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PROSPECT OF PHOTOVOLTAIC SOLAR SYSTEMS FOR AGRICULTURAL IRRIGATION IN THE STATE OF GUANAJUATO, MEXICO

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ABSTRACT

This work analyzes the current situation of solar photovoltaic (SPV) systems for agricultural irrigation in the state of Guanajuato, Mexico, with an emphasis on their technical and economic challenges. It also describes the water resource management system in Mexico and in the state, its main uses, and the applicable regulations. Based on a summary of agricultural production statistics, Guanajuato is positioned as one of the country's main producers, and the prospects for SPV systems for irrigation are examined. It also provides an overview of their advantages, disadvantages, and drawbacks. As a result, it identifies poor management of both water resources and SPVs for irrigation, which is the main contribution of the study, given the scarce or inaccurate information available in the literature and at different levels of government on the development, implementation, and projections of this technology in the state.

Keywords: agricultural pumping, water resources.

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INTRODUCTION

In the state of Guanajuato, agriculture depends heavily on the use of wells for irrigation due to the scarcity of surface water resources. Statistics on agricultural wells show intense activity in this sector, with more than 15,000 registered wells. Approximately 84% of the water extracted is used for agriculture, demonstrating its importance for production in the region (CONAGUA, 2024a). However, water resource management faces challenges such as overexploitation of aquifers, where extraction exceeds natural recharge and causes annual deficits. This situation has forced state and municipal authorities to implement restrictions and regulations on the use of wells to preserve water resources in the long term and ensure agricultural sustainability in the state.

The vast majority of wells used for agricultural irrigation use electricity from the general distribution networks, whose dealers have two rates subsidized by the government. The first rate, called "Low Voltage Agricultural Irrigation" (RABT, from the Spanish *Riego Agrícola en Baja Tensión*), applies exclusively to low voltage services that use energy for pumping irrigation water to agricultural land and for lighting the premises where it is installed (CFE, 2024a). Basically, it establishes a rate similar to those called "Low Voltage Domestic 1 and 2" (DB1 and DB2, from the Spanish *Doméstica en Baja Tensión 1* and 2) (CFE, 2024b). The second rate, "Medium Voltage Agricultural Irrigation" (RAMT, from the Spanish *Riego Agrícola en Media Tensión*), is similar to the RABT rate, with the difference that it applies to medium voltage services (CFE, 2024c).

On the other hand, the reduction in the cost of solar photovoltaic (SPV) system components has led the agricultural sector to increasingly focus its attention on this technology for pumping irrigation water, especially on farms without low- or medium-voltage electricity supply infrastructure (DNV, 2023). Negera *et al*. (2025) evaluated how SPVs impact the economy and food security of small producers in Ethiopia, obtaining promising results. For their part, Yusuf and Sanusi (2025) analyzed the reliability, availability, and profitability of small-scale SPVs.

In Mexico, Guevara *et al*. (2025) presented an economic and environmental analysis of the implementation of SPVs in approximately 3,500 chinampas in Xochimilco, Mexico City, demonstrating that it is possible to reduce operational costs by 60 to 70%. Molina *et al*. (2025) propose the "Parcelas 5.0" technology, which integrates photovoltaic energy, rainwater harvesting, precision agriculture, and vertical agriculture to optimize productivity and sustainability in small plots, representing one of the most innovative advances by integrating monitoring technologies. To date, no research or case studies have been reported for the state of Guanajuato, despite the presence of photovoltaic systems for agricultural irrigation, which represents a significant area of opportunity.

Among the main challenges to expanding the adoption of this technology are the training of farmers in its operation and maintenance, as well as ensuring the availability of components and repair services in rural areas. In addition, it is essential to develop cost-effective energy storage solutions that provide a continuous water supply for irrigation, even under conditions of low or no solar irradiation. Another important challenge concerns land use, since the installation of SPV modules can reduce the area available for cultivation. Therefore, proper integration into the agricultural environment, together with government policies that promote incentives to facilitate initial investment and address these challenges in a comprehensive manner, is required.

This article provides a documentary study of the current situation of agricultural irrigation from underground wells in the state of Guanajuato. The water resource management scheme and its associated regulations are briefly described. Moreover, aiming at highlighting the importance of irrigation systems, the state is positioned nationally according to its agricultural production, and the potential of SPV energy to transform the sector, increasing its efficiency and sustainability, is emphasized. This constitutes the main contribution of this work, given that, both in the literature and at different levels of government, there is little or no information on the development

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Review Article

and prospects of this technology in the state's agricultural sector, even though its promotion is already contemplated in public policies.

WATER RESOURCES MANAGEMENT, USE, AND REGULATIONS

Management systems

For stakeholders in the SPV sector applied to agricultural pumping, understanding the water resource management framework is essential, as project development requires fulfilling the administrative procedures necessary to demonstrate compliance with the main regulatory requirements. Water resource management in Mexico is organized into a hierarchical structure that includes various entities and agencies.

The National Water Commission (CONAGUA, from the Spanish *Comisión Nacional del Agua*) is the authority responsible for water administration and management at the national level, responsible for establishing water policies and coordinating actions at different levels. The Basin Organizations, under CONAGUA, operate in different river basins to implement policies at the regional level. In each basin, Basin Councils function as participatory and consultative bodies, composed of users, local governments, and civil organizations, which advise on decision-making. Irrigation Districts and Technified Rainfed Districts manage agricultural water use in specific areas under the supervision of the Basin Organizations. Finally, the Groundwater Technical Committees manage, protect, and monitor aquifers at the local level.

There are 13 river basin organizations that encompass the 37 hydrological regions of the country (Figure 1) (CONAGUA, 2018). The state of Guanajuato is located

Figure 1. Distribution of basin organizations and hydrological regions in Mexico (CONAGUA, 2018).

within the jurisdiction of the Lerma-Chapala River Basin Organization, which covers the Lerma River and Lake Chapala basins. The state also encompasses three main irrigation districts: District 011, known as “Alto Río Lerma”; District 085, “La Begoña”; and District 087, “Rosario-Mezquite.” This organization and distribution aim to achieve more effective water management in a region where water resources are vital for agriculture.

In Mexico, as of 2020, 39% of the water volume allocated to consumptive uses (those in which the resource is not fully returned to its source or is discharged in a different form or location, such as in domestic, industrial, or livestock uses) was extracted from groundwater sources, while the remainder came from surface sources. During the period 2005–2020, groundwater withdrawals increased (Figure 2) from 36.3% to 39.4% (CONAGUA, 2024c). Of the total percentage withdrawn from groundwater sources, the state of Guanajuato is part of a group of six states that account for 45%.

Figure 2. Volume of water used nationally by source type (CONAGUA, 2024c).

Water uses

Agricultural use is the most prevalent, accounting for 67.52% of the total national volume. During the period 2005–2020, its use for this sector increased by 11%, with national water use growing from 54.41 to 60.46 thousand hm^3 (cubic hectometers) (Figure 3). Of the total volume, 50.51% is concentrated in the states of Sinaloa, Sonora, Chihuahua, Michoacán, Tamaulipas, and Guanajuato (CONAGUA, 2024c). In particular, in the state of Guanajuato (Table 1), there are more underground concessions than surface concessions (CONAGUA, 2024d, 2024e).

When comparing the volume granted (Table 1) and the volume of water consumed (Table 2), clear overexploitation of aquifers can be observed, putting the availability of this resource at risk for future years. Hence, the importance of strengthening public policies for more effective management and monitoring. On the other hand, given the increase in groundwater extraction, the potential for development that SPVs can achieve for agricultural pumping can be visualized.

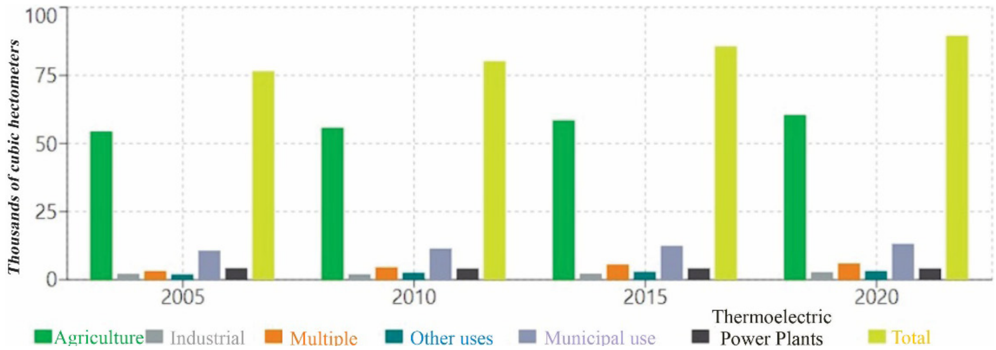

Figure 3. Evolution of water use volume by sector in Mexico (2005–2020) (CONAGUA, 2024c).

Table 1. Water concessions registered in the state of Guanajuato by type and volume (CONAGUA, 2024d, 2024e).

Type of concession	Number of concessions	Authorized Volume (hm^3 $year^{-1}$)	Observations
Groundwater	6412	1960	High dependence on groundwater; several overexploited aquifers.
Surface	1734	510	They depend heavily on annual availability, with variability depending on the climate.

Table 2. Annual consumptive water use for agriculture in Guanajuato, Mexico (2019-2023) (CONAGUA, 2022; IEE, 2024).

Year	Consumptive water use (hm^3)
2019	3850.5
2020	3910.7
2021	3965.2
2022	4010.3
2023	4050.6

Regulations for the use and management of water

Mexican legislation has established a comprehensive regulatory framework aimed at ensuring the sustainability and efficiency of water resource use, which must be considered and complied with by developers of SPV pumping projects, regardless of client requirements. The National Water Law constitutes the cornerstone of this framework, as it establishes the guidelines related to the exploration and exploitation of the nation's water resources (Chamber of Deputies, 2023). It also defines the mechanisms through which both the public and private sectors can request the use and exploitation of water.

In this context, the law distinguishes between allocation and concession: the allocation corresponds to the entitlement granted by the Federal Executive Power, through CONAGUA or the respective Basin Organization, to municipalities and states for the exploitation, use, or management of water resources; whereas the concession refers to the same type of entitlement, but granted to individuals or legal entities, whether public or private. According to Article 20, "concessions and allocations shall be granted after considering the parties involved and the economic and environmental cost of the planned works." The validity of these entitlements is established for a period ranging from 5 to 30 years, with the possibility of extensions for equivalent terms under similar conditions.

The law stipulates that the granting of a concession or allocation shall take into account the average annual water availability, which is reviewed at least every three years by CONAGUA and published through the National Water Information System (CONAGUA, 2024b). Once an allocation or concession has been granted, it will not be possible to dispose of greater volumes of water, and to permanently increase or modify water extraction in terms of volume, flow, or specific use, the issuance of the respective concession or allocation title must invariably be processed.

Moreover, the law also specifies the cases in which CONAGUA shall impose administrative sanctions on the responsible parties, highlighting the following: (a) exploiting, using, or managing national waters without the corresponding entitlement; and (b) exploiting, using, or managing national waters in volumes greater than those authorized. In both cases, fines are established ranging from 1,950 to 26,000 Units of Measurement and Update (UMAs, from the Spanish *Unidad de Medida y Actualización*), a general economic reference unit in Mexico used instead of the minimum wage for various legal and administrative purposes, which at the time this documentary research was conducted, corresponded to between 89,095 and 1,187,940 MXN.

It was found that various public agencies lack information or do not possess updated and accurate data, particularly regarding the number of concessions, the volume of water granted under concession, and current consumption levels. However, the data presented result from the consultation of several sources, which show an adequate degree of consistency among them. Therefore, it is imperative that the applicable regulations be refined and that the institutions responsible for their enforcement carry out field investigations to generate and/or update their databases, thereby enabling the implementation of appropriate management actions.

SUMMARY OF AGRICULTURAL PRODUCTION STATISTICS

According to data consulted from 2024, the state of Guanajuato ranks among the leading agricultural producers nationwide (FAO, 2024; USDA, 2024). The cultivated

area has reached 966,000 ha, of which 473,000 ha are under irrigation conditions, representing 48% of the total (Guzmán-Soria *et al*., 2009; SADER, 2024; SIAP, 2024). In terms of agricultural production, values of 9,189,000 Mg have been reached by 2023, of which 8,061,000 Mg were obtained under irrigation conditions, representing 87.72% of total production, which highlights the importance of pumping systems for irrigation.
In the state, various crops such as wheat, alfalfa, asparagus, and strawberries have seen significant increases in their yield per hectare (Figure 4). In recent years, the area planted in Guanajuato has shown a downward trend, but with an increase in productivity, especially under irrigation conditions, reflecting the technification of the sector.

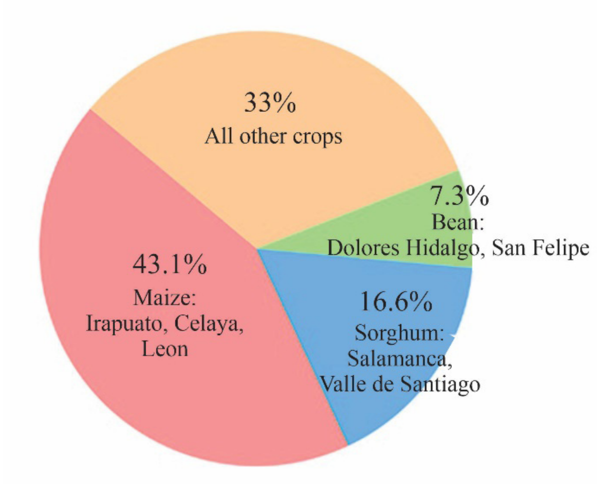

Figure 4. Percentage distribution of land area planted by crop in Guanajuato, Mexico, in 2023 (SIAP, 2024).

SOLAR PHOTOVOLTAIC SYSTEMS IN AGRICULTURE

The use of these systems in agricultural irrigation pumping has gained relevance due to their potential to reduce energy costs and promote sustainability (Cota-Espericueta *et al*., 2004; Walston *et al*., 2022; Carrausse and de Sartre, 2023). The state of Guanajuato has intense agricultural activity and is positioned advantageously in terms of solar radiation compared to other states in the country. Although no minimum average solar radiation values have been established for the development of an SPV (Matsumoto *et al*., 2014), Mexico has recorded a minimum average value of 4.14 kWh m^{-2}.
However, variability in solar energy availability poses a significant challenge. In Guanajuato, average irradiation is between 5 and 6 kWh m^{-2}, placing it in a competitive range nationally for solar energy projects (NASA, 2024). The efficiency of SPVs depends directly on the available sunlight, so days with low irradiation can affect farmers' ability to ensure a constant and sufficient supply of water, especially for crops that require continuous and uniform irrigation.

When applied to agricultural pumping, the high initial investment in solar modules, controllers, and pumps limits their adoption by small and medium-sized farmers without access to financing or subsidies, especially in rural communities where economic resources are scarce. Although the costs of SPV modules have decreased in recent years, the initial investment remains a barrier.

Although these systems require less maintenance than traditional fossil fuel-powered pumps, regular inspections and maintenance are still necessary to ensure optimal performance. The durability of components such as solar modules and pumps can be compromised by extreme environmental conditions, including high temperatures. This can result in the need for more frequent repairs or replacements, adding additional costs and complications for farmers.

Another challenge lies in the lack of technical knowledge and training among farmers on how to operate and maintain solar pumping systems. The successful adoption of this technology requires a level of technical skill and understanding that many farmers do not possess. The lack of training programs and technical assistance can limit the effectiveness and sustainability of the systems. Farmers need to be equipped with technology and knowledge to troubleshoot when necessary. Moreover, integrating these systems into traditional agricultural practices requires changes in farmers' habits and mindset, which can be a slow and challenging process.

Grid-connected systems

SPVs are classified as grid-connected or off-grid systems. The former allows farmers to continue operating on cloudy days or at night, as the grid provides a constant source of energy. However, despite government incentives, the initial installation of a grid-connected system can be costly, significantly affecting its profitability and return on investment times.

In most of the references consulted, it is mentioned that it is possible to sell surplus energy generated to the grid, which can result in a significant reduction in energy costs (Sarr *et al.*, 2023). However, given the operating paradigm of the electricity market in Mexico, this is not possible, as the prices set for the purchase of surpluses are far from competitive, being based on the average value of the local marginal price and therefore do not represent a significant income for systems under 0.5 MW (DOF, 2017). Dependence on the grid means that, in the event of grid failures, supply may be interrupted.

Off-grid systems

Off-grid SPVs are particularly useful in rural areas of the state where grid connection is limited or non-existent, allowing farmers to operate independently. Furthermore, by not relying on the grid, farmers are not subject to electricity price fluctuations or potential power outages. However, these types of systems face operational, economic, and regulatory challenges.

Their generation capacity depends on weather conditions and the efficiency of the modules, which may be insufficient to meet annual energy demand, especially during periods of intensive irrigation if they are not adequately sized. Added to this is the high cost of battery storage, which significantly increases the initial investment and maintenance costs. However, recent studies have demonstrated the viability of these installations (Babatunde *et al*., 2020).

Brief cost comparison

Mérida-García *et al*. (2019) and Mantri *et al*. (2023) demonstrated that grid-connected SPVs have a lower levelized cost of energy (LCOE) compared to off-grid systems; however, both systems have lower LCOEs than those using fossil fuel generators. On the other hand, subsidized RABT and RAMT rates represent a significant barrier to the development of grid-connected SPVs, since a detailed analysis of the LCOE of these systems shows that their profitability depends on multiple factors, including installation and maintenance costs, and fluctuations in energy generation due to weather conditions.

The subsidized RABT rate is very similar to the DB1 and DB2 rates (Table 3). On the other hand, the RAMT rate has lower costs compared to the "General Medium-Voltage High-Demand" rate (GDMTO, from the Spanish *Gran Demanda en Media Tensión Ordinaria*) and "Hourly Medium-Voltage High Demand" rate (GDMTH, from the Spanish *Gran Demanda Media Tensión Horaria*) rates (CRE, 2024). Specifically, concerning the capacity charge, the RAMT rate is 42.48% and 48.93% lower than the corresponding charges for the GDMTO and GDMTH rates, respectively. As a result, when access to the electricity grid is available, it becomes evident that agricultural producers prefer a pumping system supplied by the grid rather than considering the option of SPV systems.

Table 3. Results of the consultation on final basic supply rates for the Bajío region 2024 (All values are expressed in Mexican pesos), (CRE, 2024).

Rate	Description	Schedule	Fixed charge $/month	Variable energy charge $/kWh	Variable charge for capacity $/kWh
DB1	Domestic Low Voltage up to 150 kWh-month	NA	36.26	2.2275	0.550
DB2	Domestic low voltage greater than 150 kWh-month	NA	36.26	2.0545	0.547
RABT	Low Voltage Agricultural Irrigation	NA	36.6	1.9876	0.634
RAMT	Medium Voltage Agricultural Irrigation	NA	362.6	0.9746	268.3
GDMTO	General Medium-Voltage High-Demand	NA	362.6	1.642	466.47
GDMTH	Hourly Medium-Voltage High Demand	Base Medium High	362.6	1.1199 2.0050 2.2872	525.42

Additional Challenges of SPV Systems in the Agricultural Sector

Another critical consideration in the implementation of these systems within the agricultural sector is land use. Traditional systems can occupy significant areas, thereby reducing the land available for crop cultivation. This issue is particularly important in Guanajuato, where agricultural land represents a highly valuable resource. Effective implementation also requires careful planning to prevent shadows cast by the photovoltaic modules from decreasing agricultural productivity. Alternatives such as the use of non-arable land or floating structures on water bodies have been proposed as viable strategies to mitigate land-use impacts.

On the other hand, water resource management in the state represents an increasing challenge, particularly in terms of controlling and monitoring wells used for agricultural irrigation in rural areas that are difficult to access. Government institutions face serious difficulties in obtaining accurate data on these wells, due to a combination of complex factors.

One of the effects is the illegal exploitation of aquifers. In Guanajuato, clandestine wells have been drilled by farmers to secure a water supply, especially in regions where availability is limited (CONAGUA, 2024f). This unregulated use has led to significant overexploitation of aquifers, contributing to an alarming decline in groundwater levels in several areas of the state. Furthermore, insecurity in some regions prevents authorities from accessing these wells to carry out inspections and regulatory activities, as the state has experienced an increase in violence linked to organized crime.

The lack of control not only exacerbates the overexploitation of aquifers but also jeopardizes the sustainability of agriculture in the state. As a result, agricultural productivity in Guanajuato could reach precarious levels if these problems are not solved. The water crisis may affect not only food production but also the local economy, which depends mostly on agriculture. The need to implement effective regulation and conservation policies is becoming increasingly important to ensure the future of agriculture in the region.

Public policies for the development of SPV systems

In Mexico, the implementation of SPV systems for water pumping has been actively promoted. During the 2013–2015 period, the Shared Risk Trust Fund under the Ministry of Agriculture, Livestock, Rural Development, Fisheries, and Food supported the installation of 52 SPV systems, of which 41 were implemented in dairy farms, four in ecotourism facilities, three in the agricultural sector, three in agro-industrial operations, and one in swine facilities. The systems generate approximately 2,405 MWh per year, preventing the emission of 1,200 Mg of CO_2 into the atmosphere.

Recently, the Sectoral Program for Agriculture and Rural Development 2020–2024 (SADER, 2020) established the foundations for promoting renewable energies within "Priority Objective 3: Increase sustainable production practices in the agricultural and aquaculture-fisheries sector in response to agro-climatic risks," and specifically under "Priority Strategy 3.2: Promote adaptation and mitigation actions to climate change for comprehensive risk management; Specific Action 3.2.5: Encourage the use of and transition to renewable energies in agricultural, aquaculture, and fisheries activities."

As a result of these public policies, the National Commission for Arid Zones has promoted solar pumping through shared financing schemes. For example, in Quintana Roo, more than 2,487 SPV modules for agricultural pumping have been installed, benefiting at least seven communities. In turn, the Government of the State of Guanajuato, through the Ministry of Agriculture, Food, and Rural Development, and the Ministry of Agriculture and Rural Development (SADER, from the Spanish *Secretaría de Agricultura y Desarrollo Rural*), continually issues calls for proposals to access funding aimed at improving productivity in the agricultural sector, which includes the implementation of alternative energy sources.

However, as mentioned previously, greater knowledge is required to take advantage of these programs for the development of SPV systems applied to agricultural water pumping. Based on the authors' experience in conducting this research, there is a lack of information from the Mexican government and federal entities regarding the promotion, development, and installation of these types of systems. When addressing the development of the agricultural sector, most of the reported results focus on water harvesting, increased crop productivity, and managed subsidies, including the electricity rate subsidies, while overlooking the outcomes derived from the implementation of renewable energy sources.

PERSPECTIVE ON PVS SYSTEMS FOR AGRICULTURAL IRRIGATION IN THE STATE OF GUANAJUATO

The state of Guanajuato has experienced an 85% growth in distributed electricity generation capacity during the 2022–2024 period, ranking fourth nationwide, with an installed capacity of 290 MW (GTO, 2025a). Recently, five off-grid SPV systems with storage have been implemented in locations without access to electricity from the Federal Electricity Commission (CFE, from the Spanish *Comisión Federal de Electricidad*) grid. Such is the case of the community of El Refugio, where two of these systems were installed to power brick production kilns, one system in the Cuenca La Esperanza protected natural area, and two systems in Sierra de Lobos; however, their installed capacity is not reported (GTO, 2025b).

As a relevant outcome of the present research, it was found that there is no available information that would allow the establishment of a perspective or the performance of statistical or comparative analyses with other entities and/or countries. Government data only provide estimates regarding the number of well concessions, the volume of water granted under concession, and current consumption levels. The situation is even more critical in the case of information related to SPV systems for agricultural irrigation. For grid-connected systems, the CFE only reports data on interconnection requests without distinguishing those intended for agricultural irrigation. In the case of off-grid systems, there is no organization or bibliographic source that provides related data or information.

To overcome the aforementioned limitations, it is necessary to implement a series of strategic actions aimed at strengthening the management and utilization of SPV systems applied to agricultural irrigation. First, it is proposed to design and implement a national system for registration and monitoring of these systems, integrating key information such as their location, installed capacity, configuration type (off-grid or grid-connected), associated water source, and both electricity and water consumption volumes. Likewise, it is essential to establish inter-institutional coordination between the CFE, CONAGUA, SADER, the National Energy Commission (formerly called Energy Regulatory Commission), and state and municipal governments to integrate and standardize the available data on water concessions, energy consumption, and photovoltaic technologies used in the agricultural sector.

Another priority measure is the incorporation of a specific category for agricultural use within the official reports on distributed generation and interconnection requests issued by CFE, which will allow for the clear identification of SPV systems intended for irrigation. Likewise, it is necessary to promote the development of technical studies and specialized surveys led by academic institutions and public organizations to obtain reliable and up-to-date data on the adoption, efficiency, and sustainability of these technologies in the agricultural sector. Finally, it is proposed to strengthen mandatory technical and operational reporting mechanisms as a requirement to access financial support, subsidies, or permits, ensuring the continuous update of a public, systematized, and periodically maintained database.

The implementation of these actions will enable, in the short and medium term, the performance of qualitative and quantitative analyses on SPV systems for agricultural irrigation in the state, thereby strengthening technical decision-making and the formulation of more effective and sustainable public policies in the agricultural sector.

CONCLUSIONS

In Guanajuato, agriculture relies primarily on groundwater well irrigation, which has led to the overexploitation of aquifers and recurring annual water deficits. Illegal well drilling and lack of supervision due to rural insecurity further exacerbate the challenges to agricultural sustainability. On the other hand, the use of SPV systems for agricultural water pumping has gained relevance as a sustainable alternative to address energy and environmental challenges. The high solar irradiance in the state favors the development of SPV systems; however, the high initial investment limits their adoption, particularly among small and medium-sized producers without access to financing.

Although off-grid SPV systems have been implemented in areas without access to the electricity network, the lack of specific information limits their evaluation and planning in agricultural irrigation. The available data do not allow for an accurate determination of the number, capacity, coverage, or efficiency of the systems used for irrigation. This information gap hinders the development of technical assessments, international comparisons, and the design of effective public policies. Consequently, it is essential to establish institutional mechanisms for the collection, systematization, and publication of disaggregated data to enable more effective monitoring and promotion of solar energy adoption in the agricultural sector.

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