhancing their attractiveness. Moreover, agricultural land used for agrivoltaics can still qualify for 85% of the standard subsidies provided by the EU's Common Agricultural Policy (CAP) as long as at least 85% of the land remains available for cultivation. However, sheep-grazing beneath standard solar panels will no longer be eligible for subsidies. Protected areas and agriculturally relevant conservation lands are excluded from this eligibility (NZEMBASSY, 2022).

Currently, agrivoltaics have not been fully embedded into the legal framework, so that some legal challenges remain unresolved (TROMMSDORFF; KATHER, 2022). Although no official standards are addressing agrivoltaic systems within the body of German Standards, the document titled "Agri-photovoltaic systems - Requirements for primary agricultural use"8 (DIN SPEC 91434), published in May 2021, aims to establish a testing method for agrivoltaic systems. The document seeks to provide standardization for agrivoltaic measurements for reporting and documentation purposes before legislative bodies, funders, and approval authorities, as well as for post-testing and certification stages of agrivoltaic systems by experts and certification organizations. This is intended to significantly reduce the technical risk for all participants involved in these types of projects.

3.1.1 DIN SPEC 91434 – Definitions and categorization

The definition of agrivoltaic systems presented in the guidelines is highlighted below:

- **Agricultural photovoltaics / agrivoltaics (APV):** Combined use of the same land area for primary agricultural production and secondary electricity generation through a photovoltaic system.

The systems are divided into two main categories:

- **Category I:** Agrivoltaic systems with elevated installation: Cultivation **under** the agrivoltaic system.
- **Category II:** Agrivoltaic systems with ground-level installation: Cultivation **between** the rows of the agrivoltaic system.

Based on the specifications of eligible agricultural lands, agrivoltaic systems in both categories can be divided into four usage categories: (A) permanent and perennial crops, (B) annual and perennial crops, (C) permanent pastures for mowing, and (D) permanent pasture.

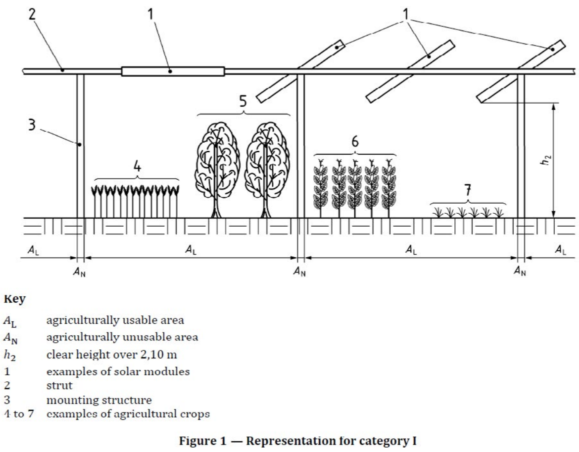
The document emphasizes the importance of **maintaining the crops in good condition**, following the European Union's cross-compliance rules and respective national standards. Furthermore, more detailed explanations about the agricultural activities in

8 https://www.en-standard.eu/din-spec-91434-agri-photovoltaic-systems-requirements-for-primary-agricultural-use/

agrivoltaic areas must be documented in an **agricultural cultivation proposal**, which should be prepared in the planning phase prior to the construction of the agrivoltaic system. Deviations from the above categories (e.g., a combination of two categories) are possible but must still comply with the requirements of the agricultural cultivation proposal.

To be classified as Category I, the system must meet certain technical specifications, notably having a minimum height of at least 2.1m (ground - bottom of the module), as shown in **Figure 12**.

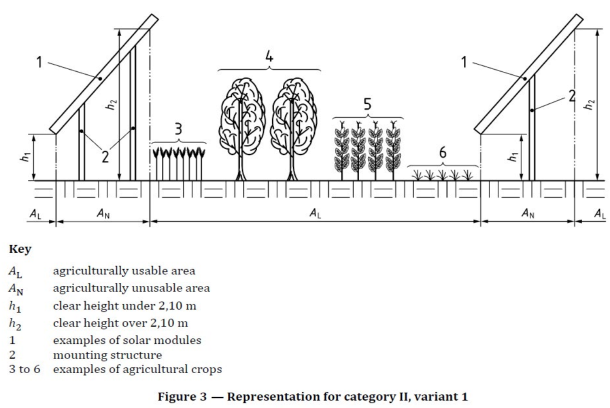
Figure 12 - Representation of Category 1



Source: DIN SPEC 91434 (2021)

On the other hand, Category II is divided into two variants: variant 1, with fixed modules at a specific angle (with module bottom height less than 2.1m), and variant 2, with modules mounted vertically or in an adjustable manner (with tracking), where the minimum height is typically less than 2.1m. The area under the modules should be considered unusable land for agriculture (referred to as area An in **Figure 13**).

Figure 13 - Representation of Category 2



Source: DIN SPEC 91434 (2021)

3.1.2 DIN SPEC 91434 – Agricultural proposal

The planned land use and agricultural production must be defined in an agricultural cultivation proposal for the next three years or in a crop rotation cycle. The cultivation possibilities for the area should be tailored to the existing crops and properly listed in the agricultural cultivation proposal.

The agricultural cultivation proposal is jointly prepared (designed) by the land user (farmer, leaseholder) and the EPC contractor (PV system installer) and must be attached to the project documentation. The proposal should include detailed information about the following points:

- **Installation:** The photovoltaic system installation in both categories must occur in a distributed manner within the project area to preserve its prior agricultural use.
- **Land loss:** The loss of arable land due to structures should be avoided, not exceeding 10% in Category I and 15% in Category II.
- **Cultivation workability:** The workability of the cultivation area must be ensured.
- **Light availability and homogeneity:** Maximizing homogeneity and light availability is essential to ensure plant growth. These aspects should be verified and adapted to the specific agricultural product needs, as agricultural production is the priority and must be guaranteed.
- **Water availability:** The availability and uniform distribution of water must be ensured for cultivation. To ensure this, an irrigation system may be used or a project with case-by-case evaluation related to the crop's water demand can be demonstrated under usual local climatic conditions.
- **Soil erosion:** The system design should minimize soil erosion effects caused by water runoff on the modules. A rainwater collection or distribution system can be implemented.
- **Residue-free assembly and disassembly:** The agrivoltaic system, particularly its foundations and anchors, must be suitable for disassembly to restore the land to its original usability after dismantling the system.
- **Calculation of economic efficiency:** An economically viable concept for agricultural use from the farmer's perspective must be presented as part of the agricultural cultivation proposal.
- **Land use efficiency:** The crop yield in the total project area after constructing the agrivoltaic system must be at least 66% of the reference yield. The reduction in agricultural crop yield results from the loss of arable

land due to the superstructure/substructure of the photovoltaic system and reduced availability of water, among other factors. The reference yield should be determined using the average yield of the last three years if the farmer has already been cultivating before the photovoltaic system installation. If not, reference yields from relevant publications of the last three years can be used. The estimation of yield reduction in the available area, which should not exceed one-third, should consider the listed factors, and can be performed by qualified professionals.

3.1.3 DIN SPEC 91434 – Planning and technical prerequisites for agrivoltaics

In order to develop an agrivoltaic project, according to DIN SPEC 91434 there are several technical decisions and prerequisites that must be considered, such as:

- **Light availability and homogeneity:** The verification should encompass all system components that influence light availability. To simplify the calculation, glass materials and encapsulation between photovoltaic cells can be considered as free cell space with 100% transparency.
- **Requirements for support structures and stability:** Structures in Germany must be designed according to Eurocode safety concepts.
- **Requirements for photovoltaic technology:** Various photovoltaic technologies can be used in agrivoltaic systems, but certain aspects need to be considered and adapted to ensure light distribution and homogeneity for cultivation.
- **Installation requirements:** In Category I, a vertical distance of 2.1m between the top of the crops and the lower base of the photovoltaic system must be maintained. Additionally, the non-arable area should not exceed 10% of the total area. In Category II (ground-level systems), the size and height of the systems must be tailored to the specific cultivation, and the non-arable area should not exceed 15% of the total area.
- **Other installation planning requirements:** The spacing between module rows is not specified but should comply with the previously listed requirements. Precautions against damage from agricultural machinery, such as protecting module structures, should be included in the planning.
- **Installation, operation, and maintenance requirements:** The continuity of cultivation throughout the project period must be ensured, along with the quality of the soil after the construction and dismantling of the photovoltaic system. Compliance with construction, area occupation, and safety requirements is essential. Maintenance of the system should adhere to photovoltaic system regulations, and working under the system during extreme weather events should be avoided. Periodic inspection for dirt on the modules is recommended, and cleaning should only be done if necessary, with care to avoid any negative impact on the crops when using cleaning agents.

3.1.4 Agrivoltaic case in Germany

Research agrivoltaic sites exist in Germany since 2013 (HERMANN; SCHÖNBERGER, 2022), and many of them were of large relevance to the development of the technology worldwide. Currently, there are a few German companies and organizations dedicated to agrivoltaics. The Fraunhofer Institute for Solar Energy Systems (ISE) offers comprehensive R&D services for the industry, covering strategy, project development, engineering, procurement, and operation monitoring.

BayWa r.e., a subsidiary of BayWa and majority shareholder of T&G, was an early adopter in this field and actively seeks farms interested in co-investing in agrivoltaics (NZEMBASSY, 2022). BayWa r.e aims to develop 250 MWp Agri-PV by 2025 (LARGUE, 2021). Other German companies in the agrivoltaic market are SunFarming, which provides elevated horizontal systems suitable for fruit and vegetable cultivation, herbs, flowers, and special crops like wine and berries, Next2Sun, which specializes in vertical, bifacial agrivoltaic systems, and Tubesolar, which is engaged in the development of photovoltaic thin-film tubes (NZEMBASSY, 2022).

One good example of a research site in Germany is at the Hofgemeinschaft Heggelbach farm near Lake Constance in Germany in 2016 (FIGURE 14), as part of the APV-RESOLA project. Test crops, including winter wheat, potatoes, celery, and clover grass, were cultivated. To ensure consistent sunlight exposure for the crops, bi-facial double-glass PV modules were installed with a ground clearance of five meters, facing south-west, and with larger gaps between the rows. The design allows for the use of large machinery like combine harvesters without significant limitations. The rows are spaced 9.5 meters apart with a row width of 3.4 meters. The installed capacity of this test system is sufficient to power 62 four-person households annually. However, due to increased row distances, the installed capacity per hectare is approximately 25% lower compared to conventional ground-mounted PV systems (HERMANN; SCHÖNBERGER, 2022).

The project's findings revealed that the land-use efficiency increased to 160% in the first year of the project (2017), confirming the practical feasibility of agrivoltaics. Crops grown under PV modules had a yield of over 80% compared to reference areas without PV modules, making them commercially viable. During the 2018 summer, there were extreme heatwaves and crop yields surpassed the previous year's results significantly. The partial shade provided by the PV modules enhanced crop yields, while the abundant solar radiation simultaneously boosted solar power generation (HERMANN; SCHÖNBERGER, 2022). This led to an 86% improvement in land-use efficiency during the potato crop testing, as shown in FIGURE 15.

Figure 14 - Heggelbach project built in 2016

Source: BayWa r.e (2023)

Figure 15 - The dual use of land for agrivoltaics and potato growing increased land-use efficiency on the Heggelbach test site to 186%

Source: Hermann et al. (2022)

3.2 Italy

The first agrivoltaic plant in Italy, which was one of the pioneering projects in Europe, was installed in 2002. It has a total capacity of 1 MW and is located in Apulia. Subsequently, the deployment of agrivoltaic systems gradually expanded, eventually gaining recognition as a strategy for achieving decarbonization objectives.

In March 2022, new national guidelines for agrivoltaic plants[9] were released in Italy. These guidelines were developed by the Ministry of Ecological Transition, in coordination with organizations such as the Agricultural Research Council and Agricultural Economics Analysis (CREA), Energy Services Manager (GSE), National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), and Energy Systems Research (RSE).

3.2.1 Italian guidelines – Definitions

9 https://anie.it/wp-content/plugins/acd-attach-document/acd-get-document.php?post_ID=65204&file_name=position-paper-agrovoltaico.pdf

The guidelines, entitled "Guidelines for The Design, Construction and Operation of Agrovoltaic Plants," aim to clarify the characteristics and minimum requirements for a photovoltaic system to be considered an "agrivoltaic system". In general, it distinguishes two types of systems: (1) agrivoltaic systems that ensure a minimum interaction between energy production and agricultural production, and (2) advanced agrivoltaic systems that meet additional requirements and are eligible for state incentives paid through the electricity tariff, as per the Legislative Decree of March 3, 2011, no. 28[10].

The guidelines are based on the Italian Law No. 108 of July 29, 2021[11], in which agrivoltaic systems are defined as those systems "that adopt innovative integrative solutions with elevated module mounting from the ground, also providing for the rotation of the modules themselves, in any case, so as not to compromise the continuity of agricultural and pastoral activities, allowing the application of digital tools and precision agriculture." Additionally, the German regulation DIN SPEC 91434 "Agrivoltaic Systems - Requirements for Primary Agricultural Use" was considered in the Italian guidelines.

Some definitions present in the guidelines are listed below:

- **Agrivoltaic System:** Refers to a photovoltaic system that adopts solutions aimed at preserving the continuity of existing agricultural and livestock activities at the installation site.
- **Advanced Agrivoltaic System:** Refers to a photovoltaic system that adopts solutions intended to preserve the continuity of agricultural and livestock activities at the installation site. This system, following the provisions of Article 65 - Decree No. 1 of January 24, 2012[12], as amended and supplemented:
  - Adopts **innovative integrative solutions** with elevated photovoltaic module mounting from the ground, also providing for the rotation of the modules themselves, in a manner that does not compromise the continuity of agricultural and pastoral cultivation activities, and may also allow for the application of digital tools and precision agriculture; and
  - Envisages the **simultaneous implementation of monitoring systems** to verify the impact of the photovoltaic installation on crops, water savings, agricultural productivity for different types of crops, continuity of farm activities, soil fertility recovery, microclimate, and resilience to climate change.

3.2.2 Italian guidelines – Categorization

The guidelines consider five types of requirements (A, B, C, D, and E) for agrivoltaic systems. To qualify as a "basic" agrivoltaic system, requirements A, B, and (possibly) D.2 must be met.

- **Requirement A.1:** Refers to the area and stipulates that 70% of it should be allocated to agricultural cultivation, floriculture, or livestock grazing.
- **Requirement A.2:** Defines the maximum percentage of the module area, which should not exceed 40%.
- **Requirement B.1:** Relates to the agricultural/livestock productivity yield in €/ha or €/Adult Livestock Unit. This requirement involves comparing the yield of the photovoltaic system with the previous years' yield in the area. If there was no production before the photovoltaic system's installation, the yield is compared to the productive areas nearby or a control area. Additionally, this requirement pertains to maintaining existing crops/production, ensuring that the photovoltaic system does not influence changes in the crops produced.
- **Requirement B.2:** Specifies that the photovoltaic generation system's productivity (yield) should be at least 60% of the reference standard system's yield in GWh/ha/year.
- **Requirement C:** Focuses on innovative solutions integrated into the agrivoltaic system to optimize photovoltaic generation performance and agricultural productivity. It establishes the following criteria:
  - (1) The minimum module height is designed to allow the continuation of existing productive activities OR (2) it is not designed to maintain agricultural production OR (3) modules are positioned vertically. In cases 1 and 3, the system would be considered an advanced agrivoltaic system.
  - Reference values: 3 meters height for animal production activity, 1 meter for agricultural activity.
- **Requirement D:** Sets rules for systems with monitoring of impacts on crops, water savings, productivity, and the continuity of activities on involved farms. Average performance values should be maintained throughout the plant's lifetime. Monitoring is essential to assess various aspects and ensure the associated agricultural production continuity.

10 https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto-legislativo:2011-03-03;28

11 https://www.bosettiegatti.eu/info/norme/statali/2021_0108_ex_DL_77.pdf

12 https://www.gazzettaufficiale.it/eli/id/2012/01/24/012G0009/sg

- **Requirement D.1:** Monitoring of water savings.
- **Requirement D.2:** Monitoring of agricultural production continuity.
- **Requirement E:** The system allows verification of soil fertility recovery, microclimate, and resilience to climate change.

3.2.3 Agrivoltaic case in Italy

Large-scale projects are present in Italy and the UK company Cero Generation has an important participation in the market. The company had a financial close of a 70 MW agrivoltaics facility in the Italian Province of Latina and one other of 48 MW in the province of Viterbo in the Lazio region (CERO, 2022).

One example of successful agrivoltaic system implemented in Italy involved the use of solar panels to provide shade for lemon and citron trees (FIGURE 16), mitigating the impacts of extreme heat and ensuring the preservation of these crops. The results demonstrated that the agrivoltaic system helped reduce the temperature under the solar panels, preventing potential fruit damage and maintaining optimal growing conditions for the trees. Moreover, the combined production of electricity from solar panels and fruit crops was observed to be more profitable than traditional monoculture practices. This implementation of agrivoltaics illustrates its potential to protect crops, enhance agricultural productivity, and contribute to sustainable energy production (PETRONI, 2023).

Figure 16 - Agrivoltaic system with citrons at the Lancellotta family farm

Source: Petroni (2023)

3.3 France

In the past years, the number of companies offering agrivoltaic services, such as Total, Sun'Agri, and Ombrea, has increased in France, backed by support from the national government. Also, large-scale energy procurements are increasingly incorporating agrivoltaic projects with association with sophisticated crop plants, such as vineyards and orchards (DOE, 2022). According to estimates of the association France Agrivoltaïsme, there are up to 200 agrivoltaic projects in the country (FIGURE 17), with many more in the planning stages (MARTIN GREENACRE, 2023).

One of the reasons for this growth might be related to the fact that the French government is encouraging the development of large-scale agrivoltaics through competitive contracts. In 2021, France allocated 40 MW of agrivoltaic projects, as a part of its innovative PV award in an energy auction (SPAES, 2021). In 2023, the French Ministry of the Ecological Transition released the results of a tender aimed at innovative PV technologies conducted under the Multiannual Energy Plan (Programmation Plurianuelle de l'Energie, PPE). In this process, a total of 172.9 MW of solar power capacity was allocated by the authorities, from which 80 MW were destined for agrivoltaic projects (DEBOUTTE, 2023).

Figure 17 - Sun'R agrivoltaic system in France

Source: Spaes (2021)

Despite the relevant growth in agrivoltaic systems, there is currently no official concept or guidelines for this technology in the country. Though there is no official document, in 2021, the French Agency for the Environment and Energy Management (ADEME) defined standards for agrivoltaic systems through a series of publications on its website[13]. These publications cover concept reviews, system characterization, case studies, system performance, and the state of the art in France and various other countries (ADEME et al., 2021).

Nevertheless, a new legislation that will regulate the agrivoltaic concept is being developed. According to the new renewable energy regulations under development, there will be a few conditions for agrivoltaic projects (MARTIN GREENACRE, 2023). The legislation will incorporate long-term maintenance or development of agricultural production, similar to other existing regulations. Additionally, the proposal emphasizes that the primary activity should remain agricultural, and the agrivoltaic system must provide at least one of the following benefits for cultivation: improvements in agricultural potential, climate change adaptation, protection against threats, and enhanced animal welfare.

The lack of guidelines or national regulation is a relevant issue and giving incentives without it generated consequences in France in the last decade. According to a report from Fraunhofer ISE (2020), the lack of well-defined criteria for agrivoltaic systems during the initial tendering process in France caused minimal or no involvement of agricultural production in some projects. Consequently, this resulted in resistance towards agrivoltaics in the country, particularly within the agricultural sector.

As an example, two concerns reported by farmers in the country, highlighted in a webinar conducted by researchers from Hochschule University of Applied Sciences[14], are the fear of increased land costs with potential for agrivoltaic energy generation and the potential replacement of existing agricultural activities with energy generation. For example, currently, it is allowed to replace tomato production with sheep rearing, which might not be permitted under the regulations in Germany or Italy.

In terms of case studies in France, one example of agrivoltaic project in France is in the vineyards of the Domaine de Nidolères (FIGURE 18). The vineyards cover 32 hectares and there is a SunAgri project over a 4.5 ha of land. The region has suffered from climate change effects in the last years, such as rising temperatures, early ripening of grapes and an increased need for water, which matches with the benefits of agrivoltaic systems. The results of the system include improved organoleptic properties of the production and a 20% reduction in water consumption (SUN'AGRI, 2023).

13 https://librairie.ademe.fr/energies-renouvelables-reseaux-et-stockage/4992-caracteriser-les-projets-photovoltaiques-sur-terrains-agricoles-et-l-agrivoltaisme.html

14 https://iea-pvps.org/events/workshop-on-legal-frameworks-for-agrivoltaics-in-france-germany-italy-and-israel/

Figure 18 - Agrivoltaics project at the domaine de Nidolères vineyard (Pyrénées-Orientales)

Source: Martin Greenacre (2023)

3.4 Japan

Agrivoltaics are well known in Japan, where there are nearly 2,000 systems installed. The first pilot project in the country, and in the World, was initiated in 2004 in Chiba municipality by Akira Nagashima. Today, it is estimated that between 500,000 to 600,000 MWh of energy are generated annually through this technology in Japan (approximately 0.8% of the photovoltaic energy generated in 2019) and the systems are associated with more than 120 kinds of crops. Most of these farms are small-scale, covering less than 0.1 ha, occupying a total of 560 ha (TAJIMA; IIDA, 2021).

Several government policies have been fundamental to achieving the country's technological development. In 2011, the Feed-In-Tariff (FIT) scheme was institutionalized in the country, and it was officially operational in 2012. This policy had the most significant impact on the growth of photovoltaic energy generation in the region, which increased by 76% from 2012 to 2019. In addition to FIT, an official ordinance was issued in 2013 that stipulated procedures and conditions to allow the conversion of agricultural land for agrivoltaic use, following the key conditions:

(1) The mounting structure is only temporary and easily removable;

(2) The chosen photovoltaic panel should not obstruct crop growth, ensuring sufficient sunlight penetration for plant growth and at least 2 m above ground panel height for agricultural machinery operation;

(3) The plot should not interfere with agricultural practices in the surrounding areas, including the agricultural drainage system, or disrupt the implementation of the "Agricultural Promotion Area Maintenance Plan";

(4) The annual yield must be reported, and the yield reduction should not exceed 20% from the period before agrivoltaic installation.

Initially, the proponent could apply the technology for a maximum period of three years, (then extended to 10 years in 2018), and it was only provided if the farmer could demonstrate competence in agriculture and management, among other conditions. In 2020, the second amendment to the FIT Act was promulgated, bringing several important changes to the policy, including a significant one for agrivoltaic systems: the requirement for small-scale photovoltaic installations (10 to 50 kW) to meet "regional use requirements" to obtain a FIT certificate. The law provides additional preferential treatment to agrivoltaics to encourage their development. There are three "regional use requirements": (1) the self-consumption rate must be at least 30%, (2) there must be a way to confirm actual self-consumption, and (3) the generated electricity must be usable during a disaster situation (TAJIMA; IIDA, 2021).

In 2021, the New Energy and Industrial Technology Development Organization (NEDO) of Japan released new guidelines to develop and construct agrivoltaic facilities in an attempt to increase the presence of these projects in the country, which is struggling with land scarcity. The guidelines were prepared under the supervision of the Ministry of Economy, Trade, and Industry (METI) (EMILIANO BELLINI, 2021). The guidelines considers that agrivoltaic projects cannot exceed a height of 9 meters due to building regulations. Additionally, projects using trackers or installations in greenhouses and horticultural sheds were excluded from the guidelines.

The most popular crops in Japanese agrivoltaic systems include mioga ginger, Sakaki or Japanese cleyera, paddy rice, shiitake mushrooms, and blueberries, fuki or butterbur, tea, green onions, pasture grass, pumpkins, and paddy rice. This last one is the third most popular crop in agrivoltaics because of its importance for the country, and not because of its fit with agrivoltaic technology (TAJIMA; IIDA, 2021).

The first vertical agrivoltaic project in Japan was built through a partnership between Luxor Solar KK and Next2Sun AG (FIGURE 19), as reported on the Next2Sun website[15]. By combining agricultural production with solar photovoltaic panels arranged in a vertical orientation, the project aims to maximize land utilization and energy generation while promoting agricultural practices. The plant was built for ISEP – Institute for Sustainable Energy Policy, which is a non-profit research organization founded in 2000 by energy experts and climate activists. The organization aims to provide resources and services to create a sustainable energy society.

Figure 19 - First vertical agrivoltaic project in Japan

Source: Next2Sun (2022)

3.5 China

China stands out in terms of installed capacity for agrivoltaics worldwide. Fraunhofer ISE reported that China had the largest share of installed agrivoltaics in 2021 with a capacity of 1,900 MW, of which 700 MW is installed over goji berries grown at the edge of the Gobi Desert (DOE, 2022). The goji berry system is the world's largest agrivoltaic system, located near the Gobi Desert (FIGURE 20). Goji berries are an ingredient in traditional Chinese, Korean, and Japanese medicine. The area was previously desertified, and the project initiators first planted alfalfa to restore the soil before installing the agrivoltaic system with goji berries. There is a plan from Baofeng Group to increase the installed capacity of this project to 1 GW (BELLINI, 2020).

Figure 20 - Largest existing agrivoltaic systems, with goji berry plantation in China

Source: Bellini (2020)

15 https://next2sun.com/en/luxor-solar-kk-is-new-exclusive-partner-of-next2sun-ag-and-realizes-first-agri-pv-project-in-japan/

Government support has played a significant role in driving the development of agrivoltaics in the country, enabling permitting and financing processes. This support comes from the growing need for both energy and food security. China imports large quantities of vegetables and fruit, and the independence from these suppliers is considered a priority by the government.

Agrivoltaic greenhouses are thriving in China, and are mostly associated with the cultivation of tea, grapes, diverse vegetables, and a range of mushroom varieties. Projections indicate over 10 GW of capacity of agrivoltaic projects in the coming years, with most projects incorporating BIPV (Building Integrated Photovoltaics) technology integrated into plastic tunnel greenhouses with conventional solar modules (FIGURE 21) (MOERMAN, 2021).

Figure 21 - Agrivoltaic Greenhouse with flowers and pomelo in China

Source: Moerman (2021)

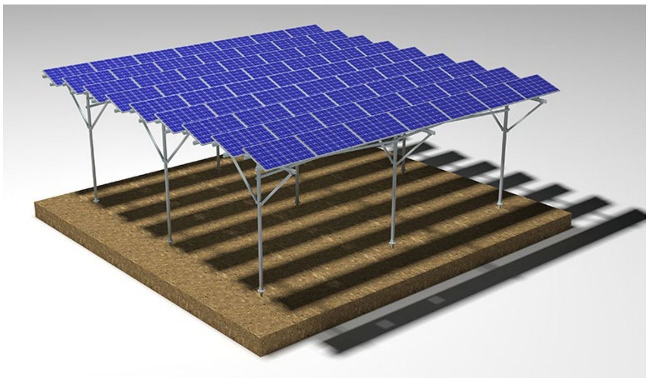
Chinese companies are investing in innovation for agrivoltaic structures. For example, researchers from the University of Science and Technology of China have worked on a new design that claims to reduce the shading effect on crops and improve light distribution. In this model, called Even-lighting Agrivoltaic System (EAS), the panels are placed at a height of at least 2.5 m from the ground and a grooved glass plate placed between the solar panels (FIGURE 22) (BELLINI, 2021).

Figure 22 - Even-lighting Agrivoltaic System (EAS), the novel chinese agrivoltaic design

Source: Bellini (2021)

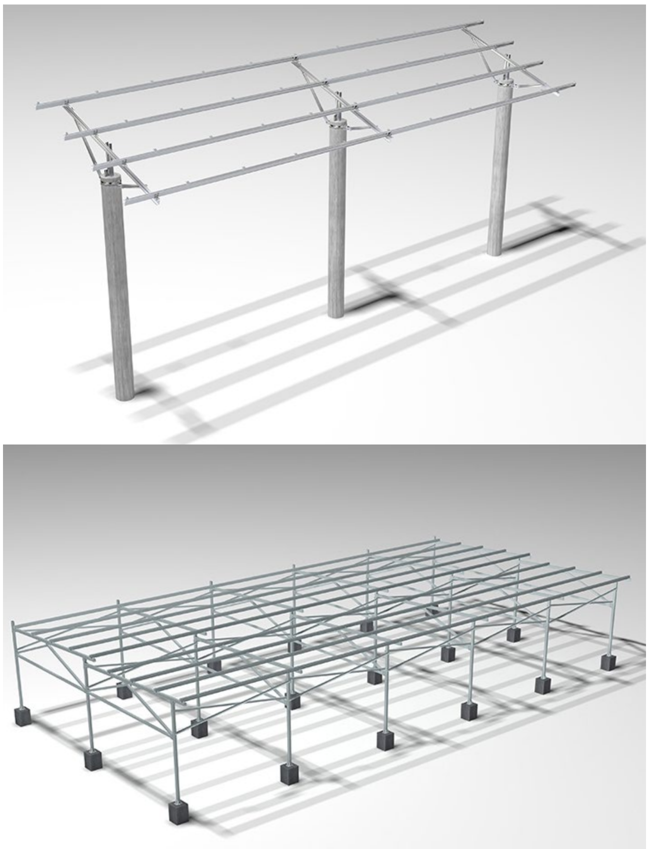
One other innovation is from the Chinese company Mibet, who is investing in agrivoltaics mounting systems that can be applied to different crops (FIGURE 23) (MIBETENERGY, 2023).

Figure 23 - MRac Agriculture PV System, from chinese Mibet company



Source: Mibet Energy (2023)

Figure 24 - MRac Agriculture PV System, from chinese Mibet company



Source: Mibet Energy (2023)

An example of Chinese companies involved with agrivoltaics is the publicly listed NESI, responsible for one of the largest BIPV agrisolar projects in China. The project has an installed solar capacity of 40 MW (Figure 25). Real glass greenhouses with BIPV modules account for 30% of all agrivoltaics in China (MOERMAN, 2021).

Figure 25 - NESI agrivoltaic system in China - one of the largests of the country

Source: Moerman (2021)

3.6 Croatia

Croatia has recently adopted a legal framework for agrivoltaics, marking a significant step towards the development of the technology in the country. The new regulations allow farmers to install PV systems on agricultural land, effectively combining electricity generation with agricultural activities. This legal framework aims to promote the adoption of agrivoltaic systems and facilitate the sustainable development of both sectors (MAISCH, 2023).

Under the new regulations, farmers can benefit from subsidies and incentives to set up agrivoltaic plants. Agrivoltaics are now permitted on various types of sites, such as agricultural land, unused plots, and areas with permanent plantations like vineyards and olive groves. These new rules grant every farmer the opportunity to install agrivoltaics on their land. This move is expected to enhance energy security, reduce greenhouse gas emissions, and boost agricultural productivity by optimizing land use. Croatia aims to achieve its renewable energy targets and promote a greener and more resilient agricultural sector (MAISCH, 2023).

A pilot project was developed in 2016 in the country, in the city of Mecini, region of Slavonie. This system has an installed capacity of 500 kW and a diversity of vegetables are produced under the agrivoltaic structure, which is under the responsibility of the University of Osijek (PVEUROPE, 2017).

3.7 United States

Currently, the agrivoltaic sites in the United States, have a significant portion associated with sheep grazing and/or providing habitat for pollinators (PVTECH, 2023). Initially, the systems were limited to research test plots, and now there are at least five commercial agrivoltaic sites in operation, situated in the states of Colorado, Massachusetts, and Maine (PVTECH, 2023).

The agrivoltaic sector in the USA is receiving investments from various organizations. The Department of Energy (DOE) is providing US$15 million in research funding to explore the feasibility of agrivoltaics for farmers, the solar industry, and communities. Some states are encouraging agrivoltaic projects through incentives and research initiatives. For instance, Massachusetts has implemented a Feed-In-Tariff adder of US$0.06/kWh for agrivoltaic projects under its Solar Massachusetts Renewable Target (SMART) program. In New Jersey, an agrivoltaics pilot program of up to 200 MW on unpreserved farmland has been authorized, along with funding for an R&D system at the Rutgers New Jersey Agricultural Experiment Station. Colorado is also investing in agrivoltaics research (PVTECH, 2023).

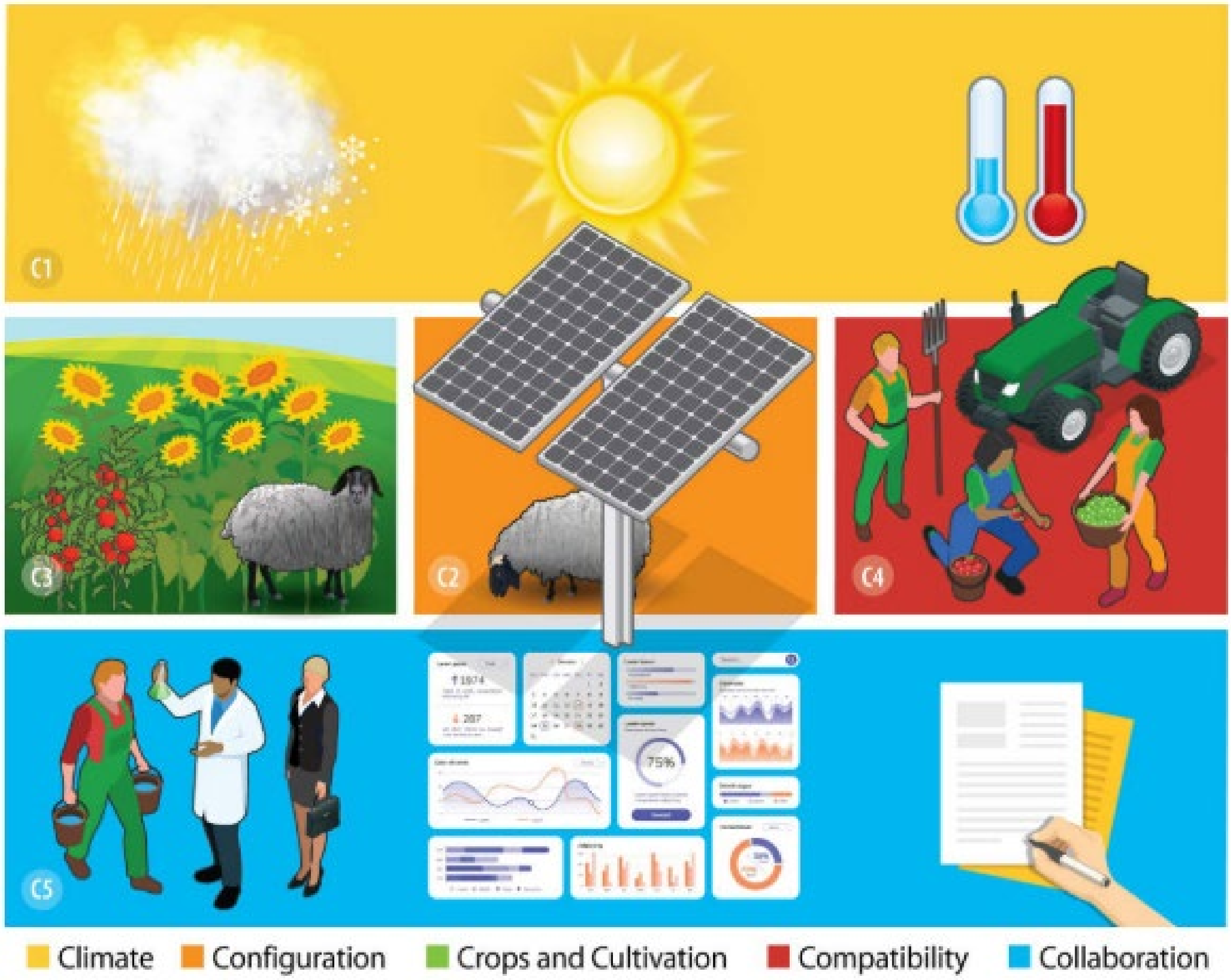
Additionally, the USA's Office of Energy Efficiency and Renewable Energy is collaborating with the Department of Agriculture on foundational research to assess the economic value, trade-offs, and ecological impacts of agrivoltaics projects. Furthermore, the Department of Energy (DOE) is providing funding to develop new technologies that could facilitate agrivoltaics and reduce associated costs (PVTECH, 2023).

DOE's research project entitled "Innovative Solar Practices Integrated with Rural Economies and Ecosystems" (InSPIRE) has been supporting agrivoltaic research initiatives since 2015. The project examined opportunities and trade-offs at more than 25 locations across the country, encompassing agricultural production, pollinator habitat, ecosystem services, and livestock production (MACKNICK et al., 2022).

The results from the pilot projects that composed the InSPIRE project served as input for a document published in August 2022 by NREL, entitled "The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons from the InSPIRE Research Study"[16]. The 5 C's are Climate, Configuration, Crops and Cultivation, Compatibility, and Collaboration (Figure 26).

16 https://www.nrel.gov/docs/fy22osti/83566.pdf

Figure 26 - The 5 Cs of agrivoltaic project success



Source: Macknick (2022)

More details about what is in each one of the C's is below, as described in the InSPIRE report:

- **Climate, Soil, and Environmental Conditions (C1):** The ambient conditions and factors of the specific location that are beyond the control of the solar owners, solar operators, agrivoltaic practitioners, and researchers.
- **Configurations, Solar Technologies, and Designs (C2):** The choice of solar technology, the site layout, and other infrastructure that can affect light availability and solar generation.
- **Crop Selection and Cultivation Methods, Seed and Vegetation Designs, and Management Approaches (C3):** The methods, vegetation, and agricultural approaches used for agrivoltaic activities and research.
- **Compatibility and Flexibility (C4):** The compatibility of the solar technology design and configuration with the competing needs of solar owners, solar operators, agricultural practitioners, and researchers.
- **Collaboration and Partnerships (C5):** Understandings and agreements made across stakeholders and sectors to support agrivoltaic installations and research, including community engagement, permitting, and legal agreements.

According to the learnings from the research sites, a module height of 1.8 m appears to be the minimum viable height for planting vegetables below the modules, considering shading patterns and interaction with farmers. However, farmers prefer a height of 2.4 m or more. Researchers from the project are evaluating microclimate, soil characteristics, shading, and interactions with workers in systems with both heights at two locations in the United States.

Module spacing, as well as spacing between rows of modules, and different photovoltaic technologies, with or without cell spacing, are being studied by American universities as part of the InSPIRE project, which, together with the results from its pilot projects, will contribute to the development of guidelines for the technology.

One important agrivoltaic project in the USA is called Jack's Solar Garden[17], which is the country's largest commercially active site for agrivoltaics research (FITZPATRICK, 2023). Jack's Solar Garden (Figure 27, Figure 28 and Figure 29) is a 1.2 MW solar farm in Boulder, Colorado, which generates sufficient energy to supply approximately 300 households and boasts over fifty residential subscribers, in addition to five commercial subscribers. Notably, the agrivoltaic system hosts a diverse range of forty plant types, including blackberries, herbs, and tomatoes. Moreover, the site has been enriched with 3,000 trees, shrubs, and pollinator-friendly plants surrounding the solar arrays (DOE, 2022).

One other example of the more than 25 research sites of the InSPIRE project is the agrivoltaic project in Grafton[18], located in Massachusetts, United States (Figure 30). This large-scale facility is an innovative 2 MW community solar farm with a battery energy storage capacity of 1.4 MW. The project integrates solar energy generation, on-site agricultural production, and numerous partnerships within the research community.

Figure 27 - Agrivoltaics farm to attract pollinators such as honeybees, bumble bees, and butterflies

Source: Macknick (2022)

Figure 28 - Harvest under the agrivoltaic system at Jack's Solar Garden

Source: Macknick (2022)

Figure 29 - A farmer harvests crops at Jack's Solar Garden

Source: Macknick (2022)

17 https://www.jackssolargarden.com/

18 https://www.aes.com/grafton-solar

Figure 30 - Grafton Solar agrivoltaic project

Fonte: AES (2023)

3.8 Chile

According to Jung (2023), Chile is among the countries most affected by climate change, posing a significant threat to its agricultural sector. The country faces the risk of consequences such as losing high-quality soil surfaces mainly by desertification, erosion, contamination, and inappropriate agriculture practices, which may result in increasing the demand for food and energy (GESE et al., 2019). The northern and central regions, for example, experience a 12-year drought, leading to severe water shortages that impact small-scale farmers. Besides the severe drought, other challenges pose risks to crop yields faced by farmers in Chile, such as unpredictable weather events like hail, frost, heavy rainfall, and excessive solar irradiation (JUNG, 2023).

The first agrivoltaic project in Latin America was installed in Chile in 2017 (FIGURE 31) and it is constituted by three systems with a capacity of 13 kWp installed in the outskirts of Santiago, in the municipalities of El Monte, Curacaví, and Lampa (HERMANN; SCHÖNBERGER, 2022). The region is characterized by high solar radiation and low annual precipitation. As mentioned, there is a continuous drought in the already dry and sunny climate, and this condition has caused precipitation to decrease by 20% to 40% in the last ten years (HERMANN; SCHÖNBERGER, 2022).

Due to the climatic conditions, farmers are seeking shading facilities to protect plants from sunburn and dehydration. The project is supported by the local government and the Fraunhofer Chile Institute, and the results are very positive, both in terms of agricultural productivity and energy generation (HERMANN; SCHÖNBERGER, 2022).

Figure 31 - Pilot projects in Chile

Fonte: Hermann (2022)

The results show a measured reduction in solar irradiation by 40%, leading to a 29% increase in soil moisture, which could reduce overall irrigation water demand. The reduced solar irradiation also protects crops from excess sun, and the cooling effect during the day and temperature increase at night can safeguard crops from frost. Within the pilot plant, land use efficiency for lettuce cultivation increased by up to 187%, with agricultural yields unaffected by the agrivoltaic system. Electricity generation reached 87% of the total produced by a conventional PV system on the same area, mainly due to suboptimal panel orientation and increased row distance (JUNG, 2023).

3.9 South Korea

South Korea heavily relies on energy imports from other countries, with 95% of its energy supply being sourced from fossil fuels such as coal and oil. The current Korean Agricultural Land Law prohibits any use of agricultural land other than for farming, given the country's small and densely populated nature. Since most Koreans live in apartments, roof-top systems have a small potential of contributing to solar energy generation, which makes the dual use of agrivoltaics an interesting alternative to provide a vast land for PV generation for the energy transition. In this context, in recent years, several lawmakers have proposed revising the Agricultural Land Law to permit agrivoltaic systems (KIM; OH; JUNG, 2022).

As of 2021, there were 44 agrivoltaic projects in the country, mainly in pilot and research scales, implemented since 2016. The primary motivation for developing national regulations stems from the potential of agrivoltaic systems to provide additional income to small-scale farmers (KIM; OH; JUNG, 2022).

The regulation of agrivoltaics in South Korea is currently undergoing revisions to allow its implementation. Several proposals were made, and the final one in 2021 allows up to 100 kW for each farmer and a temporary usage period of 23 years. It also includes government financial support and preferential purchase of agrivoltaic electricity. The revised proposal is expected to pass in the near future after the required legal procedures in the Korean Congress (KIM; OH; JUNG, 2022).

South Korean companies have shown a strong interest in agrivoltaics. Hanwha's Q Cells Division was selected as a partner in the Agrivoltaic System Standardization Project by the South Korean government. In collaborating with Yeungnam University and a local enterprise, Hanwha Q Cells is working on advances in agrivoltaic systems associated with various agricultural settings, including rice paddies, farm fields, and orchards. The company has made significant investments in research and development, particularly in next-generation solar power technologies and products and is planning to allocate KRW 1.5 trillion (US$1.2 billion) into research and manufacturing facilities by 2025 (HANWHA, 2022). Q CELLS has created a compact PV module, which is half the size of a traditional PV module (FIGURE 32). This ensures the efficient utilization of solar installations in agricultural settings, allowing for electricity generation while simultaneously providing sufficient sunlight for optimal crop growth (QCELLS, 2021).

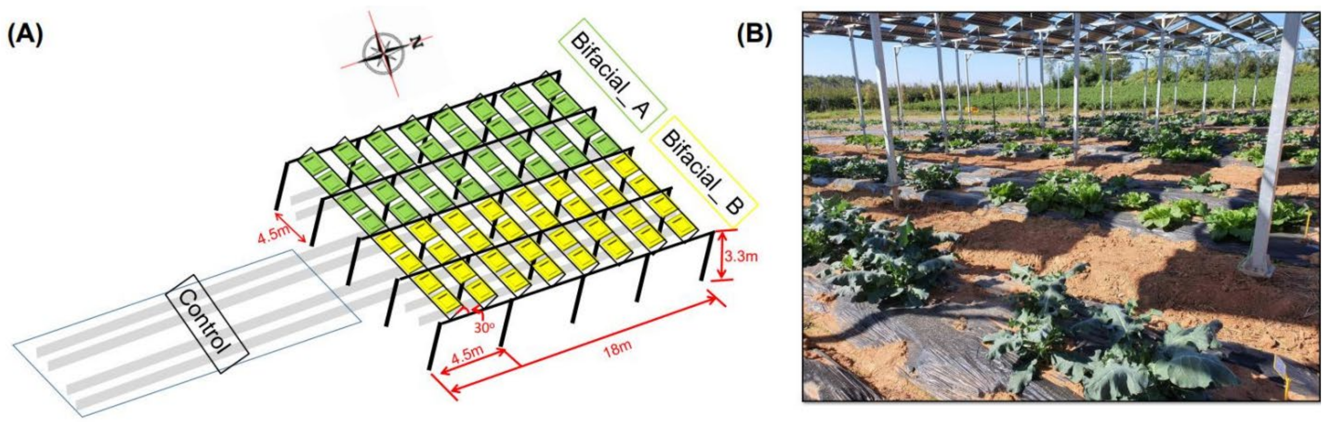
Figure 32 - Agricultural photovoltaics farmland fostered by Q CELLS in Gwandang village in Namhae

Source: Q Cells (2021)

The use of agricultural land is crucial for national food security, therefore, there is a large concern about the impacts of agrivoltaics in food production. From the South Korean context there are three highlight lessons: 1) Research and proof projects should demonstrate that agrivoltaics' impact on harvest rates is acceptable for food security; 2) Time should be taken to persuade the agriculture sector and environmentalists about the acceptability of the technology's impact on food security and landscape; 3) Gradually revising the agriculture land law will ensure the interest of all stakeholders, including the government, farmers, and environmentalists (KIM; OH; JUNG, 2022).

In 2022, researchers from Chonnam National University published the results of a study that assessed the combination of an agrivoltaic system with broccoli and cabbage cultivation (FIGURE 33). The system utilized bifacial modules at a height of 3.3 meters. The researchers analyzed the microclimate, including photosynthetic photon flux density (PPFD) and soil temperature, under the agrivoltaic system, which led to a slight decrease in crop production and alterations in metabolites in broccoli. However, the additional shading in the agrivoltaic system had a positive impact on broccoli's color, which was more interesting for consumer preference (CHAE et al., 2022).

Figure 33 - Agrivoltaic structure information for this experiment (A) and photo of growing crops under the solar panel (B)



Source: CHAE et al. (2022)

3.10 Australia

Large utility-scale solar farms began to emerge in Australia around 2015, initiating as well the development of agrivoltaic practices, primarily dominated by sheep grazing. The first agrivoltaics experience started in 2015, the Royalla Solar Farm, with sheep grazing, followed by over a dozen other solar farms with grazing activities (CLEANENERGYCOUNCIL, 2021). By 2020, there was register of at least 13 large-scale solar farms grazing sheep in Australia (FIGURE 34). At present, this activity is still the prevalent form of agrivoltaic model in Australia, but other forms of dual-use such as with horticulture, viticulture, aquaculture and cropping exist in the country, but usually in a much smaller scale (CLEANENERGYCOUNCIL, 2021).

Although Australia developed the pioneers agrivoltaics plants several years ago, the country still lacks a clear policy and regulation for the technology. Knowledge gaps and technical and economic impediments have slowed the development of the sector (RENEWECONOMY, 2023).

Figure 34 - Sheep enjoy the shade of the dual-axis tracker array on the University of Queensland's Gatton Solar Farm (Photo Credits: Sarah Haskmann)

Source: Clean Energy Council (2021)

3.11 Brazil

In Brazil, currently, there is no discussion regarding regulating agrivoltaic systems in the country, nor commercial agrivoltaic systems in operation. Up to the date of the conclusion of this report, there were only a few pilot projects in operation or planning stage (see sub-section 4.1 Existing systems for more information about the existing pilot projects in Brazil).

However, some companies from the solar market are increasing their interest in investing in agrivoltaic projects in Brazil. According to news reported by Canal Solar, a group of four companies, ARaymond, SNEF Brasil, MMA Advogados, and Grupo Port Trad, have shown interest in installing agrivoltaic systems on Brazilian soil, but they have not yet provided a specific date or location for the implementation of the first systems (HEIN, 2021). In addition, BYD Brasil launched in August 2023 at the Smarter E South America fair, in São Paulo, their PV Module adapted for agrivoltaic systems. The PV module is named BTV48T and it has a nominal power of 355Wp-370Wp (Figure 35), it is fully produced in Brazil and developed by the national R&D team of the company. The module is not yet commercial, but it could be produced under demand.

Figure 35 – New BYD PV module produced for agrivoltaic Applications at The Smarter E South America fair

Source: authors (2023)

Despite there being no regulation in Brazil regarding agrivoltaic systems, it is possible to adapt agrivoltaic applications to the existing distributed generation legal framework mainly when considering small-scale agriculture.

In Brazil, distributed generation was regulated by the National Electric Energy Agency (ANEEL) in 2012 through Normative Resolution REN 482/2012. REN 482/2012 then allowed Brazilian consumers to generate their own electricity from renewable sources or qualified cogeneration and supply the surplus to their local distribution network (MME, 2023).

REN 482/2012 went through a review process and in 2016 REN 687/2015 came into force, which brought some changes and updates to the previous resolution. In 2022, the legal framework for distributed micro and mini-generation (MMGD) and the Electricity Compensation System (SCEE) was established through Law 14300[19], which is currently the legal instrument in force that regulates and provides all the legal provisions for distributed generation in the country. In February 2023, ANEEL published REN 1059[20], which revoked REN 482/2012 and brought improvements to the connection and billing of MMGD plants as well as the rules for the SCEE, bringing the regulations into line with the provisions of Law 14300. The main changes between the old REN 482/2012 and the current Law 14300 can be found in a publication by GREENER (2023) .

According to the current legislation, a distributed micro generation power plant is one with an installed capacity of up to 75 kilowatts (kW). Distributed mini generation has an installed power above 75 kW and less than or equal to 3 MW for non-dispatchable sources or up to 5 MW for dispatchable sources.

The SCEE allows, for example, the surplus energy generated by a photovoltaic MMGD system during the day to be injected into the grid and, at night or anytime, the grid returns the energy to the consumer unit and supplies additional needs. When the energy generated in a given month is greater than the amount used to offset the energy consumed in that period, the consumer is left with surplus energy that can be distributed in the same month to other consumer units, depending on the type of participation in the SCEE, or transformed into credit to offset consumption in the following months. According to the rules, credits are valid for 60 months.

Under REN 482/2012, all the components of the electricity tariff were compensated, i.e., every 1 kWh injected into the grid meant that 1 kWh was compensated. With Law

19 Lei 14300/2022: https://in.gov.br/en/web/dou/-/lei-n-14.300-de-6-de-janeiro-de-2022-372467821

20 REN 1059/2023: https://www.in.gov.br/en/web/dou/-/resolucao-normativa-aneel-n-1.059-de-7-de-fevereiro-de-2023-463828999

14300 currently in force, compensation takes into account all tariff components, with the exception of the so-called "TUSD Fio B", which represents the costs of the distribution network and is calculated by the National Electricity Agency based on the costs of the distribution utilities, i.e. this value will vary depending on the local utility. According to an analysis carried out by GREENER (2023), on average TUSD B represents around 30% of the total value of the tariff, using the 58 most important distribution utilities in the country as a basis. In other words, for every 1 kWh injected into the grid, 0.70 kWh is offset against the energy bill.

Given this context, with the current legal framework for distributed generation, farmers can generate their own energy through the SCEE by means of solar photovoltaic MMGD systems, adapting this technology to the agrivoltaic application. It is understood that distributed generation would therefore be more suitable for small-scale and family farmers since these systems are limited to 3 MW for non-dispatchable sources or 5 MW for dispatchable sources.

As a rule of thumb, the calculation for photovoltaic plants on the ground can be simplified so that 1 MW of photovoltaic solar energy occupies an average of 1 hectare of land. In other words, for large-scale agriculture, a distributed generation system would occupy an average of approximately 3 to 5 hectares of land, which is quite insignificant for these large-scale farmers.. Agrivoltaic systems that produce energy for the open market could be more appropriate for them. However, due to the complexity of the Brazilian open market usually only big commercial energy companies get involved.

3.12 Considerations regarding the national and international regulatory context

Agrivoltaic technology is experiencing global growth, with several countries taking significant steps towards its implementation and maintenance. While official regulations for agrivoltaic systems may not be widespread, notable guidelines have been established or are in the process of being developed in countries like Germany, Italy, Croatia, Japan, the United States, South Korea, and France. Additionally, several nations, including Japan, China, France, the United States, and South Korea, have already introduced national funding programs to support the adoption of these innovative systems. General incentives, such as the Feed-In-Tariff, that are not specific to agrivoltaic systems, exist in some of these countries and can serve as a tool to enhance the agrivoltaic systems' viability.

An important aspect when analyzing the existing guidelines in Italy, Germany, and other countries is the concern for maintaining existing agricultural activities with the introduction of agrivoltaic technology. Actions are mentioned for monitoring and ensuring the continuity of existing agricultural production, **with agriculture being the primary activity and energy generation being secondary.**

In Germany, the elaboration of a production planning plan is required, ensuring the existence of crop planning, monitoring and maintenance.

The lack of national guidelines or regulations in Brazil could lead to some negative consequences, as seen in France in the past decade, where the absence of clear criteria for agrivoltaic systems in the initial round of tenders led to some projects having very low or even non-existent agricultural production participation. This outcome has created resistance to agrivoltaics, particularly within the agricultural sector (ISE, 2020).

In Brazil, agriculture constitutes a major pillar of the economy, and electricity generation from photovoltaic energy is experiencing exponential growth. However, agrivoltaic systems are not yet part of the country's reality. Some companies have shown interest in installing agrivoltaic systems in Brazil, but the market is still in the very early stages of implementation of the first five systems. Learning from the experiences of other countries, it is evident that agrivoltaic generators can yield numerous economic, environmental, and social benefits for the regions where they are implemented.

As Brazil enters the pilot project phase for agrivoltaic technology, it is crucial for project stakeholders and system operators in the country to be aware of the lessons learned from the technology's evolution in other nations. This awareness will ensure efficient energy generation, food production, and appropriate crop maintenance, enabling the system to be characterized as agrivoltaic throughout its lifespan.

A summary of international regulatory frameworks on agrivoltaics is organized in TABLE 2. The table was based on the document "Characterizing photovoltaic projects on agricultural land and agrivoltaics", published in 2021 by the French Agency for Environment and Energy Management (ADEME).

Table 2 - Summary of international regulatory frameworks

Country	Japan	United States	Germany	Italy	China	South Korea	France	Croatia
Regulations related to PV on agricultural lands	Installation of PV requires temporary conversion to non-agricultural lands. - Temporary conversion for 3 renewable years or 10 years in disadvantaged areas if: - Pillars are over 2 meters high. Not more than 20% loss of yield.	Restrictions in conservation areas, specific to states. In Massachusetts, eligibility criteria for specific assistance: minimum height (2.44m for tilting modules, 3m for horizontal modules), shading rate <50%.	PV on buildings (including greenhouses) allowed if they were previously erected for purposes other than solar energy production. 10 ground-mounted PV structures authorized per year through public tender: maximum capacity of 10 MW, in disadvantaged areas. PV greenhouses allowed if they have a minimum height of 2m and module coverage rate <50%.	Regional regulations may add restrictions (e.g., yield in the Puglia region). Regulatory contradictions on ground-mounted PV: national authorization revoked, sometimes prohibited at the regional level, but implemented on the ground through land leasing to developers. Conversion prohibited on basic permanent agricultural lands.	PV on agricultural lands authorized if capacity <20 MW. Since 2017, possibility to maintain agricultural land status regardless of capacity if joint agricultural production.	There are restrictions, but, in recent times, several lawmakers have proposed revising the Agricultural Land Law to legally permit agrivoltaic systems.	The French Conseil d'Etat's jurisprudence accepts the coexistence of an activity of agricultural production and PV production as long as the agricultural project is real and credible. A new renewable energy legislation is under development, which will define a few conditions for agrivoltaic projects, such as long-term maintenance or development of agricultural production.	Croatia recently adopted a legal framework for agrivoltaics. The new legislation allows every farmer to install agrivoltaics on their own land. Also, it mentions that agrivoltaics can be installed on sites defined as agricultural land, disused plots, and locations that host permanent plantations.

Definition of Agrivoltaics	Named “solar sharing,” defined as “a PV installation on agricultural lands with continuity of agricultural activities.” Criteria: no deterioration of quality, yield > 80% on an annual average, height > 2m.	There is currently no official definition for agrivoltaic systems.	Definition within the scope of the APV-Resola research program: “A system that enhances land efficiency, allowing for simultaneous primary agricultural production and secondary electrical production, to achieve optimal utilization of technical and economic synergies between these two productions.”	There is currently no official definition for agrivoltaic systems.	There is currently no official definition for agrivoltaic systems.	There is currently no official definition for agrivoltaic systems.	There is no official concept or guidelines for agrivoltaics. However, the French Agency for the Environment and Energy Management (Ademe) defined in 2021 standards for agrivoltaic systems and mentions the systems as the “coupling of a secondary PV production to a main agricultural production with a demonstrable operating synergy”	Information not available.
Crops / Livestock associated with agrivoltaics mentioned in the literature	Mioga ginger, Japanese cleyera, paddy rice, shiitake mushrooms, blueberries, fuki, tea, green onions, pasture grass, punpkins.	Beehives, sheep, tomatoes, wildflower for pollinators, blackberries, herbs.	Wheat, celery, potatoes, clover grass, blueberries, raspberries, apples, strawberries	Olives, almonds, figs, tomatoes, lemon,	Tea, grapes, vegetables, mushrooms, berries	Broccoli, cabbage, rice, potatoes, onion, barley, beans, garlic, lettuce, green onion	Sheep, beehives, vegetables, arboriculture, cereals, viticulture, orchards	Vegetables, olives, viticulture
Presence of Investments or financial tools that support agrivoltaics	National funding opportunity available for agrivoltaics. Japan was the first country to develop a support scheme for agrivoltaics, in 2012.	Yes. Several organizations investing in Agrivoltaic systems and research. E.g., DOE is providing $15 million in research funding to explore the feasibility of agrivoltaics.	National funding opportunity available for agrivoltaics.	Yes. Italian government recently created a €1.1 billion ($1.2 billion) incentive program for agrivoltaics	Subsidies implemented at the regional level for PV greenhouses and ground-mounted PV systems.	National funding opportunity available for agrivoltaics.	National funding opportunity available for agrivoltaics.	Information not available.

Source: Elaborated by the authors based on Ademe (2022).

4. Agrivoltaic systems in Brazil

4.1 Existing systems

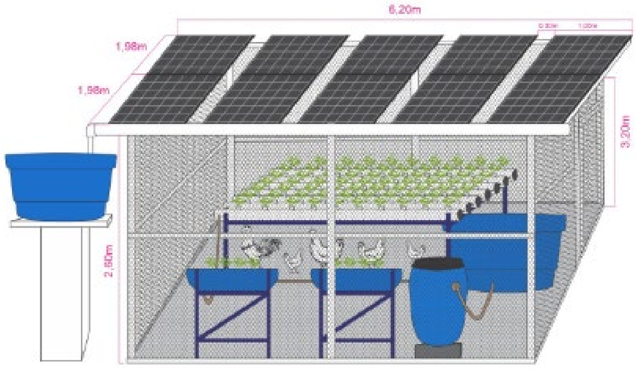
In Brazil the agrivoltaic technology is not yet widespread, andfive agrivoltaic systems shown below are among the few implemented in the country so far. All of them are pilot projects and have a connection to research institutions. The location and detailed technical description of these existing agrivoltaic projects follow in the subsequent subchapters, along with information about their installed capacity, energy output, agricultural characteristics, and available information on the results of the projects.

4.1.1 Ecolume

An example of an agrivoltaic system developed for agricultural family units in the semi-arid region of Brazil is the Ecolume project, located in Ibimirim-PE. The project was developed by a network of over 40 researchers and was installed at an agroecology school in Pernambuco in 2019. The proposed model consists of distributed “family units” that combine energy generation with the production of vegetables, fish in tanks, and chickens, aiming to generate environmental, social, and economic benefits for a large number of people in the northeastern semi-arid region. The Ecolume agrivoltaic system produces 17 types of vegetables using also an aquaponics system and two animal proteins, intended for consumption by the students and staff of the Serta school, as well as umbu seedlings, which is a native Caatinga tree, that are donated for reforestation of the biome (Caatinga is a typical biome of the semi-arid region in Brazil) region (MARTINEZ, 2022). Figure 36 shows a schematic of the experimental prototype, consisting of 10 PV modules, and a total PV installed capacity of 3.3 kWp.

The experimental unit (Figure 37) was designed to suit the region’s climatic conditions and occupies an area of 24 m², with an approximate cost of US$ 4,000. According to the project’s results, the unit demonstrated a production potential of 4,800 kWh/year of energy, 130 kg of fish, 730 free-range chicken eggs, 816 units or 336 kg of vegetables, and 200 units of native plant seedlings. This production would generate a total annual revenue of around US$ 2,000. The project’s findings revealed possibilities for development in the Brazilian semi-arid region, considering aspects of climate change and the significant potential of solar energy in the region through local productive arrangements that contribute to family income generation and the conservation of the Caatinga Biome (LACERDA et al., 2022).

Figure 36 - Agrivoltaic system proposed in the Ecolume project



Source: Lacerda et al. (2022)

Figure 37 - Agrivoltaic system and assembly of aquaponics system below the modules

Source: Lacerda et al. (2022)

The proposed system has generated promising results so far, confirming its potential to generate environmental, social, and economic benefits for the region; however, structural challenges were observed, especially the lack of public incentive policies (MARTINEZ, 2022).

4.1.2 Pankara Village

Another pilot project in the Northeast region was carried out with the Federal Rural University of Pernambuco in partnership with the Pankará Indigenous Community in December 2020. The project aimed to provide safe drinking water and vegetable cultivation through a solar-powered water pump, combined with agrivoltaic technology (Figure 38). The project is located in the Brazilian Caatinga Biome, in the region of Aldeia Serrote dos Campos, Itacuruba (PE).

The project consists of a 33 kWp solar system with structures 3 meters high above the ground, under which a 400 m^2 community vegetable garden was established (ZELLER, 2023). According to the report published by Atmosfair[21], the shading protects from the strong sun and high temperatures of the Brazilian Caatinga. Melon cultivation[22] has been integrated into the agrivoltaic system in partnership with researchers from the Federal Rural University of Pernambuco (FIGURE 39). The project prioritizes organic food production, energy generation, and environmental preservation, aligning with the concept of agroecology (ARAGÃO, 2023). Beside the agriculture under the agrivoltaic plant, an aquaculture facility was also implemented, where the water and waste water of fish tanks is used to irrigate and fertilise fruit trees. In addition, an aquaponics system for efficient vegetable and herb cultivation is under construction (ZELLER, 2023).

Figure 38 - Representatives of the Pankará village and of the project

Source: Atmosfair (2023)

Figure 39 - Melon plantation in the agrivoltaic system

Source: Agrega (2023)

21 https://www.atmosfair.de/en/climate-protection-projects/solar-energy/brazil-agriphotovoltaics-in-the-village-of-the-indigenous-pankara/

22 https://www.agrega.org.br/2023/06/13/sistemas-agrofotovoltaicos-e-o-papel-fundamental-do-povo-pankara-junto-a-comunidade-cientifica-em-itacuruba-pe-%ef%bf%bc/

4.1.3 CCampo

In the Brazilian North region, in the state of Pará, another pilot project was recently developed with the support of the German Cooperatives association DGRV[23], the Brazilian Cooperatives association OCB[24], and the Solar Photovoltaic Laboratory at UFSC[25]. The agrivoltaic system of the cooperative CCampo[26] was installed in January 2023 and combined agrivoltaic techniques with agroecological and organic farming practices (FIGURE 40). CCampo is an agricultural cooperative in the western region of the Pará state in North Brazil, comprising over 200 cooperating families, with a mission to strengthen family farming and provide regional products to consumers with safety and reliability. The agrivoltaic system will produce bell peppers, kale, cilantro, and scallions. Additionally, the project involved training the cooperative members in agrivoltaic systems and organic agriculture practices.

The energy credits generated by the agrivoltaic system will be used to reduce the energy costs of the cooperative's agro-industry, which incurs high energy expenses in the production of fruit pulps, sometimes reaching 8.000 kWh/month, equivalent of R$ 10,000 energy bill per month. Agrivoltaic systems, as in the case of CCampo cooperative, present a significant opportunity for Brazilian cooperatives, as agricultural cooperatives can invest in agrivoltaic systems and create new Cooperative Energy business models using the generated credits. These energy credits can be utilized to lower the cooperative's own electricity bill, and they can also be distributed to cooperative members and other partner organizations.

Figure 40 - Members of CCampo, OCB and Fotovoltaica UFSC in front of the under-construction agrivoltaic system, and cooperates planting in the control area next to the power plant

Source: OCB Pará (2023)

4.1.4 UFAL

Another pilot agrivoltaic project was carried out by researchers of the Campus of Engineering and Agricultural Sciences of the Federal University of Alagoas (UFAL)[27], funded by the Alagoas Research Support Foundation (Fapeal) (FIGURE 41). The main objective of the system is to assess the performance of sugarcane cultivated in association with a PV system, aiming to better understand and determine the land use efficiency under this condition. The metallic structures are 8 meters high, and research will be conducted to evaluate the feasibility of this production method with sugarcane as the crop. According to a researcher from the project, agrivoltaic activities at the site started in December 2021 (GONZAGA, 2022).

The project coordinators highlighted the need for increased height in the structures to accommodate sugarcane cultivation, which is higher than typical agrivoltaic projects worldwide (FIGURE 42). Maintenance of the metallic structures, including painting every six months, special treatments, and coatings were part of the project activities. The foundation is made of reinforced concrete, designed to withstand the region's wind gusts. The agrivoltaic system

23 https://www.dgrv.coop/project/brazil/

24 https://somoscooperativismo.coop.br/ocb

25 https://fotovoltaica.ufsc.br/sistemas/fotov/en/about/

26 https://paracooperativo.coop.br/noticias/1921-cooperados-da-ccampo-foram-capacitados-para-atuar-com-sistema-agrifotovoltaico

27 https://ufal.br/ufal/noticias/2022/6/pesquisa-vai-avaliar-sistema-agrofotovoltaico-em-plantacao-de-cana-de-acucar

was integrated into an area where sugarcane cultivation was already established (FIGURE 43) (UFAL, 2023).

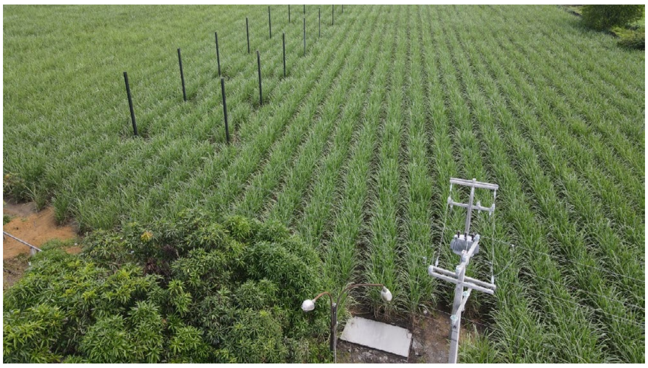
Figure 41 - Project of the agrivoltaic system

Source: Gonzaga (2022)

Figure 42 - Agrivoltaic system with seven PV module structures

Source: Jornal de Alagoas (2023)

Figure 43 - Area that the system was installed, with sugar cane plantation



Source: Gonzaga (2022)

4.1.5 CEMIG, EPAMIG and CPQD agrivoltaic project

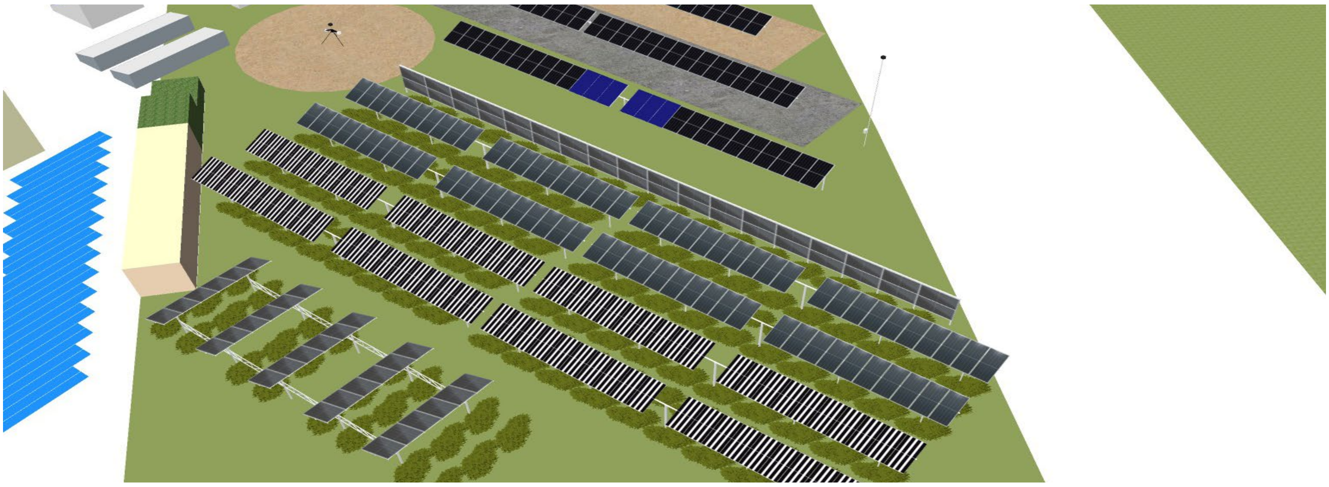
One agrivoltaic project in Brazil is located in the state of Minas Gerais, a state with significant agricultural importance and a leading contributor to solar energy generation in Brazil. The project was developed in collaboration between the Minas Gerais Energy Company (Cemig), the Agricultural Research Company of Minas Gerais (Epamig), and the Center for Research and Development in Telecommunications (CPQD). With an investment of approximately R$10.5 million, the project involves the installation of pilot units to test various crop arrangements and adapt technologies to different climate and soil conditions (CEMIG, 2023).

The project aims to address technical challenges, social implications for small-scale farmers, and the development of potential industry suppliers (CEMIG, 2023). The selected agricultural activities for the experimental sites are melons, strawberries, beans, lettuce, and pastures for cattle. The project is expected to continue for 30 months and evaluate agronomic aspects, water usage efficiency, and the final quality of both energy and food production (AGÊNCIAMINAS, 2024).

4.1.6 FOTOVOLTAICA/UFSC Repsol R&D AGRIVOLTAIC project

Another project (Figure 44) that is still in the development phase stems from a collaboration between the Solar Energy Laboratory Fotovoltaica/UFSC at Universidade Federal de Santa Catarina (www.fotovoltaica.ufsc.br), and the Brazilian arm of the Spanish oil&gas company Repsol. The project's focus is to assess various photovoltaic technologies for agrivoltaic application and their impact on agricultural production coffee cultivation. The different PV technologies that will be tested are bifacial modules in fixed mounting structures, bifacial modules in standard tracking systems, bifacial modules in tracking systems with optimized for agricultural production, tubular modules, and bifacial modules on a tracking system with spectrally selective PV technology, promoting the transmission of light in wavelengths suitable for photosynthesis. The project started in 2024 and will be carried out for two years.

Figure 44 – Fotovoltaica/UFSC and Repsol R&D agrivoltaic project scheme



Source: Fotovoltaica UFSC (2024)

4.1.7 Considerations regarding the existing agripv systems in brazil

Agrivoltaic technology is gaining momentum in Brazil, with only a few projects showcasing its potential in diverse agricultural settings so far. Considering the available data, all the agrivoltaic projects in Brazil are still pilot projects and were installed in the last four years. These pilot projects highlight the country's diversity regarding climate conditions and agricultural potential, which can reflect in a great potential for diverse agrivoltaics applications adapting to a regional context and need.

A summary table of all identified agrivoltaic projects in Brazil is available in Table 3.

Table 3 - Summary table of the identified agrivoltaic projects in Brazil

Project Name	Institutions involved	Year	Agricultural Production	PV Characteristics	Location	Climate
Ecolume (in operation)	More than 40 researchers and staff from: IPA, Serta, VertSol, Inpe, Embrapa, Insa, and others	2019	Aquaponic system with various vegetables, seedlings of native trees, fish and eggs	3,3 kW, small replicable family units	Ibimirim (PE)	Semi-arid (Caatinga region)
CCampo (in operation)	CCampo (Agriculture cooperative), Fotovoltaica UFSC, DGRV, OCB	2023	Peppers, kale, cilantro, and scallions	2,5m height; 74,5 kWp	Santarém (PA)	Humid (Amazon region)
Pankará (in operation)	Pankará indigenous community, Atmosfair, CCBA, Funai, UFPE	2020	Melon	3m height, 33 kWp, associated with water pumping system	Aldeia Serrote dos Campos, Itacuruba (PE)	Semi-arid (Caatinga region)
UFAL (in operation)	Ceca / UFAL, Fapeal, Usina Santa Clotilde	2021	Sugar Cane	8m height	Rio Largo (AL)	Humid (Atlantic rainforest region)
CEMIG, EPAMIG and CPQD (in development)	CEMIG, EPAMIG and CPQD	2023	Melons, strawberries, beans, lettuce, and pastures for cattle	Various technologies: monocrystalline and bifacial PV panels, fixed and tracker structures	Jaíba and Prudente de Morais (MG)	Tropical / Semi-arid (Jaíba is in Caatinga region and Prudente de Morais in Cerrado / Atlantic rainforest region)
Fotovoltaica/UFSC and Repsol (in development)	Repsol and Fotovoltaica UFSC	2024	To be defined	Various photovoltaic technologies totalling 100 kWp	Florianópolis (SC)	Humid (Atlantic rainforest region)

Source: Elaborated by authors (2024)

4.2 Potential of different agricultural products for agrivoltaics in Brazil

Brazil has a great contribution to food production worldwide. Of the 3054 million tons of grains produced in the world in 2020, 239 (7.8%) were in Brazil, placing the country in fourth place in the world production ranking behind China, the United States and India (FAOSTAT, 2021).

The Brazilian agricultural sector plays a crucial role in contributing to the country's Gross Domestic Product (GDP). Also, this activity is of great relevance because of its high competitiveness and its role in generating jobs, wealth, food, fibers, and biofuels for Brazil and other nations (EMBRAPA, 2023). Regarding the economic impact of the agricultural sector, according to the Brazilian agricultural census of 2019, the activity is the economic basis for 90% of the Brazilian municipalities with up to 20 thousand inhabitants (IBGE, 2017).

In this chapter, different agricultural and livestock productions in Brazil were analyzed, in order to study their potential for agrivoltaic application purposes. The analysis is divided into three main aspects: (1) Socio-economical aspects, (2) Agriculture and livestock systems aspects and (3) Solar photovoltaic systems aspects.

4.2.1 Socio-economical aspects

In this chapter, an overview of the primary agricultural and livestock practices in Brazil is provided, focusing on their potential for expansion and sustainability. Large and small-scale agricultural scenarios were analyzed, with a highlight in the key regions associated with the main agricultural activities, as well as the socio-economical aspects related to each of them. Also, a characterization of the farming practices was elaborated, as well as the context of the farmers engaged in this vital sector. The content of this chapter also includes the special case of the Matopiba (Region that comprises parts of the states Maranhão, Tocantins, Piauí and Bahia) and the Northeast region.

4.2.1.1 Large-scale agricultural production

The large-scale agricultural production in Brazil is led by **soybeans, corn, coffee and sugarcane**, which are the main contributors to the Gross Production Value (VBP) (IBGE; CNA, 2021). The VBP of the agricultural sector in Brazil is approximately US$ 250 billion, with over 80% of the revenue concentrated in the regions of Central-West, Southern, and Southeastern regions according to data from the Ministry of Agriculture and Livestock (ESTADAO, 2023). These figures indicate the significant impact and contribution of the agricultural industry to Brazil's economy.

Soybeans alone account for approximately US$ 1.00 out of every US$ 3.55 generated by the agricultural sector in Brazil – the country is responsible for 50% of the global share of soy production (IBGE; CNA, 2021). As of 2006, the national production was concentrated in the Central-West region, especially in Mato Grosso state (ESTADAO, 2022). After soybeans, the second-ranking product in the VBP of Brazilian agriculture is beef cattle, representing US$ 40 billion in 2020, followed by corn with US$ 25 billion. Dairy cattle and sugarcane rank third and fourth, respectively, with US$ 15 billion and US$ 14 billion. Poultry production, particularly chicken, is also showing significant growth, as well as coffee and pork (IBGE; CNA, 2021).

Regarding **corn** production, the top Brazilian producers are Mato Grosso, Paraná, Mato Grosso do Sul, and Minas Gerais, in this respective order. In particular, Mato Grosso's production alone surpasses that of other Brazilian states together (COÊLHO, 2021).

The estimated total **sugarcane** production in Brazil, according to data from the 1st survey of the 2022/23 harvest, estimates the total production in the country to reach around 600 million tons. Among the leading states producing sugarcane in Brazil are São Paulo, with over 300 million tons, Goiás, with 75 million tons, and Minas Gerais, with 67 million tons (CONAB, 2022). Globally, there are approximately 1.8 billion tons of sugar cane every year, and Brazil was the leading producer in 2023 (YARA BRASIL, 2023).

According to Barros et al. in a study published by CEPEA, in Brazil there are nearly 20 million people working in the agricultural sector, which represents close to 20% of the total Brazilian active workforce (BARROS et al., 2023). The study used data from PNAD (National Household Sample Survey) which also show that soybeans production had over 504 thousand people and sugarcane over 315 thousand people employed in total in 2022. The most relevant sector regarding to the number of workers is beef cattle production, which had over two million active workers in the same year.

4.2.1.2 Small-scale agricultural production (Family farming)

Small rural properties or rural "family farming" possession refers to land that is cultivated through the personal labor of family farmers and rural family entrepreneurs, including settlements, that meet the requirements stipulated in the Law 11326 of 2006[28]. For instance, such properties must not exceed an area larger than 4 (four) fiscal modules.

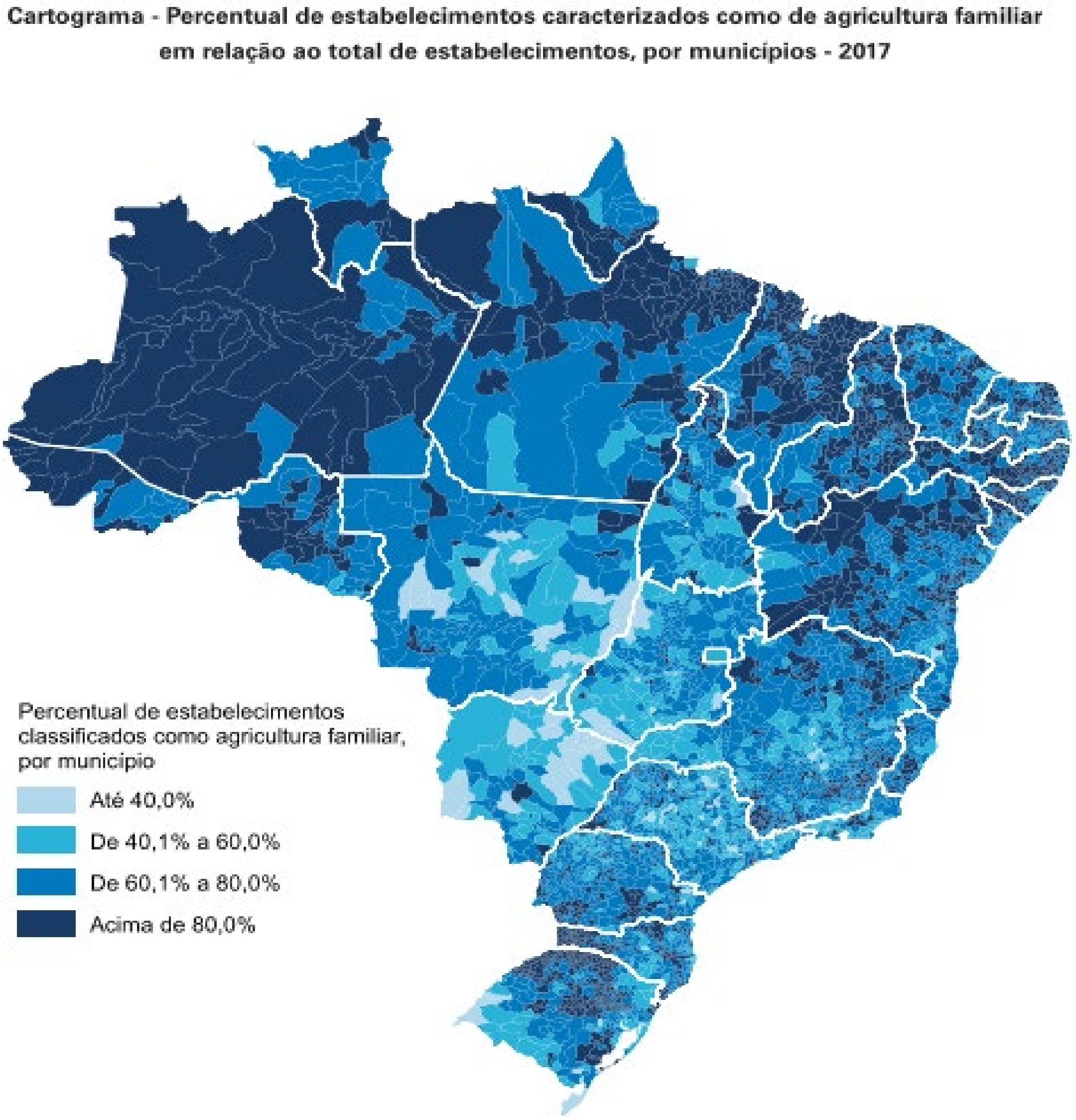
In Brazil, the fiscal module is an agrarian measurement unit expressed in hectares, which varies for each municipality, ranging from 5 to 110 hectares, depending on the economic activities carried out and on the income that can be obtained from them in the municipality. For example, in the case of some municipalities located in the Cerrado biome (most of the Center-West region of Brazil), a property owner with 4 fiscal modules may have up to 400 hectares, and in the Caatinga biome (present in the Northeast region of Brazil), up to 260 hectares (MICCOLIS et al., 2016).

Small-scale family farming represents 77% of agricultural establishments in Brazil (IBGE, 2019b) and makes a significant contribution to the national Gross Domestic Product (GDP). According to data from the 2017 Agricultural Census conducted by the Brazilian Institute of Geography and Statistics (IBGE) (2017), family farming accounts for approximately 24% of the gross value of agricultural production in the country. The census data also highlights the sector's importance in job creation, as family farming employs about 10.5 million people, representing over 70% of the workforce in the Brazilian agricultural sector (IBGE, 2017).

Establishments characterized as family farming are prevalent in many municipalities, particularly in the Northern and Northeastern regions (IBGE, 2017). The Southern and Southeastern regions also have a significant number of municipalities where small-scale producers predominate in percentage terms. In contrast, the Central-West region of the country shows a stronger presence of large-scale producers and landowners (FIGURE 45).

28 https://legislacao.presidencia.gov.br/ficha?/legisla/legislacao.nsf/Viw_Identificacao/lei%2011.326-2006&OpenDocument

Figure 45 - Percentage of establishments classified as family farming in relation to the total number of establishments, by municipalities - 2017



Source: IBGE (2019)

Family farming plays a crucial role in the Brazilian food supply, accounting for approximately 70% of the food consumed by the population, according to the Brazilian Institute for Geography and Statistics IBGE. Thus, these establishments are of great significance regarding food security. Notably, family farmers contribute significantly to the production of fruits, vegetables, and staple products. For instance, they are responsible for at least 80% of cassava production, 69% of pineapple supply, and 42% of the total bean consumption in the country (ZAFALON, 2023).

Despite its vital contribution to the food supply, family farming establishments still face challenges regarding food security in the country. The Northeast region is where47.2% of these establishments are located (ZAFALON, 2023), and yet, it is the second region in the food security ranking. The population under these circumstances in the North and Northeast region gets to 71,6% and 68%, respectively (PENSSAN, 2022). To address these challenges and support family farmers, government involvement in essential assistance programs is crucial (ZAFALON, 2023). Programs like water provision and the Bolsa Família social welfare program are considered essential in ensuring the stability and growth of family farming practices (ZAFALON, 2023).

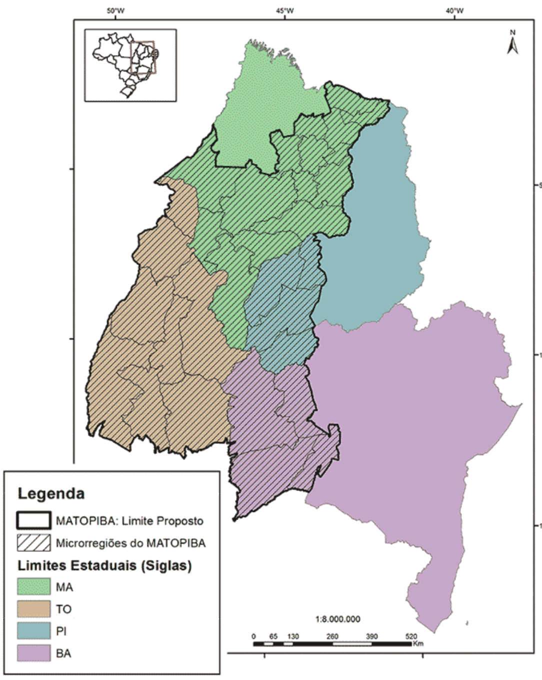
4.2.1.3 Case of the North region and Matopiba region

The Northern Brazilian region has experienced a substantial growth in agriculture, and in 2020, the region recorded grain exports of approximately 6 million tons, marking a remarkable increase of 15% compared to the previous year(DIERINGS, 2023). This region is considered an agricultural frontier, and produces a wide range of crops from traditional ones like cassava, maize, and rice to export-oriented crops such as soybeans (DIERINGS, 2023). This last one has been associated with deforestation in the Amazon rainforest, and also contributes to the decrease in rainfall in the region (DIERINGS, 2023) . One particular state that relies in agribusiness, especially grains agriculture, is Roraima (VELA, 2023). In this state, soybean cultivation has shown substantial growth in the region, and 2022 projections indicated a 40% increase in productive areas by 2023 (SALES, 2023).

One of the origins of the expansion of the extensive agricultural practices to regions such as the North region are economic and financial motivations, which are driving current migrations in Brazil. Agricultural producers seek to maintain or increase their profitability rates and expand their business, which encourages them to move in search of new land with lower costs. Regions within the states of Maranhão, Tocantins, Piauí, and Bahia (also known as MATOPIBA) are under a trend of expanding cultivated areas in Brazil. This agricultural transition is justified by some essential characteristics of "modern agriculture", such as extensive and flat areas, potentially productive soils, availability of water, and a favorable climate with long days and high solar irradiation intensity. The transition of land use involves both expansion and conversion of land, particularly in the replacement of pastures with large-scale agriculture, facilitated by mechanization and production intensification (EMBRAPA, 2023a).

The North region is receiving the main expansion from the Northeast and Central-West large-scale extensive agriculture. The region comprises the Matopiba states and the state of Pará. This MATOPIBA region is considered a "new agricultural frontier" (FIGURE 46). It produced 20.5 million tons in the 2016/2017 harvest, and the projections indicate that this production is expected to reach 26 million tons by 2026/2027 (EMBRAPA, 2023a).

Figure 46 - Proposed delimitation for Matopiba region



Source: Embrapa (2023a)

Despite the economic growth associated with this agricultural transition in Matopiba states, the scenario is marked by high deforestation rates. Almost half of the native Cerrado vegetation has been deforested – and out of the 54,5% of the remaining area, 44% is in the Matopiba region (IPAM, 2022). According to an article published by Rodrigues et al. (RODRIGUES et al., 2022), the conversion of the native Cerrado vegetation into grassland and pasture has already caused climate impacts to the region, which became almost 1°C warmer and 10% dryer.

Given the environmental challenges posed by deforestation and the resulting climate impacts observed in the Matopiba region, there is an urgent need to explore innovative and sustainable agricultural practices in the respective states. In this context, agrivoltaic systems present a promising solution, by generating renewable energy while optimizing land use, and enhancing overall ecosystem and social resilience.

4.2.1.4 Case of Northeast region

In Brazil, the so-called "modern agriculture", which refers to mainly large-scale production, seems to benefit only a privileged few, leading to a significant concentration of production and income in rural areas. Data from the latest Census in 2006 reveals that 8% of rural establishments are responsible for generating 85% of the agricultural value, while the remaining 4.7 million properties contribute only 15% to the overall wealth. And these disparities are expected to increase, according to experts (EMBRAPA, 2023a).

Rural poverty is a widespread issue in Brazil, with the Northeast and North regions experiencing the highest levels of this problem. Brazilian North region accounts with 94% of establishments with an area equal to or smaller than 100 hectares fall under the 'very poor' and 'poor' income categories. In establishments larger than 100 hectares, the percentage is also high, 74% (EMBRAPA, 2023a).

In the Northeast region the presence of family farming stands out as an important characteristic, especially in the semi-arid region. On the other hand, Zona da Mata, the most humid part of the region, is dominated by an agricultural system focused on export-oriented monoculture. Horticultural crops, especially fruits like melons, grapes, mangoes, and pineapples, are the main expressions of this region's agriculture. Also, similar to the Southeast region, the Northeast is also prominently involved in sugarcane production. Furthermore, it exports soybeans, mainly from Bahia and Piauí (SYNGENTA, 2023).

The agricultural behavior in the Northeast region of Brazil showed varying trends in harvested areas and crop production between 2002 and 2017. States like Piauí, Maranhão, and Sergipe experienced notable increases in harvested areas, driven by soybean and corn cultivation. In contrast, other states faced declines due to drought effects, particularly in the caatinga biome(CARNEIRO; LIMA, 2017).

Considering the proven benefits of agrivoltaic systems, such as protection from extreme heat and irradiation, reducing evaporation and the need for irrigation, these systems show a potential match with the climate and social characteristics of the Northeast region. One pilot project that represents a model of agrivoltaic system that can address the local challenges of the region is the Ecolume Project, which is explained in detail on the sub-chapter 2.1.1 of this document. The model can provide energy and food security for the family agriculture establishments, while allowing the restoration of degraded or desertified land (ENVIRONMENTALNEWS, 2022).

4.2.2 Agriculture and livestock systems aspects

In this topic the context of the main Brazilian agricultural and livestock is explained, as well as a specific perspective on water availability and irrigation. Also, the situation of the specific Brazilian Northeast region will be highlighted.

4.2.2.1 Agriculture and livestock

According to the Land Cover and Land Use Monitoring by IBGE, from 2000 to 2018, the agricultural area has grown by 44.8% in Brazil, reaching close to 665 thousand km². This land is equivalent to 7.6% of the national territory, including both land and maritime areas. Certain regions stand out in this land transition, such as the Northeastern part of Mato Grosso, and the municipalities of Santarém and Paragominas in Pará, and Imperatriz in Maranhão, all experiencing an increase in soybean cultivation. On the other hand, the study reveals that in over 18 years, Brazil lost 7.6% of its forest vegetation. The forested area, which was

over 4 million km² in 2000, decreased to 3.7 million km² in 2018, representing 42.4% of the country's territory. Additionally, other vegetation, including the biomes of Cerrado, Caatinga, and Pampas, lost more than 10% of its area during the same period (IBGE, 2020).

According to a survey carried out by the Institute for Forestry and Agricultural Management and Certification (Imaflora), soybean, corn, sugarcane, rice and beans are the largest crops in Brazilian agriculture in terms of planted area. These five agricultural products accounted for over 70% of the total cultivated land in Brazil from 1985 to 2017(ESTADAO, 2022).

4.2.2.1.1 Soy

The soybean crop cultivated in Brazil for grain production is an herbaceous plant. The height of the plants varies depending on the environmental conditions and of the variety. Ideally, the plant height should range between 60 to 110 cm, which facilitates mechanical harvesting in commercial fields and helps prevent lodging. The soybean flowering is influenced by the photoperiod, which is the duration of the day. As a short-day plant, soybean delays its flowering and elongates its cycle under long-day conditions. Along with radiation intensity, the duration and quality of the light spectrum significantly affect soybean's morphological and phenotypic characteristics, such as plant height, flowering induction, and ontogeny (NEPOMUCENO; FARIAS; NEUMAIER, 2021).

In terms of production data, Brazil reported a soybean production of 123.8 million tons on an area of 40.9 million hectares, with a productivity of 3,026 kg/ha as of May 2022 (CONAB; EMBRAPA, 2023). Brazilian soy production accounts to approximately 42% of the world production (USDA, 2023). Mato Grosso state stands as the largest soybean producer in Brazil, accounting for 39.9 million tons of production on an area of 10.9 million hectares, with a productivity of 3,663 kg/ha in the same period (CONAB; EMBRAPA, 2023).

Although soybeans are among the crops that suffer the most with shading effects, Italian researchers found though experiments with agrivoltaics that the impact is less significant than expected (BELLINI, 2022). The study encompassed different configurations with various shading rates, and the results showed an average grain yield reduction of soybeans for the whole agrivoltaic system of only 8%, which is largely under the limits established in agrivoltaic plants in Germany and South Korea.

4.2.2.1.2 Corn

In the Central-Southern region of Brazil, corn cultivation takes place after soybean harvest, with sowing concentrated in the Brazilian Summer/Fall season, commonly known as the second crop. Over the past decades, corn has become the largest agricultural crop globally, surpassing the production of former contenders like rice and wheat, and becoming the first crop to exceed 1 billion tons production (FAEB, 2022). In the 2021/2022 harvest, corn production was globally around 1.22 billion tonnes (COÊLHO, 2022). According to Conab (2019) state of Mato Grosso has emerged as the leading corn producer in the country, yielding 31.3 million tons, with the second crop of corn accounting for 95% of the total production in the 2018/19 harvest (REHAGROBLOG, 2023). Corn cultivation exhibits a reasonably distributed pattern across different regions, with the key producing states being Mato Grosso, Paraná, Goiás, Mato Grosso do Sul, and Minas Gerais, in this order (FAEB, 2022).

Even though corn and soybeans are considered shade-intolerant crops, researchers in the United States are developing practical studies on the compatibility of these crops with agrivoltaic systems (FIGURE 47). The researchers are working on determining the optimal spacing between PV arrays in order to keep excessive shadows from interfering with the crop production (BOWMAN; MILLER; ROSENBERG, 2022). In addition, an article published by Sekiyama et al. (2019) showed that it is possible to grow corn, under the shade of agrivoltaic PV panels without a relevant yield reduction. The results of the study show that the biomass of corn stover grown under PV module arrays spaced at 0.71 m intervals was no less than 96.9% that of the production on the control area (SEKIYAMA; NAGASHIMA, 2019).

Figure 47 - Purdue University research agrivoltaic system over soy and corn plantations

Source: Bowman, Miller and Rosenberg (2022) | Photo credits: Kelly Wilkinson

4.2.2.1.3 Sugarcane

In 2021, Brazil became the largest productor of sugarcane globally. The value of sugarcane production amounted to over 15 billion US$, with over 715 million tons harvested from an area of close to 10 million hectares. This performance was spread across over 170 thousand establishments, reflecting the country's robust sugarcane industry. The average yield per hectare reached over 70 kg, highlighting the efficiency and productivity of sugarcane cultivation in Brazil (IBGE, 2023).

Regarding the 2020/21 harvest, Brazil was responsible for producing 654.5 million tons of sugarcane, dedicated to the production of 41.2 million tons of sugar and 29.7 billion liters of ethanol (CONAB, 2021). Notably, the state of São Paulo, took the lead in sugarcane production, contributing to 54.1% of the total quantity produced during the harvest. São Paulo's production numbers included 48.4% of ethanol (14.3 billion liters) and 63.2% of sugar (26.0 million tons) (CONAB, 2021; NACHILUK, 2021).

4.2.2.1.4 Beef cattle

The beef cattle industry in Brazil is widely developed across all states and ecosystems, exhibiting great diversity in terms of cattle density in different regions, herd growth rates, and practiced production systems. These systems encompass distinct stages of breeding, rearing, and fattening, either independently or in combination, utilizing both native and cultivated pastures, with or without supplementary feeding in grazing or confinement settings. However, more intensive systems, involving pasture supplementation or confinement, have been gaining increasing significance, particularly in the Central-West and Southeast regions. The Brazilian beef cattle industry showcases a wide range of production systems, spanning from extensive livestock farming supported by low-productivity native and cultivated pastures with minimal input usage, to so-called intensive livestock farming, characterized by high-productivity pastures, pasture supplementation, and confinement (CEZAR et al., 2005).

Globally, beef production is expected to reach 59.6 million tonnes in 2023, according to estimates from the United States Department of Agriculture (USDA) (GLOBO RURAL, 2023). Brazil had in 2021 a bovine herd of 224.6 million heads (more cattle than people!), according to data from IBGE as part of the Municipal Livestock Survey (PPM). Among the states, Mato Grosso remains the leading cattle producer with 32.4 million heads, accounting for 14.4% of the national herd, followed by Goiás (10.8%). At the municipal level, São Félix do Xingu, in Pará, holds the top position with 2.5 million heads (BRASIL, 2022). In the year-to-date of 2022 compared to the same period in 2021, Brazil increased beef sales by 40.88% (in US$) and 22.66% (in Kg) and exported beef to 153 countries (SOARES; XIMENES, 2023).

The integration of crop-livestock-forest systems (ILPF) in Brazil is a production strategy that combines different agricultural, livestock, and forestry systems within the same area. It aims to optimize land use, increase productivity, and diversify production while reducing the need for opening new areas. ILPF provides numerous benefits, including improved animal welfare, enhanced nutrient cycling in the soil, biodiversity preservation, and sustainability in agriculture (EMBRAPA, 2023b). Additionally, it leads to a diversified production output and greater efficiency in utilizing natural resources. The implementation of ILPF is gaining momentum, with approximately 15 million hectares already adopting this approach in Brazil (JOHNDEERE, 2023).

4.2.2.1.5 Vegetables

The Brazilian vegetable market is characterized by high diversity and segmentation, with the majority of production concentrated in six main crops: potato, tomato, watermelon, lettuce, onion, and carrot. Interestingly, more than half of this production is attributed to the efforts of small-scale family agriculture (VILELA; LUENGO, 2022). According to the 2017 Agricultural Census (IBGE), there were 336 thousand agricultural establishments engaged in horticulture across Brazil, with the distribution as follows: Northeast (41.0%), Southeast (28.0%), South (16.5%), North (9.7%), and Central-West (4.7%). Regarding tomato production, 29.3% of all tomatoes in the country are produced in the state of Goiás, and 21.4% in São Paulo. The state of Santa Catarina leads in onion production (28.1%), followed by Bahia (15%) (CNA, 2021).

Leafy vegetables are widely grown throughout Brazil, with the Southeastern and Southern regions being the major contributors, accounting for 84% of the production. In the 2016 harvest, São Paulo emerged as the largest lettuce producer, yielding 14,199.3 crates of nine dozen each. Notably, lettuce production in São Paulo is primarily concentrated in the "cinturão verde" or green belt, with key production centers in Sorocaba (54.2%), São Paulo (16%), and Mogi das Cruzes (12.2%) (VILELA; LUENGO, 2022).

The estimated total area dedicated to cultivating leafy vegetables in Brazil covers 174,061 hectares, with lettuce occupying the majority at 49.9%, followed by arugula (22.8%), cabbage (15.3%), kale (6.1%), spinach (1.0%), and other varieties (4.9%). The total production of over 1,317.6 tons is distributed among different leafy vegetables, with lettuce leading at 43.7%, followed by cabbage (31.7%), kale (9.1%), watercress (7.6%), spinach (3.1%), arugula (2.0%), and other varieties (2.1%) (VILELA; LUENGO, 2022).

4.2.2.2 Water Availability and Irrigation

On a global scale, the agricultural sector is the largest consumer of land and water resources. Projections indicate a 40% increase in global water demand by 2030 and 55% by 2050, with over 40% of the world's population expected to reside in regions facing severe water stress. In the Brazilian rural context, water usage accounts for 83% of the total Brazilian water intake, with 72% being allocated for irrigation purposes. Irrigation is rapidly expanding in Brazil, with the irrigated land area increasing significantly from 462 thousand hectares in 1960 to 6.1 million hectares in 2014, primarily through the adoption of center-pivot systems (EMBRAPA, 2023c).

One of the needs for the present and the future is to enhance irrigation practices' efficiency. Currently, it is estimated that approximately 40% of water is lost due to inadequate irrigation systems or leaks in pipelines in Brazil (EMBRAPA, 2023c). Despite having substantial reserves of freshwater, including the world's largest Guarani Aquifer, Brazil faces an uneven distribution of water among its regions: the North holds 68.5%, Central-West 15.7%, South 6.5%, Southeast 6.0%, and Northeast 3.3%.

The IBGE data shows that several crops, including sugarcane, rice, soybean, and corn, are commonly irrigated in Brazil (EMBRAPA, [s.d.]). However, despite the growth in the number of establishments with irrigation (4,7% per year from 2016 to 2021, according to IBGE data) some important crops like beans, coffee, and green corn have irrigation systems just in a limited percentage of agricultural establishments (EMBRAPA, [s.d.]).

To address water variability in some regions, small reservoirs, underground dams, and rainwater harvesting are potential solutions to enhance water availability and reduce vulnerability in regions with fluctuating water resources (EMBRAPA, 2023c). Automation and technology, such as geographical information systems and precision agriculture, can greatly improve irrigation management, optimizing when and how much to irrigate. Additionally, enhancing the capacity and training of the agricultural sector is crucial to effectively implement these advancements (BASSOI, 2021).

4.2.3 Solar photovoltaic systems aspects

The level of solar irradiation varies in the different regions of Brazil due to factors such as latitude, altitude, climate, and cloud cover. However, in all regions of the country, the potential for solar irradiation is notable, which creates opportunities for the development of solar energy projects on different scales. This includes large-scale solar photovoltaic plants, as well as the implementation of distributed generation systems in homes, commercial establishments and industries, and agrivoltaic systems.

FIGURE 48 illustrates the annual average value of total daily solar irradiation in the five regions of Brazil. The Northeast region has the greatest solar potential, with a daily average of global horizontal irradiation of 5.49 kWh/m². The Southeast and Midwest regions have daily horizontal global irradiation values close to 5.07 kWh/m². In the South, the daily average of global horizontal irradiation is 4.53 kWh/m² and in the North it is 4.64 kWh/m². The relatively lower solar irradiation values in the northern region are explained by the climatic characteristics, with frequent cloudiness reducing the amount of solar radiation incident on the surface. As a result, the average daily global irradiation in the horizontal and inclined planes is close to that of the southern region, and the normal direct irradiation is lower than in all the other regions of the country.

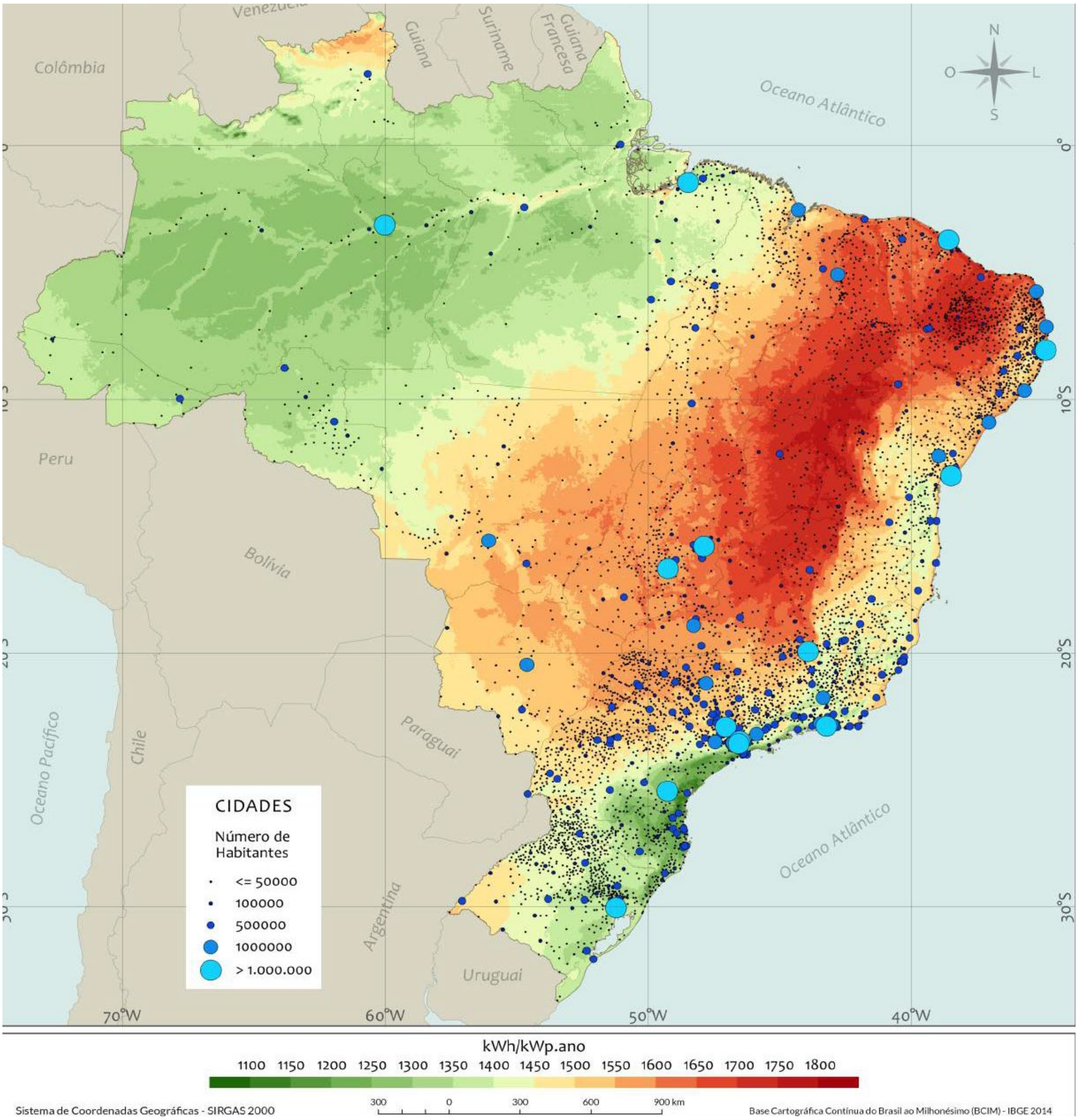
Figure 48 – Solar Irradiation levels per region

Source: INPE (2017)

In Brazil, the generation of electricity using photovoltaic solar panels has immense potential, as can be seen in the map shown in Figure 49. The map illustrates the maximum annual energy yield (measured in kWh of electricity generated per year for each kWp of installed photovoltaic power) throughout Brazil. In addition, the figure shows blue circles spread across the Brazilian territory to highlight areas of population concentration. Even in regions with lower solar incidence, such as the South and North, it is possible to generate more solar electricity than in highly sunny parts of Germany, for example.

Therefore, there is a huge potential for solar photovoltaics in Brazil in all regions of the country, which is already proven with the significant growth of solar distributed generation systems in the country.

Figure 49 - Solar photovoltaic generation potential in annual energy yield (kWh/kWp.year)



Source: INPE (2017)

4.3 Business models and financing opportunities for agrivoltaics in Brazil

The concluding section of this Informational Report will primarily describe existing business and financing models currently utilized in Brazil, highlighting their potential applicability to agrivoltaic systems. In addition to presenting an overview of the current context and opportunities, this report offers recommendations for policy incentives to promote the adoption of agrivoltaic systems, drawing inspiration from global best-case practices.

4.3.1 Possible business models within the Brazilian context

As mentioned in the sub-chapter AUSTRALIA, large utility-scale solar farms began to emerge in Australia around 2015, initiating as well the development of agrivoltaic practices, primarily dominated by sheep grazing. The first agrivoltaics experience started in 2015, the Royalla Solar Farm, with sheep grazing, followed by over a dozen other solar farms with grazing activities (CLEANENERGYCOUNCIL, 2021). By 2020, there was register of at least 13 large-scale solar farms grazing sheep in Australia. At present, this activity is still the prevalent form of agrivoltaic model in Australia, but other forms of dual-use such as with horticulture, viticulture, aquaculture and cropping exist in the country, but usually in a much smaller scale (CLEANENERGYCOUNCIL, 2021).

Although Australia developed the pioneers agrivoltaics plants several years ago, the country still lacks a clear policy and regulation for the technology. Knowledge gaps and technical and economic impediments have slowed the development of the sector (RENEWECONOMY, 2023).

Brazil, the current legal framework for distributed generation farmers can generate their own energy through the SCEE by means of solar photovoltaic MMGD systems, adapting this technology to the agrivoltaic application. It is understood that distributed generation would therefore be more suitable for small-scale and family farmers since these systems are limited to 3 MW or 5 MW. For large-scale farmers, agrivoltaic systems into generating energy to the open market might be more suitable. However, the open market it is a very complex market where usually only big players from the electricity market get involved.

According to the Brazilian Law 14300, the distributed generation can be applied in four different modalities. They are:

- **Local self-consumption:** energy is generated and consumed in the same consumer unit;
- **Remote self-consumption:** energy is generated and consumed in different consumer units, as long as both are under the name of the same owner (whether an individual or a business) and in the concession area of the same distributor;
- **Development with multiple consumer units:** generation of energy for the common areas of a complex with multiple consumer units located on the same property or on adjoining properties, as long as they are not separated by public roads or third-party properties that are not part of the complex;
- **Shared generation:** generation for a group of consumers who are organized in a cooperative, consortium, voluntary civil or building condominium, or any form of civil association set up for this purpose, as long as all the consumer units are in the concession area of the same distributor.

All of the aforementioned distributed generation options provide the legal framework needed to make the business models for agrivoltaic systems viable as the ones mentioned in **Table 1** shown in the sub-chapter **1.2 Business Models**. In this context, it is seen a huge potential of the shared distributed generation modality, for example, to be applied to existing family farming cooperatives and associations, which could easily adapt their existing legal structure to share energy credits through agrivoltaic systems in their existing agricultural productions.

4.3.2 Existing financing opportunities for solar energy in agricultural lands

In recent years, different types of financing options for solar energy projects have emerged in Brazil. Some of them are exclusive to individuals or businesses, while others cover both. There are also those exclusive to the rural sector, which aim to foster the development of rural producers and rural businesses. This chapter aims to present the currently available financing opportunities available to agricultural properties for the use of solar energy technologies.

The **Safra Plan** is one of the main programs of the Brazilian federal government, via the Ministry of Agriculture, to promote rural production in the country by guaranteeing credit for investment and cost of agricultural production. The Safra Plan is mainly aimed at small and medium-sized rural producers and every year, since 2003, the government has allocated funds for the program, which is valid for one year, starting on July 1st until June of the following year. For the 2023/2024 edition of the Safra Plan, the government has made available an amount of over US$ 90 billion in various rural credit options (CNN BRASIL, 2023; GOVERNO FEDERAL, 2023a). The resources announced for small farmers amount to over US$ 16 billion, while resources for large and medium-sized producers account for close to US$ 75 billion.

The credit lines of the Safra Plan belong to various programs, the main ones being the National Program for Strengthening Family Farming (**PRONAF**) and the National Program to Support the Medium Rural Producer (**PRONAMP**). There are also resources for other programs such as **INOVAGRO**, **MODERAGRO**, **PRODECOOP**, **PROIRRIGA**, **RENOVAGRO**, among others. Each program of the Safra Plan has specific subdivisions, with interest rates that vary according to the particular program. The classification in one or another modality varies according to the activity carried out by the rural producer, according to the corresponding annual income and the size of the property. This differentiation exists precisely to stimulate the production of small producers, since they tend to have lower competitive advantages compared to large-scale producers.

Another financial instrument that can be used by rural farmers to adopt solar photovoltaic energy systems is the **Constitutional Financing Funds** (**FCO**, **FNE** and **FNO**). These funds are established in the Brazilian Constitution, through Law 7827 of 1989, which aims to promote the economic and social development of certain regions (MINISTÉRIO DA INTEGRAÇÃO E DO DESENVOLVIMENTO CONSTITUCIONAL, 2023). Each fund is directed to a specific region of the country: Constitutional Financing Funds of the **Center-West (FCO), Northeast (FNE) and North (FNO)**.

Another financing option that may be interesting for farmers is **FINAME** (Financing of Machinery and Equipment). FINAME is a BNDES (National Bank for Economic and Social Development) program that offers credit for the acquisition of machinery, equipment, vehicles and other capital goods to be used in the exercise of the client's economic activity.

These financing lines and programs are presented in more detail in the following sub-chapters.

4.3.2.1 Program for Strengthening Family Farming (PRONAF)

The **National Program for Strengthening Family Farming (PRONAF)** is a credit line and part of the Federal Government "Safra Plan", which aims to provide differentiated assistance to various family farming groups such as: agrarian reform settlers, land credit beneficiaries, low-income family farmers, dynamic family farmers and even traditional peoples and communities such as indigenous peoples, quilombolas, artisanal fishermen, riverside dwellers and others.

PRONAF is present in almost all municipalities in the country and its implementation takes place through public and private banks, the BNDES and rural credit cooperatives. PRONAF provides credit lines tailored to the needs of family farming, each with its own specificity, to meet certain purposes or target groups. The rural credit lines currently available under PRONAF are: PRONAF Custeio, PRONAF Mais Alimentos (Investment), PRONAF Microcrédito Produtivo Rural, PRONAF "A", PRONAF "A/C", PRONAF Agroindústria, PRONAF Industrialização, PRONAF ABC + Floresta, PRONAF ABC + Semi-arid, PRONAF ABC + Agroecology, PRONAF ABC + Bioeconomy, PRONAF Woman, PRONAF Youth, PRONAF Quotas-Parts, Productive Oriented PRONAF (PROGRAMA NACIONAL DE FORTALECIMENTO DA AGRICULTURA FAMILIAR, 2023).

Among these available lines, the ones that can finance solar photovoltaic systems are **PRONAF ABC + Bioeconomy and PRONAF Agroindustry**, both presented in more detail in the following sub-chapters.

4.3.2.1.1 PRONAF ABC + Bioeconomy

The **PRONAF ABC + Bioeconomy** financing mechanism allows financing for investment in the use of renewable energy technologies, environmental technologies, water storage, small hydro-energy uses, forestry and the adoption of conservation practices and correction of soil acidity and fertility, aiming at its recovery and improvement of productive capacity (PROGRAMA NACIONAL DE FORTALECIMENTO DA AGRICULTURA FAMILIAR, 2023).

This financing mechanism may be requested by farmers and family rural producers, individuals, who present a valid PRONAF Aptitude Declaration (DAP) and who meet the requirements for enrollment. Table 4 presents the general conditions of this financing line for the acquisition of renewable energy technologies. It is important to note that the availability of the credit line may vary according to the region and the bank branch, in addition to the credit conditions offered.

Table 4 - Conditions of the PRONAF ABC + Bioeconomy line for financing renewable energy technologies.

Interest rate	Up to 5% p.a.
Maximum financing amount	R$ 200 k (approx US$ 40 k)
Maximum financing period	10 years
Maximum grace period	5 years
Banks where this credit line is available	BNDES, Banco do Brasil, Banco do Nordeste, Banco da Amazônia, Banrisul, Sicredi, Sicoob, among others

Source: Elaborated by authors (2024)

4.3.2.1.2 PRONAF Agroindústria / PRONAF AgroIndustrty

PRONAF Agroindustry was created to support the implementation, expansion or modernization of family agroindustries, which transform agricultural production into products with higher added value. PRONAF Agroindustry resources can be used for the acquisition of machinery, equipment, utility vehicles, construction and renovation of facilities and acquisition of raw materials, and investments in renewable energy technologies, such as the use of biomass, wind, mini biofuel plants and the replacement of fossil fuel technology by renewable in agricultural equipment and machinery for use in agroindustry.

In order to have access to PRONAF Agroindustry, the agribusiness must be registered in the National Family Agriculture Program (PRONAF) and be considered a family rural production unit. In addition, the agro-industry must be located in a rural area and have as its main activity the processing of agricultural products produced by the family unit itself.

The purpose of PRONAF Agroindustry is to promote the addition of value to agricultural production, generating income and improving the quality of life of farming families. In addition, the program seeks to foster sustainable development and diversification of productive activities in the countryside. Table 5 presents the general conditions of this credit line. It is important to note that the availability of the line may vary according to the region and the bank agency, in addition to the credit conditions offered.

Table 5 - Conditions of the PRONAF Agroindustry line

Interest rate	Up to 6% p.a.
Maximum financing amount	**Individual** – Up to R$ 200 k (approx US$ 40 k) **Legal entity** – Up to R$ 7 million (approx US$ 1.4 million) ***Cooperative*** – Up to 35 million (approx US$ 7 million), with R$ 45 k (approx. US$ 9 k) per cooperative member
Maximum financing period	Up to 10 years
Maximum grace period	Up to 3 years
Banks where this credit line is available	BNDES, Banco do Brasil, Banco do Nordeste, Banco da Amazônia, Caixa, others

Source: Elaborated by authors (2024)

4.3.2.2 National Program to Support the Medium Rural Producer (PRONAMP)

The **National Program to Support the Medium Rural Producer (PRONAMP)** is also, just like PRONAF, a program belonging to the Safra Plan. The difference lies in the target audience of each initiative. While PRONAMP caters for medium-sized properties, PRONAF is for family farmers. Rural producers who have a gross annual income of up to R$ 2.4 million (approx US$ 500 k) can apply for a PRONAMP credit line. In addition, it is necessary that the offtaker is up to date with any financial and tax obligations and present a technical project for the use of credit.

PRONAMP can finance costing and investment activities. The PRONAMP Costing modality meets operating expenses, which assist in the maintenance of the property. In turn, the PRONAMP Investment modality serves to improve the agricultural production of the requesting producer, either through the acquisition of machinery or the implementation of a renewable energy system, for example.

Table 6 presents the PRONAMP financing conditions in more detail. It is important to note that financing conditions and criteria may vary according to the financial institution offering the credit line.

Table 6 - Conditions of PRONAMP credit line

Interest rate	8% p.a.
Maximum financing amount	Up to R$ 430 k (approx. US$ 90 k) per crop year
Maximum financing period	Up to 8 years
Maximum grace period	Up to 3 years
Banks where this credit line is available	BNDES, Banco do Brasil, Caixa, Santander, among others.

Source: Elaborated by authors (2024)

4.3.2.3 Program to Promote technological Innovation in Agricultural Production (INOVAGRO)

The **Program to Promote Technological Innovation in Agricultural Production (INOVAGRO)** aims to support investments needed to incorporate technological innovation in rural properties, in order to increase productivity, the adoption of good agricultural practices and rural property management, and the competitive entry of rural producers in different consumer markets. The beneficiaries of this program are rural producers (individuals and companies) and their cooperatives.

Table 7 presents in more detail the INOVAGRO financing conditions. It is important to note that the financing conditions and criteria may vary according to the financial institution offering the credit line.

Table 7 - INOVAGRO financing conditions

Interest rate	10.5% p.a.
Maximum financing amount	Individual enterprise - R$ 1.3 million (approx. US$ 260 k) per client Collective enterprise - R$ 3.9 million (approx. US$ 800 k), within individual limits
Maximum financing period	Up to 10 years
Maximum grace period	Up to 3 years
Banks where this credit line is available	BNDES, Banco do Brasil, Caixa, Santander, among others.

Source: Elaborated by authors (2024)

4.3.2.4 Financing Program for Irrigated Agriculture and Protected Cultivation (PROIRRIGA)

The **Financing Program for Irrigated Agriculture and Protected Cultivation (PROIRRIGA)** aims to:

- Support the development of irrigated agriculture that is sustainable, both economically and environmentally;
- Encourage the use of structures for production in protected environments, to increase crop productivity and quality;
- Protect the cultivation of fruits in temperate climate regions against the incidence of hail.

The beneficiaries of the program are rural producers (individuals and legal entities) and their agricultural production cooperatives. Photovoltaic solar energy systems are not directly mentioned among the program's bankable items, however it is mentioned that "investments related to all items inherent to irrigation systems, including electrical infrastructure, water reserve and equipment for monitoring soil moisture" are bankable (BANCO CENTRAL DO BRASIL, 2022a). Therefore, it is possible that projects related to photovoltaic solar energy can be financed, provided they comply with the program guidelines. If the rural producer is interested in implementing an irrigation system with a solar energy system using PROIRRIGA as a financing line, it is important to check with the chosen financial institution what are the conditions and requirements for financing this type of equipment.

Table 8 presents the financing conditions of PROIRRIGA. Financing conditions and criteria may vary according to the financial institution offering the credit line.

Table 8 - PROIRRIGA financing conditions

Interest rate	10.5% p.a.
Maximum financing amount	Individual enterprise - R$ 3.3 million (approx. US$ 660 k) Collective enterprises - R$ 9.9 million (approx. US$ 2 million), respecting the individual limit
Maximum financing period	Up to 10 years
Maximum grace period	Up to 3 years
Banks where this credit line is available	BNDES, Banco do Brasil, Caixa, Banrisul, among others.

Source: Elaborated by authors (2024)

4.3.2.5 Programme of Cooperative Development for Adding Value to agricultural Production (PRODECOOP)

The **Programme for Cooperative Development for Adding Value to Agricultural Production (PRODECOOP)** aims to provide credit for the modernization of production systems and marketing of the agro-industrial complex of Brazilian cooperatives. The beneficiaries of this programme include:

- Singular agricultural, agro-industrial, aquaculture or fishing production cooperatives;
- Central cooperatives formed exclusively by agricultural, agro-industrial, aquaculture or fishing production cooperatives;
- Federations and confederations that act directly in the manufacture of inputs and in the processing and industrialization of production, provided that they are formed exclusively by agricultural, agro-industrial, aquacultural or fishing production cooperatives.

PRODECOOP provides financial resources for investment projects in infrastructure, acquisition of machinery and equipment, improvement of production processes, including "implementation of systems for energy generation and cogeneration and connection lines, for own consumption as an integral part of an agribusiness project" (BANCO CENTRAL DO BRASIL, 2022b). In other words, among the program's bankable items, there is no specific mention of solar photovoltaic energy systems; however, it is possible that these systems may be eligible for financing as long as they comply with the program guidelines.

Table 9 presents the financing conditions of PRODECOOP. Financing conditions and criteria may vary according to the financial institution offering the credit line.

Table 9 - PRODECOOP financing conditions

Interest rate	11.5% p.a.
Maximum financing amount	Up to R$ 150 million (approx. US$ 30 million) per cooperative
Maximum financing period	Up to 10 years
Maximum grace period	Up to 3 years
Banks where this credit line is available	BNDES, Banco do Brasil, Caixa, Banrisul

Source: Elaborated by authors (2024)

4.3.2.6 Constitutional Financing Funds (FNE, FNO e FCO)

The **Constitutional Financing Funds (FNE, FNO and FCO)** are public credit policy instruments created by the 1988 Federal Constitution to promote the economic and social development of the North, Northeast and Central-West regions of Brazil, respectively.

These funds are administered by **Banco do Nordeste (FNE)**, **Banco da Amazônia (FNO)** and **Banco do Brasil (FCO)** and have resources coming from the country's tax revenues. The resources of these funds are used to finance productive projects of individuals and legal entities that are located in the areas covered by the corresponding funds. Financing can be allocated to various sectors of the economy, such as agriculture, industry, commerce, services, infrastructure, among others.

The funds have differentiated interest conditions, terms, and grace periods, which vary according to the type of project and the location of the company. In addition, the funds also have specific credit lines for strategic sectors, such as renewable energy, tourism, family farming, among others. The objective is to contribute to the generation of employment and income, as well as to the sustainable development of the benefited regions.

The following sub-chapters outline the lines of the Constitutional Funds that can be good opportunities for rural producers to enable investments in solar PV in the field.

4.3.2.6.1 FNE SOL – Banco do Nordeste

The **Northeast Constitutional Fund (FNE)** aims to promote the economic and social development of the Northeast region of Brazil. The FNE is administered by the Banco do Nordeste do Brasil (BNB) and has as its area of application all the northeastern states, in addition to the north of the states of Minas Gerais and Espírito Santo, included in the area of operation of the Superintendence of Northeast Development (SUDENE) (GONÇALVES; ESTEVES, 2019).

The BNB's Financing Program for Distributed Micro and Mini-generation of Electricity and Off-grid Systems (FNE SOL) aims to finance distributed micro and mini-generation projects from renewable sources. The beneficiaries of the program are companies, rural producers and individuals, and the components and installation of photovoltaic solar energy systems, wind, biomass, or small hydroelectric plants (SHP) are eligible for financing.

Table 10 presents the FNE SOL financing conditions available from BNB for rural producers.

Table 10 - FNE SOL financing conditions for rural producers

Interest rate	4.39% p.a. - 4.94% p.a. (depending on the size of the rural producer)
Maximum financing amount	R$ 100 k (approx. US$ 20 k)
Maximum financing period	Up to 12 years
Maximum grace period	6 months
Banks where this credit line is available	Banco do Nordeste do Brasil (BNB)

Source: Banco do Nordeste do Brasil (2021)

4.3.2.6.2 FNO Rural Verde – Banco da Amazônia

The **Northern Constitutional Financing Fund (FNO)** aims to foster the development of the Northern region, with resources aimed at financing the productive sectors of industry, agribusiness, agriculture, tourism, trade and services, innovation, technology and essential biodiversity products, followed by support for the region's economic infrastructure, with projects aimed at logistics and sanitation.

The execution of resources is carried out by Banco da Amazônia (BASA) and, in its conditions as administrator of FNO resources, BASA carries out operations that primarily serve smaller productive segments (mini/micro, small entrepreneurs, individual microentrepreneurs and family-based agriculture) (BANCO DA AMAZÔNIA, 2023). The FNO's area of operation comprises the seven states of the Northern region: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins.

One of the FNO lines that can be used to finance investments in renewable energy production systems for rural enterprises' own consumption is the FNO Rural Verde line. The beneficiaries of the FNO Rural Verde line include:

- Rural producers, individuals or legal entities;
- Traditional populations of the Amazon (indigenous peoples, quilombola communities, riverine communities, extractivists, artisanal fishermen, among other forest peoples) not covered by PRONAF;
- Legal entities under private law in the rural sector, including individual entrepreneurs, individual limited liability companies (EIRELLI), associations

and cooperatives, organized in accordance with the legislation in force in the country.

In addition to investments in renewable energies, this line also supports enterprises with the adoption of electric, hybrid or renewable energy vehicles, including the electric supply structure; ecological works; projects that support biodiversity and activities within the scope of Low Carbon Agriculture. **Table 11** outlines the financing conditions for renewable energy systems from FNO Rural Verde.

Table 11 - FNO Rural Verde financing conditions for renewable energy projects

Interest rate	6.87% p.a.
Maximum financing amount	Varies according to the beneficiary's payment capacity
Maximum financing period	12 years
Maximum grace period	6 years
Banks where this credit line is available	Banco da Amazônia

Source: Banco da Amazônia (2023)

4.3.2.6.3 FCO Rural – Banco do Brasil

The **Constitutional Financing Fund of the Central-West (FCO)** has lower interest rates than those of the market, longer payment term and longer grace period than many financing lines, and R$ 20 million (approx. US$ 4 million) is the maximum amount financed by the Fund (GOVERNO FEDERAL, 2023b). The beneficiaries of the FCO are rural producers or entrepreneurs (from micro to large) who develop their activities in the states of Mato Grosso, Mato Grosso do Sul, Goiás or the Federal District (GOVERNO FEDERAL, 2023b). People interested in obtaining funding with FCO resources should seek a bank accredited with this line of financing.

One of the available FCO lines for rural producers at Banco do Brasil is the **FCO Rural** line, which is available to production cooperatives, rural producers, individuals or legal entities and associations located in the Central-West region. FCO Rural aims to serve the agricultural and agro-industrial production sector.

Table 12 presents the financing conditions of the FCO Rural offered by Banco do Brasil.

Table 12 - FCO Rural financing conditions for renewable energy projects

Interest rate	7% p.a – 10% p.a.
Maximum financing amount	R$ 20 million (approx. US$ 4 million)
Maximum financing period	Up to 20 years
Maximum grace period	Up to 12 years
Banks where this credit line is available	Banco do Brasil

Source: Banco do Brasil (2023)

4.3.2.7 BNDES Finame Low Carbon

The Agency for Special Industrial Financing (FINAME) is a Brazilian public company that is a subsidiary of BNDES. That is, BNDES is responsible for managing, supervising and coordinating FINAME programs. FINAME offers several lines of credit and aims to finance the production and commercialization of new national machinery and equipment accredited at BNDES for nationals operating in various sectors of the economy in the country. The purpose of FINAME is to foster the modernization of Brazilian industry and stimulate the country's economic development.

Among the different existing financing lines, the **FINAME Low Carbon** line presents opportunities for rural producers to acquire their own solar energy systems. The BNDES FINAME Low Carbon line finances the acquisition of low-carbon goods and services, such as equipment and technologies that help reduce greenhouse gas emissions. The following can be financed: solar and wind power generation systems, solar heaters, electric buses and trucks, hybrid buses and trucks powered exclusively by biofuel and other machinery and equipment with higher energy efficiency rates.

The beneficiaries of this line include:

- Companies based in the country;
- Public administration;
- Individual entrepreneurs and micro-entrepreneurs;
- Rural producers (individuals resident and domiciled in the country);
- Autonomous cargo transporters and individuals associated with road cargo transportation cooperatives;

- Foundations, associations and cooperatives based in the country;
- Individuals resident and domiciled in the country; and
- Condominiums.

The interest rates of FINAME Low Carbon vary according to the size of the company, the amount financed, the payment term and the guarantee offered. TABLE 13 presents the financing conditions of this line.

Table 13 - BNDES FINAME Low Carbon financing conditions

Interest rate	TFB, TLP or SELIC interest rate + BNDES rate (0.95% p.a.) + Financial Agent rate (3.5% p.a.)[29]
Maximum financing amount	Varies according to the project and the company's financial capacity.
Maximum financing period	Up to 10 years
Maximum grace period	Up to 2 years
Banks where this credit line is available	Financial institutions accredited to BNDES

Source: Banco Nacional de Desenvolvimento Social (BNDES) (2023)

4.4 Benefits and drawbacks of agrivoltaic systems within the Brazilian context

This section comprises an analysis of the strengths, weaknesses, opportunities, and threats regarding the agrivoltaic technology in the Brazilian context, as well as the technical, economic and social benefits of agrivoltaic applications, considering the different regions and analysis of the previous topics. Also, it includes the potential drawbacks and challenges to the implementation of agrivoltaic systems in these regions.

4.4.1 SWOT analysis

The main aspects of agrivoltaic technology in the Brazilian context were organized in a SWOT matrix. This SWOT analysis is available in TABLE 14, and offers a comprehensive view of the prospects for agrivoltaic technology in Brazil, including the identified strengths, weaknesses, opportunities, and threats.

29 The rates of the FINAME Low Carbon line are calculated by indirect operations and are composed of the Financial Cost, BNDES Fee and Financial Agent Fee. Understand how this is calculated.

Table 14 - Swot analysis of the agrivoltaic technology in Brazil

	STRENGTHS +	WEAKNESSES -
INTERNAL FACTORS	+ Solar energy sector well established and growing rapidly Agricultural sector drives the economy of the country + Abundance of natural resources (irradiance and agricultural land) + Agricultural diversity + Existing funding opportunities for solar energy + International collaboration + Environmental and climate change awareness increase + Existence of internationally recognized research centers and universities in solar energy and agriculture research + Existence of R&D programs + Demand for renewable energy applications in rural areas	- Technology still unknown in the country - High CAPEX - Few projects in the country and worlwide - Lack of agrivoltaic adapted components and structure - Lack of technical knowledge on the integration between local crops and agrivoltaic systems - Lack of professionals specialized in agrivoltaic systems - Lack of data on agrivoltaics crop and animal production
	OPPORTUNITIES +	**THREATS -**
EXTERNAL FACTORS	+ Creation of funding opportunities specific for agrivoltaics + Technology development + Promotion of food and energy security (especially on semi-arid regions) + Creation of new business models and qualified jobs + Possibilities in distributed generation + Cooperation between organizations and sectors + Potential to increase family agriculture resilience and income diversification + Potential tool for addressing the water-food-energy nexus challenges + Existing agricultural cooperatives or associations adopt the shared solar energy model and generate energy credits to its associates.	- Competition for land between sectors - Lack of national guidelines and regulation - Low educational level of family farming population - Low power of investment of the small rural establishments

Source: Elaborated by authors (2024)

4.4.2 Benefits

As mentioned in SUB-CHAPTER 2.2, the two basic categories of agrivoltaics, according to Macknick et. al (2022), are elevated systems with crop production below the PV array, and lower systems with crops grown between rows of PV modules. The authors also define the main application categories as **Crop and food production**, **Livestock production**, **Provision of ecosystem services** and **Greenhouses**. Among these various applications, the technical configurations of agrivoltaics also vary, and their benefits can range from providing shading, protection against frost or extreme heat to reducing evaporation rates. Also, the authors identified 5 relevant success aspects for agrivoltaic projects: Climate, Configuration, Crops and Cultivation, Compatibility, and Collaboration (see SUB-CHAPTER 3.7).

The wide range of possible agrivoltaic configurations might be a good aspect of the technology for Brazil, considering the vast diversity of agricultural establishment scales and climate characteristics. The North and the Matopiba region, for example, could benefit from the dual-use aspect of the technology. In the context of high deforestation rates for creation of new pasture and agricultural lands, the dual-use might be a tool to create additional income for local families, avoiding the removal of native forest vegetation for the creation of new agricultural fields. Also, the income increase for small scale farmers of the region could make it possible for these farmers to have a better profitability per area and to have resources to transition to more sustainable agricultural practices.

In the Central-West region, the higher structures configurations adapted to large machinery could be suitable for the large-scale agriculture in that region, and the benefit of reducing evaporation and the need for irrigation would benefit many of the local crops, such as soybeans and corn plantations. The Southeast region leads with the highest percentage of irrigated area, accounting for 39.8%, followed by the South with 25%(BADRA, 2022). Agrivoltaics can optimize existing irrigation systems where available and, also offer benefits in regions where such systems are not present, making them economically feasible. This irrigation optimization aspect is also a relevant considering the Northeast region conditions, which is considered semi-arid and suffers from water scarcity and high irradiation levels, as mentioned in SUB-CHAPTER 4.2.1.4. Additionally, as this region is also marked by high rates of rural poverty, these systems can offer relevant social and economic benefits.

In general, agrivoltaic systems present social and economic opportunities for farmers in various regions of the country, offering greater autonomy in energy generation for self-consumption and the potential to create an income aggregation to farmers through leasing or to create energy credits through the generation distributed system. As an inspiration, a national funded program for agrivoltaics in small scale farmer context, such as the ones in Japan and South Korea, could create dual-revenue streams and increase the quality of life of these populations.

4.4.3 Challenges

In Brazil, agrivoltaic systems are not yet widely adopted, which may present an initial barrier for implementing these projects as installers may not have access to appropriate project models, adapted modules (such as those with larger spacing or tubular modules), and adapted structures (e.g., taller structures or fewer support pillars) for agrivoltaics. In addition, the lack of professionals with technical experience in agrivoltaic projects and integration between these systems and the crops is a barrier to the implementation of the technology at this stage. Also, agrivoltaics have higher CAPEX compared to regular PV installations, what can represent a relevant challenge, especially for family farming establishments, which have, in most cases, a low power of investment.

Apart from the initial limitations concerning equipment, professionals and costs, the lack of national guidelines or regulations in Brazil might be a barrier for the development of agrivoltaic projects at first. The adoption of the technology without an adequate study of the climate context, agricultural practices compatibility and the agrivoltaic configuration may compromise the resulting yields and impact the credibility of the technology, which has already happened in France, for example.

5. Case study context

The utilization of photovoltaic (PV) systems has emerged as an important strategy to address energy needs while optimizing land use. These systems of dual-use of land, for energy generation and agriculture, agrivoltac technology, constitute the context of this case-study. The present case-study revolves around the Association of the Organic Producers of Iranduba (APOI), situated in the Amazonas state of Brazil. Founded in 2017, APOI is dedicated to fostering small-scale family farming.

The heart of APOI's initiatives lies in the adoption of the "Comunidade que Sustenta a Agricultura" or "Community Supported Agriculture" (CSA) business model—a pioneering venture in sustainable agriculture. Besides the regular household energy consumption of the APOI members, the association plans to build an industrial kitchen, with the support of the Amazon Fund[30]. The industrial kitchen would increase considerably energy expenditures of the association.

In this context, the main objective of this Case Study is to develop a **technical & economic feasibility study** of an agrivoltaic project, with two specific configurations. The results aim to support the APOI association in future PV projects, and to serve as an inspiration to other agrivoltaic projects in the Brazilian context.

This initial section provides an explanation of the definition process and offer contextualization of the Case Study location. Additionally, a comprehensive characterization of the chosen location will be included in this section.

5.1 Association of the Organic Producers of Iranduba (APOI)

The chosen initiative for the case-study -*Associação dos Produtores Orgânicos de Iranduba* (APOI) - is led by President Neiliane Paz, and was funded in 2017. APOI Association is located in the municipality of Iranduba (Figure 50) in the state of Amazonas. The families involved in this case-study reside in the areas of Ramal do Peixe Boi and Ramal do Pupunhal. The organic small-scale family producers who participate in the association were displaced from the banks of the Solimões River due to the phenomenon of landslides, where water erosion causes the riverbanks to collapse, affecting the land they used to cultivate food as their source of income. The main crops produced by the families are vegetables, cabbage, arugula, lettuce, chives, gerimum, coriander, parsley, banana, lime and *cupuaçu*[31](Figure 51 and Figure 52). Their farming practices include organic and agroforestry strategies.

Figure 50 - Location of the case-study - APOI Association

Source: Authors (2024)

30 https://www.fundoamazonia.gov.br/pt/home/

31 Native Amazonian fruit

Figure 51 – Crops production from APOI's families

Source: Photo by Ramom Morato (2023)

Figure 52 – Woman farmer from the APOI Association

Source: Photo by Ramom Morato (2023)

Regarding their energy consumption, currently, the main energy expenses for the producer families are for air conditioning systems for their homes, for water pumping from wells, and water pumping for irrigation. There is currently a project to build an industrial kitchen to support the local farmers. The goal of the industrial kitchen is to allow the farmers to better clean, explore processing alternatives and storage their products. It will enable activities such as vacuum-packing cassava and vegetables, processing (minimally) vegetables, and making fruit pulp. The kitchen is planned to be built with resources from Amazon Fund and it is expected to start operating between the second semester of 2024 and 2025. This project will increase the energy bill of the association and the agrivoltaic project can assist with this energy bill. The families' energy bills currently range from R$200 to R$450/month (equivalent to 300-600 kWh/month), but this will increase with the operation costs of the industrial kitchen.

When it comes to the climate conditions of the region, Iranduba is in the heart of the Amazon Forest, which means it is under an equatorial climate characterized by high temperatures with minimal variations year-round. Daytime temperatures range from 25°C to 32°C, with nights remaining relatively warm. The region experiences heavy, consistent rainfall, and is marked by two main seasons: a wet and a dry one. The wettest period spans from December to May and the drier season from June to November, though rainfall persists even during the drier period.

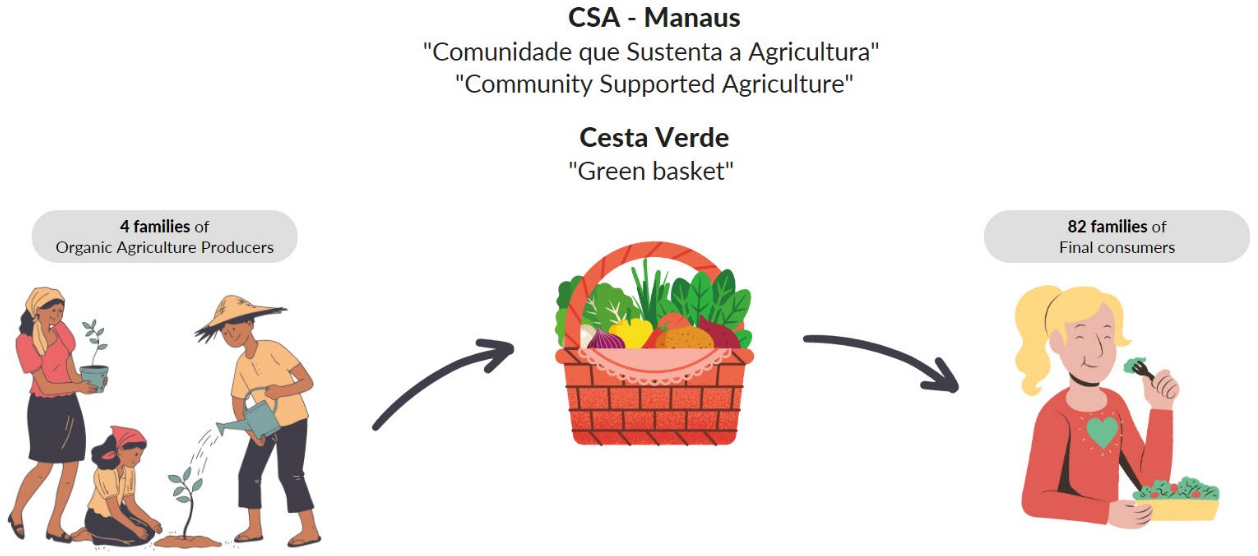
5.2 Initiatives: CSA Manaus and Green Basket (Cesta Verde)

APOI has a goal of bringing sustainable agriculture to community-driven farming, and it makes use of a business model known as "Comunidade que Sustenta a Agricultura" or "Community Supported Agriculture" (CSA). CSA model is a partnership between farmers and consumers in which the responsibilities, risks and rewards of farming are shared. It has emerged as a successful model and it thrives on collaboration, uniting organic and agroecological food producers with conscientious consumers in a shared commitment to support local agriculture.

For a successful CSA model, a fixed group of consumers commits to covering the annual budget of the agricultural entity for a period, typically a year. In return, these consumers receive the farm's produce through monthly "food baskets" without any additional costs. This approach allows the farmer to dedicate themselves freely to cultivation without the pressures of the market and pricing. This model has been active in Brazil since 2011, and it is present in almost all of the country states (CSA Brazil, 2023).

There are currently 12 families of agricultural producers associated with APOI, that forward their production through CSA model (CSA Manaus Initiative), and another initiative called "Cesta Verde" (Green Basket). This last one consists of the same model of "food baskets". Besides supporting the producers, APOI also aims to provide healthier food to consumers by incentivizing the associates to adopt agroecological production techniques. Four of the 12 families produce organics and supply 82 consumer families, which receive the monthly production and support the business model financially (FIGURE 53). These four families are the ones considered in this case-study.

Figure 53 - APOI operacional model



Source: Elaborated by authors (2024)

5.3 Agrivoltaic system design

5.3.1Agrivoltaic System Design

5.3.2 Photovoltaic System Design

The main objective of this case study was to evaluate the technical and economical viability of an agrivoltaic project to attend to the specific needs of small-scale farmers. Thus, the design of the systems was proposed to align with the economic realities of these farmers, as well as their resource availability. In order to define the agrivoltaic system designs, a few steps were followed:

- Information regarding the future plans of the association was gathered, as well as number of associates and the way the association business model functions;
- The location of the farms and existing infrastructure was investigated;
- The climate conditions and irradiation data was obtained in data bases;
- The needed PV systems size was estimated;
- Definition of the PV system components and project aspects;
- Simulations on PVSyst showed energy output;
- Simulations on Google Sketchup showed shading impacts.

Across the study, two systems were proposed: an elevated agrivoltaic system and a vegetation house agrivoltaic system. The latter is a structure similar to a greenhouse, but it is open in the sides and it has the objective of protecting the crops from heavy rain. As mentioned, the shade that affects the crops was simulated, in order to avoid intense shading in the agricultural production and find the best system design. Some of the aspects of the systems proposed and their components are available in the following topics.

- **PV module technology**

For the vegetation house and elevated agrivoltaic, bifacial modules were chosen.

The simulation was done using PV modules that are available in PV Syst software (Table 1), which are from a manufacturer known to be reliable according to ratings such as the PVEL and PV-tech. The modules were also chosen because they are widely used in the country on a commercial scale.

Table 15 - PV module characteristics

System	Module Material	Bifacial	Power	Dimensions
Ground System	Mono PERC, Double Glass	Yes	440 Wp	2117mm x 1052mm
Vegetation House	Mono PERC, Double Glass	Yes	440 Wp	2117mm x 1052mm

Source: Elaborated by authors (2024)

- **PV module tilt, angle and orientation**

For the positioning of the systems, it was taken into consideration the geographical position of the sites and existing structures and agricultural production. The main objective is to minimize any impact that the agrivoltaic system proposed might cause on the existing agricultural production. Results are available in TABLE 15.

Throughout the shading analysis, it was possible to observe that the best orientation for both systems, in this aspect, would be facing west (azimuth 90°), because in this orientation the shading on the crops would be better distributed if the crops were positioned differently, but it was opted to maintain the original orientation, facing north (azimuth 0°), since the crops are already established and one of the premises used in this project was to make the least possible interference in the existing agricultural production. A simulation with the system facing west showed that, with this orientation, the energy production decrease would be small compared to the north and ideal orientation – 0,78% for the elevated system and 0,76% for the vegetation house.

Table 16 - System characteristics

System	Coordinates	Module Tilt	Azimuth
Elevated agrivoltaic system	-3.2528 S, -60.1365 W	10°	0° North
Vegetation house	-3.2528 S, -60.1365 W	10°	0° North

Source: Elaborated by authors (2024)

The proposed locations for the systems would be the elevated agriPV system installed on Doquinha's farm, as in FIGURE 54.

Figure 54 – Elevated agrivoltaic location

Source: Authors (2024)

And the vegetation house system installed at Dona Walda's household, as shown in FIGURE 55, where there are other vegetation houses already installed.

Figure 55 – Agrivoltaic vegetation house location

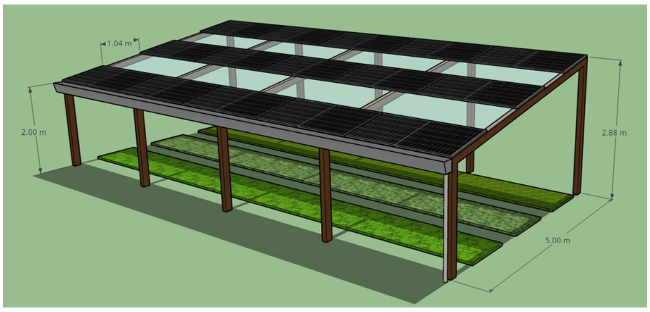
Source: Authors (2024)

- ### Mounting structure design

For the agrivoltaic vegetation house and elevated agrivoltaic system, the aim was to create a system that could be replicated and to use materials that are already used by the families, such as wood for the physical structure and plastic film in the vegetation house for the areas without modules. Instead of plastic, glass panels could also be applied to the vegetation house.

The agrivoltaic vegetation house system is approximately five by eleven meters with fifteen modules as seen in Figure 56.

Figure 56 - Agrivoltaic vegetation house

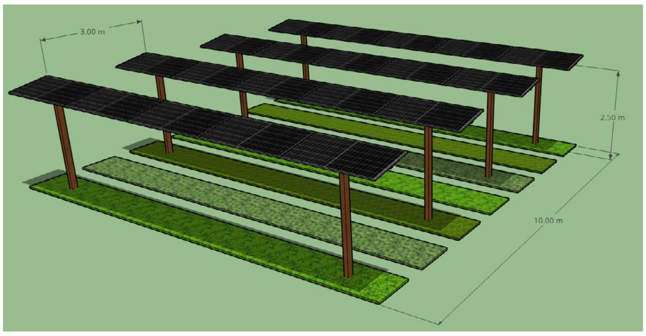


Source: Elaborated by authors (2024)

A water capture system was designed for the possibility of adding a water reservoir to irrigate the crops. This application would work better with glass panels instead of plastic film in the transparent sections.

The elevated agrivoltaic system occupies an area of approximately eleven by ten meters with twenty modules divided in four roles of five modules, as shown in Figure 57.

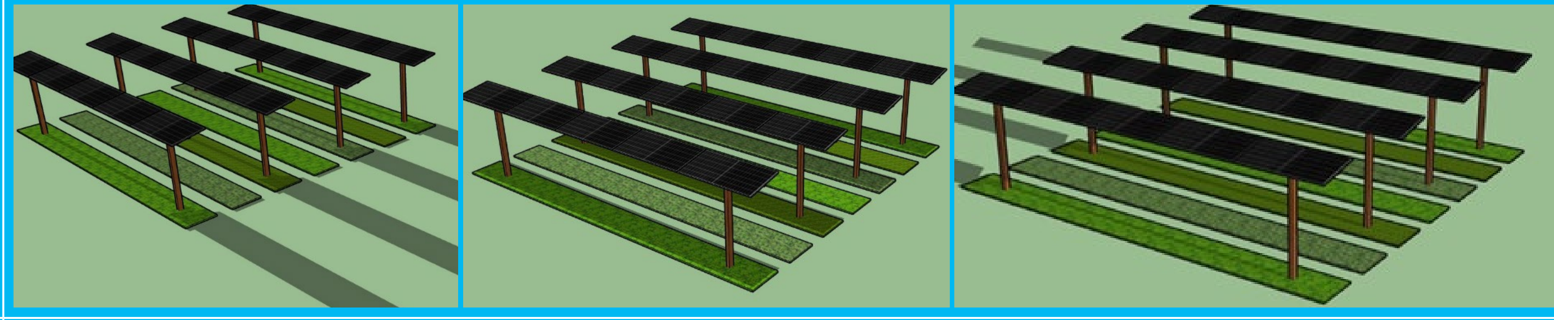
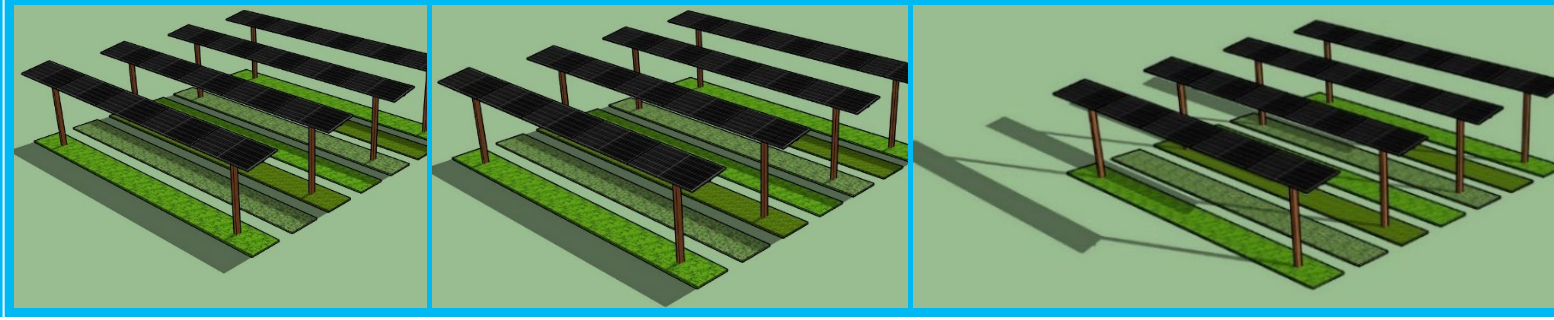
Figure 57 - Elevated Agrivoltaic System Design

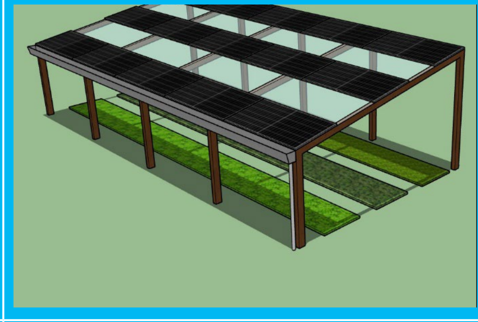
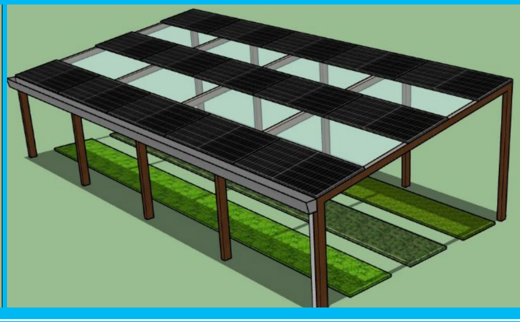
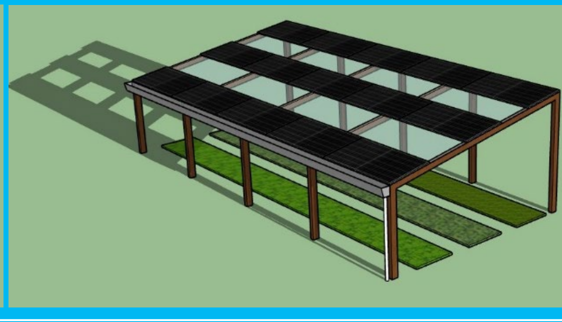


Source: Elaborated by authors (2024)

Another factor considered when designing the agrivoltaic systems was the amount of shade in the crops during the day. A shading analysis was made using SketchUp for the days September 22nd and December 22nd, dates close to the seasons of the highest and lowest temperatures, respectively, which are also the dates for the equinox and solstice (Table 17).

Table 17 - Shading analysis

System	Date	Shading
Ground System	22/09	Shading on the crop beneath the string starts at 6:50am and ends by 5:00pm. The shade is above of the crop below the respective string throughout midday. The crops between string are not shaded during this day. 
	22/12	Shading varies throughout the crops during the morning and stabilizes between crops around 12:00am. Then, it begins to vary along crops again. 

Green House	22/09	Shading starts at 6:30am centered on the crops, around 12:00am it covers the middle crop completely and the adjacent ones partially. Shading stops around 5:00pm.   
	22/12	Shading covers most of the two crops beneath the lower part of the roof around 8:30am, then shifts to the space between the crops during midday, goes back to covering the two initial crops around 3:30pm.   

Source: Elaborated by authors (2024)

Analyzing the shading pattern, we can conclude that during the hottest season, in September, the shade covers the crops beneath the modules, while during December, when the temperatures have cooled down, the shade covers between crops. Although there can be a more equalized shading pattern with the system facing west, it was opted to follow the existing plantation pattern.

- **Expected energy output**

The expected energy output of the two mentioned systems was calculated and is available in Table 18.

Table 18 - Expected energy output

System	PV Power	Yearly Energy Output
Ground System	8,8 kWp	12,3 MWh/year
Green House	6,6 kWp	8,9 MWh/year

Source: Elaborated by authors (2024)

- **Expected yield.**

The daily yield expected by the simulations follows Table 19:

Table 19 - Simulated Daily Yield

System	Yield
Elevated AgriPV	3,8 kWh/kWp/day
Vegetation House	3,7 kWh/kWp/day

Source: Elaborated by authors (2024)

5.3.3 Agricultural System Design

It is recommended that all crops receive a minimum of 6 hours of direct sunlight throughout the day, ideally around 8h. Another suggestion is that leafy vegetables and tomatoes, which are more prone to dehydration, can be planted in areas with shade around noon.

In order to provide a better simulation of productivity impact with the implementation of agrivoltaic projects, softwares as the ones mentioned below could be used:

- **SPADE**[32]: a software developed by Sandbox Solar, which was released in 2023 in a beta version. The software is a modeling tool made specifically to agrivoltaics systems, that aids in the design and optimization of solar panels and the crops underneath. It has outputs such as PV and crop performance and economic revenue. It is still in development, and it is not available for use in Brazilian context, only for the USA context.
- **Agricultural crop simulation softwares:** softwares that focus on crop simulation that could be adapted to agrivoltaic systems, with the alteration of some factors like irradiation and soil moisture, for example. A few examples of crop simulation softwares are: STICS33, WOFOST, APSIM, DSSAT and CropSyst.

5.4 Economic Analysis

One of the main challenges of agrivoltaic technology in the Brazilian context, especially in "family agriculture" cases, is the cost of the system. Thus, this study comprises an economic analysis of the proposed agrivoltaic project. In order to develop the economic analysis, a few methodology steps were followed:

(1) Gathering current electricity bills of 4 producer families involved in the project;

(2) Estimating the future electrical consumption of the industrial kitchen;

(3) Calculating the power capacity and energy output of the proposed pilot agrivoltaic systems aiming to attend the energy consumption from the 4 families + the industrial kitchen;

(4) Calculating the CAPEX and OPEX of the proposed systems;

(5) Comparing potential agricultural productivity loss scenarios with the electricity savings associated with the agrivoltaics;

(6) Calculating economic indicators: NPV (Net Present Value), IRR (Internal Rate of Return), and discounted Payback period of three different subsidy scenarios:
   - 100% farmers investment
   - 80% farmers investment
   - 60% farmers investment

A period of 25 year project was defined in order to calculate the economic indicators for the project. The methodology steps are detailed in the topics of this chapter, as well as the main results of the economic analysis.

5.4.1 Electricity costs of the families and industrial kitchen

Electricity bills from the 4 farmer families were gathered in order to calculate the total average electricity cost for their households. These data are available in Table 20.

32 https://www.agrivoltaic.design/

33 https://www6.paca.inrae.fr/stics_eng/About-us/Stics-model-overview

Table 20 - Average energy consumption of the four families

Household	Average energy consumption (kWh/month)	Average energy consumption (kWh/year)
Household 1	475,2	5702,5
Household 2	486,3	5835,0
Household 3	296,8	3561,5
Household 4	270,1	3241,0
Total	**1.563,1**	**18.340,0**

Source: Elaborated by authors (2024)

Also, the electricity consumption of the industrial kitchen was estimated, considering some of the appliances associated with the activities and products the families produce. This estimative is available in TABLE 21.

Table 21 - Average energy consumption of the industrial kitchen

Appliances	Qtd	Power (W)	Daily hours of use	Average consumption (kWh/month)
Pulper	1	245	3	14,7
Freezers	2	-	-	144,2
Vacuum sealer	1	700	3	42,0
Industrial blender	1	1000	2	40,0
Electric oven	1	5000	6 per week	120,0
			Total	**360,90**

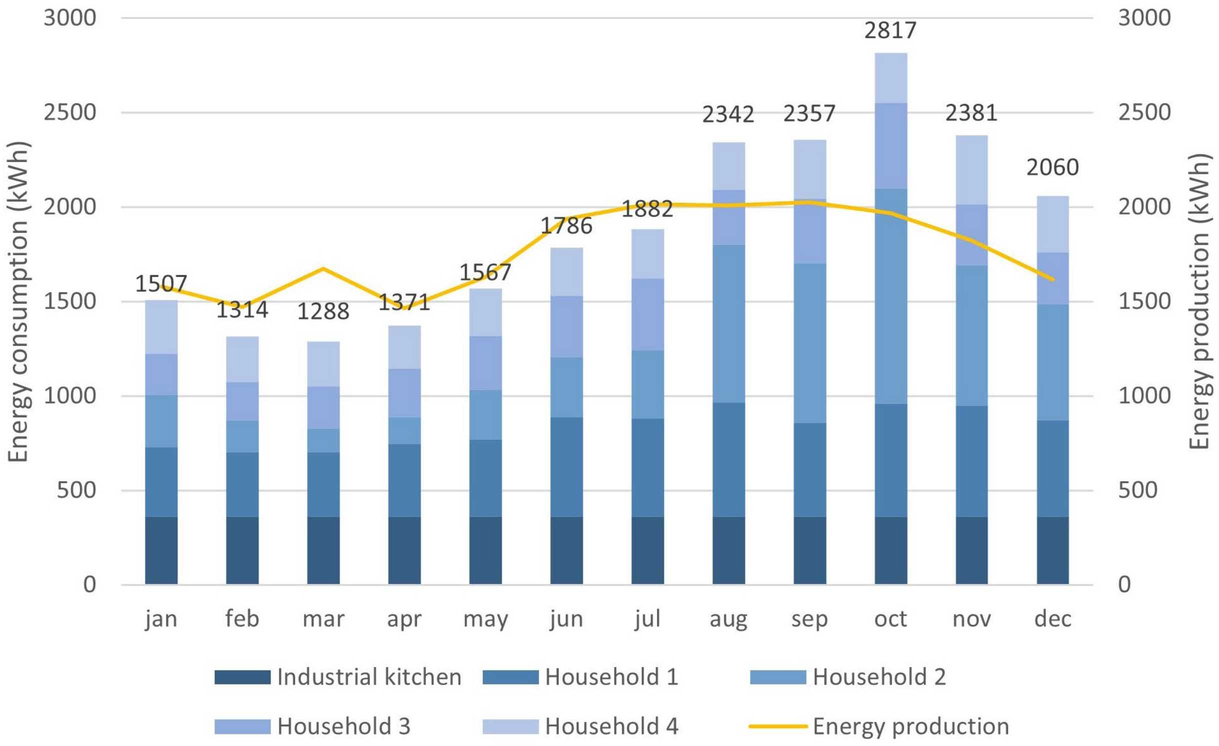
Source: Elaborated by authors (2024)

In total, the estimated average energy consumption is 1889,2 kWh/month, which results in an average annual consumption of **22,7 MWh/year**.

5.4.2 Proposed agrivoltaic Systems power and energy output

Considering the agrivoltaic systems proposed in item 3.2.1 of this document, and the PV modules of the brand JA Solar, the estimated power of the project would be **15,4 kWp**. The estimated energy output of the agrivoltaic systems was calculated, resulting in average electricity production of 1767,3 kWh/month, what results in an average annual electricity production of **21,2 MWh/year**. The average electricity consumption of each of the households and the industrial kitchen, as well as the estimated electricity production are represented visually in the Graph of FIGURE 58.

Figure 58 – Graph of Energy consumption and Energy production per month



Source: Elaborated by authors (2024)

The system size was calculated in order to supply the necessary electricity for the 4 households and the industrial kitchen, taking into account the current compensation system, i.e. net metering, regulated by Law 14,300[34]. The compensation system establishes that there is a value that must be paid regardless of the consumption and energy generation, which is called "minimum tariff". The value of the minimum tariff varies according to the types of electricity distribution/connection: if it is single-phase, two-phase or three-phase, and the values are 30 kWh, 50 kWh and 100 kWh, respectively.

The consumer units involved in this case study are all under single-phase connections, and the industrial kitchen will be connected to one of the consumer units, thus, this results in 120 kWh of electricity that will be charged every month (30 kWh x 4 consumer units), regardless of the photovoltaic generation associated with their electricity bills. The electricity consumption, production and the minimum tariffs are disposed in TABLE 22.

Table 22 - Average energy consumption of the industrial kitchen

Description	Value	Unit
Average electricity consumption (per month)	1889,2	kWh
Average electricity generation (per month)	1767,3	kWh
Minimum tariff for the 4 consumer units (per month)	120	kWh
[Electricity consumption – electricity production]	122	kWh

Source: Elaborated by authors (2024)

It is important to emphasize that this economic viability study was developed to verify the viability of the project in a wide perspective, and the electricity credits distribution among the households were not considered individually. If the project is to be implemented, different scenarios of proportional investment from each family and the amount of electricity credits that would go to each consumer unit would have to be further analyzed.

5.4.3 CAPEX of the proposed systems

The agrivoltaic vegetation house proposed in this case-study was designed to attend to their needs without adding much complexity to the structure. Thus, the structure of the vegetation house is wooden, similar to the existing ones, and the PV metallic structure and PV modules considered in the design are the conventional ones. The cost data for the standard PV system in Brazil was sourced from the Greener Market study[35].

In order to estimate the CAPEX of the proposed elevated system, data from the NREL Report "Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark for Ground-Mounted PV Systems with Pollinator-Friendly Vegetation, Grazing, and Crops"[36] (Horowitz et al., 2020) were used (FIGURE 59).

Figure 59 - Typycal PV installed costs compared to different agrivoltaic configuration costs

Source: Horowitz et al. (2020)

34 https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/lei/l14300.htm

35 https://www.greener.com.br/estudo/estudo-estrategico-geracao-distribuida-2022-mercado-fotovoltaico-2-semestre/

36 https://www.nrel.gov/docs/fy21osti/77811.pdf

The percentage of additional value obtained from both the standard PV system and the alternative elevated agrivoltaic system (last column in Figure 59) was utilized to calculate the additional cost associated with the elevated agrivoltaic system when compared to a standard PV system in Brazil (Table 23).

Table 23 - Estimated elevated Agrivoltaic cost

Description	Value	Unit
Regular PV cost 6kWp Greener (Brazil) – Vegetation house	4,15	R$/Wp
Aditional cost (normal PV -> elevated agrivoltaic)	52,29%	
Regular PV cost 8kWp Greener (Brazil)	3,92	R$/Wp
Estimated agrivoltaic cost (Brazil)	5,97	R$/Wp

Source: Elaborated by authors (2024)

The CAPEX for each of the proposed systems and the total CAPEX for the project is available in Table 24.

Table 24 - CAPEX of the different proposed PV system configurations

	Power (kWp)	Unit	CAPEX (R$)	
Vegetation house system	6,60	kWp	R$ 27.423,00	**Total**
Elevated agrivoltaic system	8,8	kWp	R$ 52.533,12	R$ 79.956,12

Source: Elaborated by authors (2024)

5.4.4 OPEX of the proposed systems

The operational costs considered in the project are the ones related to the maintenance of the PV systems. The maintenance cost of the photovoltaic system was considered 1% p.y. of the total initial investment value of the system in the first year, the same value adopted in other research studies on the economic feasibility of photovoltaic systems in Brazil (Schneider et al., 2018).

Also, since the inverters usually have a shorter lifespan when compared to PV modules, the substitution of the two inverters of the proposed systems was considered in the year 10 and year 20 of the economic analysis. The cost for the inverter replacement was obtained considering data of the proportion of the inverter costs from Figure 59 (Horowitz et al., 2020), and the CAPEX each system, shown in Table 24. Also, in the analysis an inflation rate of 3,16% considered[37] for estimating future maintenance costs.

5.4.5 Potential agricultural productivity loss scenarios and electricity savings associated with the agrivoltaics

In many cases, especially in shade resistant crops, the presence of an agrivoltaic structure might benefit the crops and increase agricultural productivity. A study from 2016, reported that agrivoltaic farms planting shade-resistant crops could benefit from a 30 percent higher economic value than conventional farms, according to their simulations (Dinesh & Pearce, 2016). Even though the agricultural production can increase, a possible yield reduction might also occur. Regulations in France, Japan, and Germany have established the maximum permissible yield reduction levels achievable within agrivoltaic systems at 10%, 20%, and 34%, respectively (Bellini, 2022)

In this study, three productivity loss scenarios were considered, in order to compare an estimated income loss due to the possible productivity loss, to the energy savings associated to the PV and agrivoltaic systems proposed. In this analysis, the CAPEX was not considered, only the operational values: productivity loss, energy savings and PV system OPEX.

In order to estimate the productivity loss in R$, it was considered that that the elevated agrivoltaic installation and vegetation houses would cover approximately 5% of the productive land of the farmers. Also, to find the equivalent income reduction associated to the productivity loss, the number and price of vegetable baskets was considered. The four families supply 82 families with organic vegetable monthly baskets, which are available in two sizes – small and large. Considering that half of them would be small size (R$140) and half large (R$200), the total monthly income of the selling of the baskets would be R$13,940.00 per month.

The results of the analysis are in Table 25 .

37 https://www.cnnbrasil.com.br/economia/depois-de-8-meses-brasil-tem-inflacao-negativa-de-008-em-junho-diz-ibge/#:~:text=No%20ano%2C%20o%20IPCA%20acumula,Conselho%20Monet%C3%A1rio%20Nacional%20(CMN)

Table 25 - Productivity loss and energy savings scenarios

Estimated productivity loss (%)	Productivity loss per year(R$)	Energy savings (R$) in year 1 considering maintanence PV costs
5%	R$ 418,20	R$ 15.127,95
10%	R$ 836,40	R$ 15.127,95
15%	R$ 1.254,60	R$ 15.127,95
20%	R$ 1.672,80	R$ 15.127,95

Source: Elaborated by authors (2024)

5.4.6 Economic indicators: NPV, IRR and discounted Payback period

In this economic analysis the NPV (Net Present Value), IRR (Internal Rate of Return), and discounted Payback period were calculated to investigate if the agrivoltaic systems proposed in the case-study were viable. It is relevant to note that the cost of implementation of the industrial kitchen will be covered by the Amazon Fund, and does not enter in this analysis.

The MARR (Minimum Attractive Rate of Return) use in the calculations was 13,5%, which corresponds to the Selic Rate[38] (a Brazilian Interbank Deposit Rate) and represents the minimum rate of return that an investment must generate to be considered attractive or viable. An increase rate of 9,2% for the electricity tariff was considered in this analysis, according to data from the study developed by Montenegro et al. (2020).

The NPV, IRR and discounted Payback were calculated for three different subsidy scenarios: 100% farmers investment; 80% farmers investment and 60% farmers investment. The results of the economic indicators are available in Table 26.

Table 26 – NPV, IRR AND DISCOUNTED PAYBACK PERIOD

Farmers investment	NVP	IRR	Discounted Payback
100%	R$ 98.232,76	24,41%	7 years 10 months
80%	R$ 114.223,99	29,01%	5 years 10 months
60%	R$ 130.215,21	36,59%	4 years 1 month

Source: Elaborated by authors (2024)

All the scenarios analyzed in this study show attractive economic results, with positive NPVs, IRRs higher than the MARR and discounted Payback periods under the 25 years of project period.

5.5 Recommendations on operation and maintenance

In Brazil, there are no regulations that provide guidelines for the characterization and maintenance of agrivoltaic systems, however, documents from other countries suggest that ensuring the continuity of crops throughout the project period and maintaining soil quality after the construction and dismantling of the photovoltaic system should be a priority. Therefore, it is recommended to plan the implementation and maintenance of the crops associated with agrivoltaics.

In this chapter some maintainance guidelines are suggested, based on documents from other countries and existing practices for regular PV systems, which were adapted to agrivoltaic systems.

5.5.1 PV system maintainance guidelines

Modern photovoltaic system inverters have the alternative of monitoring energy generation through applications. Through the application, individuals can access general system information and the daily, monthly, and annual generation of each linked system. Additionally, the application also allows the viewing of an error history. **It is necessary to designate a responsible individual to monitor monthly generation and, also, the energy bills associated with the system, in order to ensure that generation is occurring as expected and that credits are being generated and distributed correctly.**

5.5.2 Problem identification and types of maintainance

When monitoring energy generation, attention should be paid to periods in which generation is significantly reduced compared to the expected yield. This could indicate a system error, and once an error is identified, **it is recommended to hire a specialized company to perform maintenance and identify the existing problem**.

In addition, other indicators of issues in the plant that can be easily identified through visual inspection may include:

- Checking for abnormal or electrical noises;
- Observing cracks in the modules or modules that are crooked or loose;
- Noticing breaks or twists in the mounting structures.

It is important to emphasize that cables should not be disconnected by untrained individuals to prevent electrical shocks or the creation of electrical arcs, which can lead to accidents. Furthermore, walking on or applying strong pressure to photovoltaic modules should be avoided to

38 https://www.bcb.gov.br/controleinflacao/taxaselic

prevent damage to the photovoltaic cells.

Corrective maintainance

Corrective maintenance of PV systems aims to repair defects or failures in the photovoltaic system after they occur and also aims to prevent them from recurring. Corrective maintenance also includes the replacement of parts and equipment with manufacturing defects. This type of maintenance **should only be carried out by employees of specialized third-party companies** in the field, with appropriate safety equipment. Among the actions of corrective maintenance are:

- Current measurement of the strings;
- General maintenance of the string boxes;
- Voltage and polarity;
- Insulation resistance;
- Inspection and replacement of operated SPDs (Surge Protective Devices);
- Evaluation of the integrity of DC fuses;
- MC4 connector crimping;
- Replacement of damaged PV modules.

Preventive maintainance

Preventive maintenance of the systems involves a set of actions aimed at ensuring the proper operation and longevity of the equipment and the photovoltaic system as a whole, as well as preventing system malfunctions. These actions are carried out in accordance with the equipment maintenance manuals, following the manufacturer's guidelines and recommendations to ensure their warranty.

As part of preventive maintenance, some farmers may be responsible for activities such as observing dirt on the modules and electrical board. It is not necessary to clean the system frequently, it is recommended to be done annually or in moments such as when a thick layer of dirt and a decrease in generation efficiency are observed (FIGURE 60). In locations with frequent rainfall, like the case study area, it is often unnecessary to clean the modules as rain, combined with the module tilt, naturally removes accumulated dust.

Figure 60 - Example of dirty modules and clean modules

Source: Authors (2024)

In order to clean the PV modules, it is advisable to hire a specialized third-party company. During the cleaning process, it is essential to ensure that the system is not in operation, the strings are open-circuited, and cleaning should not be conducted during rain or lightning storms. Cleaning can potentially damage the modules and other system components. The encapsulation material and glass that compose PV modules provide protection against electrical shock when they are intact. However, if cracked or broken, the module's integrity is compromised, leading to a loss of electrical insulating properties and posing a risk of electrical shock.

Additionally, when cleaning the modules, care should be taken with the cleaning products to prevent spillage onto the ground, which could impact the crops below.

Another component that may require preventive maintenance is the **electrical board**. Insects, small rodents, and bird droppings can enter the boards, so periodic cleaning is necessary to maintain their good condition. Cleaning can be performed every six months or as determined by assessments and need.

Initially, a visual inspection of the boards should be conducted, and if only surface dirt is observed, farmers can perform the cleaning themselves using a soft brush or sponge. However, any more severe damage or maintenance requiring alterations to connections and electrical components should be carried out by a specialized company. Maintenance should preferably be conducted at dawn or dusk to avoid disrupting production. It is recommended not to perform this procedure during rain, drizzle, or lightning storms. To minimize the risk of electrical shock, electrical boards cleaning should be carried out with the systems de-energized.

Other safety guidelines

Regarding agricultural activities beneath the system, an important note is to avoid working beneath the system during extreme weather events. Also, during module cleaning, there should be caution regarding the use of cleaning agents to prevent any impact on the crops.

5.6 Conclusions

The agrivoltaic project in this case-study would directly support 4 riverside families and impact 82 consumer families, as well as it would support organic production and agroforestry practices in the Amazon region. Also, the project would financially support the operation of the industrial kitchen, which will enhance and add value to these families' production.

In this study, the primary focus was on the implementation of small-scale agrivoltaic systems tailored to the specific needs of small-scale farmers. While it is evident that the initial cost of these systems is slightly higher than that of conventional photovoltaic (PV) setups, the design of the systems was proposed in order to align with the economic realities of these farmers, as well as their resource availability. In this context, wooden structures were employed as a cost-effective and locally accessible solution.

In total, the 2 topologies proposed in the study consist in 15,4 kWp and would generate 21,2 MWh of electricity yearly. One of the key findings of this study is that the final capital expenditure (CAPEX) for agrivoltaic systems, although higher than that of conventional PV systems, remains within a reasonable range. This suggests that the financial barrier of adopting agrivoltaics may not be significantly greater for small-scale farmers, especially when considering the long-term benefits.

In the economic analysis, productivity loss scenarios were considered, and even in the one that considered 20% loss in agricultural production, the results would be considerably lower than the energy savings with the implementation of the project. The economic indicators, such as the discounted Payback period of 7 years and 10 months for the scenario of 100% farmers investment, resulted in numbers that closely resemble those of conventional PV systems, reinforcing that agrivoltaics can be an economically feasible choice for small farmers looking to integrate renewable energy generation with agricultural activities.

The positive results of the study show that the agrivoltaic systems have synergy with "shared energy" business models, which can benefit from the existing association structure. In Brazil, this model refers to the practice of multiple consumers collectively generating renewable energy, often through solar panels, and the surplus is distributed back to the grid for others to use, in this case, in the occasion of expansion of the project in future years, the future agrivoltaic system's surplus energy could benefit the individual energy expenses of other families from the association.

One relevant topic for further investigation is the quantification of the impact of agrivoltaic systems on agricultural productivity. Future studies should seek to determine whether these systems positively contribute to crop yields or, conversely, if there are any related productivity loss in association with specific crops. This would provide important insights into the implications of agrivoltaics on the small-scale farmers ecossystem and the sustainability of their agricultural practices.

6. Conclusions and Recommendations for agrivoltaics within the Brazilian context

Considering the Brazilian context, this section focuses on providing recommendations for best practices in future agrivoltaic systems. It encompasses technical and agricultural recommendations for large and small-scale agricultural practices highlighting the main potentials of each national macro region, highlighting the most suitable designs for agrivoltaic systems. It also presents recommendations on best agricultural practices and policies incentives to promote agrivoltaics systems in Brazil.

Considering **large-scale agricultural** systems, these are led in Brazil by soybeans, corn, sugarcane, rice, coffee and beans. These six agricultural products accounted for over 70% of the total cultivated land in Brazil from 1985 to 2017 and are mainly located in the regions of Central-West, and some in the Southern and Southeastern regions. Large-scale agriculture is one of the main contributors to the Gross Production Value of the country. However, only few benefit from the income generation of the so-called modern agriculture as that 8% of rural establishments are responsible for generating 85% of the agricultural value. As large-scale agriculture occupies a considerable extension of land for agricultural and livestock production, it is understood that for this context, when considering business models, agrivoltaic systems for generating energy for the open market might be more suitable. However, the open market it is a very complex market where usually only big players from the electricity market get involved. Furthermore, with the electrification of transport and eventually all machinery involved in agriculture (i.e. trucks, tractors, etc.), energy demands in agriculture are expected to increase and energy self-production and self-sufficiency will be an important aspect in the agricultural landscape in the near future.

Agrivoltaic systems applied to the large-scale agriculture should be more robust and consist of taller structures that allow large machinery to pass through. In addition, increasing the spacing between PV modules to allow greater distribution of irradiation in the crop can be also a good practice when applying the agrivoltaic technology large-scale agriculture and monocultures like soy and sugarcane. See Figure 61 for an example.

Figure 61 - Overhead system with large machinery in Italy

Source: REM TEC (2024)

Large-scale agriculture also encompasses the beef cattle industry, and it is widely developed across all states and ecosystems, particularly in the Central-West and Southeast regions. The beef cattle industry is directly related to the increase in deforestation in some regions of the country, and, besides that, it can cause soil degradation and it is responsible for high fractions of CO_2 emissions to the atmosphere. Agrivoltaic applications for livestock production could become an option to increase animal welfare and support the promotion of more sustainable practices in this branch of large-scale agriculture. PV vertical applications for animal fencing should also be considered as a potential agrivoltaic application for livestock production (FIGURE 62).

Figure 62 - Bifacial, vertically installed PV modules for fencing applications

Source: Next2Sun (2019)

On the other side of the spectrum, small-scale and family farming, represents 77% of agricultural establishments in Brazil, supplies approximately 70% of the food consumed by the Brazilian population and plays a significant role in job creation as it employs about 10.5 million people, representing over 70% of the workforce in the Brazilian agricultural sector. Establishments characterized as family farming are prevalent in the Northern and Northeastern regions, where rural poverty presents its highest levels in the country. Considering the proven benefits of agrivoltaic systems, such as protection from extreme heat and irradiation, reducing evaporation and the need for irrigation, these systems show a potential match with the climate and social characteristics of the Northeast region.

For small-scale farmers, the current legal framework for distributed generation provides them means to generate their own energy through the electricity compensation system, adapting the solar energy technology to an agrivoltaic application. Therefore, agrivoltaic systems present social and economic opportunities for family farmers by offering greater autonomy in energy generation for self-consumption and the potential to create them an income aggregation through leasing or generating energy credits through the distributed generation system.

In terms of policy incentives for the development of the agrivoltaic technology in Brazil, some recommendations include:

- Elaborate a national guideline and/or legal framework that regulated the agrivoltaic technology in the country. This guideline/legal framework should be aligned with the Law 14300;
- Provide R&D project funding to advance research on the subject and assess the potential of agrivoltaics in the country, taking into account the country's regional diversity and seeking to identify the potential and particularities of each region;
- Create credit lines for family farming (including electrification of all transport and machinery involved in farming) that supports agrivoltaic installations for this public;
- Promote teacher training programs on agrivoltaic technolovy at federal institutes and other educational institutions.

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