PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, **C**OST, **O**PTIMIZATION, **S**IMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

Energy-Based Design of Agrivoltaic Irrigation Systems for Corn and Bean Crops under Different Climatic Conditions in Mexico

***M. D. Duran-Garcia*[a]*, Alma Chavez*[b]*, Bernd Weber*[c] *and Eduardo Gonzalez*[d]**

[a] *Facultad de Ingeniería, Universidad Autónoma del Estado de México, México,*
e-mail:mddurang@uaemex.mx
[b] *Instituto de Ingeniería, UNAM, CDMX, México, e-mail:AChavezM@iingen.unam.mx*
[c] *Facultad de Ingeniería, Universidad Autónoma del Estado de México, México,*
e-mail:bweber@uaemex.mx
[d] *Facultad de Ingeniería, Universidad Autónoma del Estado de México, México,*
e-mail:egonzalezmo@uaemex.mx

Abstract:

Irrigated agriculture in Mexico faces two primary challenges: escalating pressure on water resources and a sustained increase in energy demand related to water extraction and conveyance. Integrating photovoltaic (PV) systems into irrigation pumping systems offers a promising technological alternative to reduce environmental impacts and improve the energy sustainability of the agricultural sector.

In this paper, a preliminary, integrated modelling tool was developed to optimize the sizing of agrivoltaics systems for corn and bean plots across diverse climatic regions of Mexico. The methodology estimates water requirements using the FAO Penman-Monteith approach, incorporating crop-specific coefficients for each phenological stage and accounting for theoretical evapotranspiration during the dry season. Based on these calculations, irrigation flow rates, required pumping power, and the optimal capacity of the photovoltaic system are determined through hourly simulations of solar radiation and ambient temperature.

The analysis was conducted at three representative sites—Jalisco, Veracruz, and Chiapas—disclosing significant variation in total evapotranspiration and water volumes required per crop. Results indicate that the required pumping power ranges from 3.22 to 6.9 kW per hectare, which can be achieved with relatively small photovoltaic arrays, even under challenging climatic conditions. These findings demonstrate the potential for PV systems to replace or supplement fossil energy sources, thereby directly reducing fossil-based electricity consumption. Environmentally, the implementation of these systems leads to a substantial reduction in greenhouse gas emissions associated with agricultural irrigation and promotes more efficient water use by better aligning water demand, pumping operations, and energy supply.

Additionally, the proposed approach enables the evaluation of controlled deficit irrigation strategies, which are especially relevant for bean cultivation, and expands decision-making beyond the sole objective of maximizing production. The study demonstrates that employing sizing tools based on seasonal simulation and actual climate data offers a substantial improvement over simplified methods that rely on averages.

Keywords: Agrivoltaic Systems, FAO Penman-Monteith approach.

1. Introduction

Corn and beans are the staple crops of the Mexican diet; however, their production faces increasing challenges due to water resource pressures and natural disasters. According to national statistics, more than a half of the corn consumed in Mexico is imported, while bean production reaches 85% food self-sufficiency. The main problem is that most of these crops are rainfed, particularly for corn, where this exceeds 65%.

The Mexican government has proposed strategies to achieve food self-sufficiency in these grains. These strategies include modernization of agricultural practices and intensifying irrigated crops, replacing rainfed ones. However, this intensification of traditional irrigation systems increases water stress and leads to significant dependence on fossil fuels, with substantial environmental, economic, and vulnerability impacts. To support farmers in installing irrigation systems, programs such as the Special Energy Program for Agriculture (PEUA) have been established, offering subsidies of up to 95% of the electricity costs used for pumping and repumping water for irrigation. However, access to this subsidy is subject to specific requirements that prevent many farmers from benefiting [1]. For this reason, many farms use gasoline-powered pumping systems, which are unsustainable and have high greenhouse gas emissions.

On the other hand, programs such as FIRCO support small and medium-sized producers in incorporating mitigation and adaptation measures to address the effects of climate change, with the aim of implementing sustainable production practices in the agricultural sector, such as PV pumping systems.

Other public policies established by the National Commission of Arid Zones have promoted photovoltaic pumping with financing schemes. Under these schemes, more than 2,487 PV pumping systems were installed in Quintana Roo, demonstrating the feasibility of generating megawatt-scale power and supplying water to dozens of hectares of farmland, significantly reducing greenhouse gas emissions.

Furthermore, several studies analyze the feasibility of installing agrivoltaic systems, including that of [2] Robles-Lecona et. al., who examine the general perspectives on the potential of photovoltaic systems for irrigation in states like Guanajuato, highlight the technical and economic challenges inherent in implementing PV technologies in this context. Other studies, such as that of [3] presented an economic and environmental study of implementing photovoltaic systems in more than 3,000 *chinampas* in Xochimilco, Mexico. This study analyzed the implementation of gasoline-powered pumping systems and PV systems, demonstrating more than a 60% reduction in operating costs and a 100% reduction in greenhouse gas emissions from system operation. Likewise, some of the studies analyzed indicate that one of the main challenges in the expansion of agrivoltaic systems is the lack of knowledge about technology, the high cost of the initial investment, and the lack of simple tools for their proper sizing [2].

In this regard, several tools exist for designing PV irrigation systems. Internationally, Muhsen et al. [4] (2017) conducted a review of the design and control methods for photovoltaic water pumping systems (PVPS), covering modeling, reliability, operating strategies, and field performance. This work concludes that the self-sizing of PV systems is also relevant. More recently, Mahmoud et. al. [5] presented an online pre-sizing tool for solar photovoltaic pumping systems, tested and validated through more than 30 real-world cases, and compared with commercial tools such as PVsyst [6]. This tool calculates the size of the PV system and performs techno-economic analyses. Finally, recent studies analyzing the design of PV systems for humid tropical climates highlight the importance of considering the variability of water demand at the seasonal and phenological stages of the crop, an approach that is still relatively unexplored in the literature and constitutes a central contribution of this study [7].

It is observed that integrated tools for sizing PV systems exist internationally; however, as Maity R. et al. [7] noted, most of these tools do not account for water demand at each phenological stage of the crop, nor the effect of temperature on PV system performance.

Meanwhile, in Mexico, there are works such as that of [8] who present a tool that uses climate- and evapotranspiration-based models to justify the experimental-scale design of a PV irrigation system for jalapeño pepper cultivation.

However, there are no tools available to optimize the performance of PV systems in agricultural applications for corn and beans according to Mexico's water requirements. Scientific literature focused on this context is still emerging.

Furthermore, in Mexico, there is a knowledge gap regarding integrated sizing tools that simultaneously consider the water needs of crops, local climate variability, solar availability with hourly data, and territorial criteria (such as distance to bodies of water and the electrical grid) to comprehensively evaluate the technical, energy, and environmental viability of agrivoltaics irrigation systems in Mexico. Addressing this gap is fundamental to supporting small and medium-sized producers in making efficient and sustainable technological decisions.

Considering the context above, the current administration in Mexico has established new programs, such as *Sembrando Vida*, which aims to achieve food sufficiency, mainly for the most important crops, corn and beans. This program includes the use of bio-inputs and bioremediation agents, as well as the modernization of agriculture, including automated irrigation systems that utilize existing water bodies or treat and reuse wastewater from nearby communities. However, without tools to properly size the irrigation system, this will lead to increased water stress and the agricultural sector's dependence on fossil fuels.

The presented work is part of the project “Decision Matrix for Technology Selection and the Design of Agricultural Irrigation System Models for Small and Medium-Sized Maize and Bean Producers in Mexico,” sponsored by the SECIHTY with the Sembrando Vida program, whose main objective is to promote sustainable production systems that increase the well-being of small producers through agroecological practices and appropriate technologies for water and energy management in rural areas. This paper proposes a preliminary methodology for estimating water needs for maize and beans using the FAO Penman-Monteith method [9] and the CROPWAT 8.0 software [10], incorporating crop-specific coefficients for each phenological stage and accounting for theoretical evapotranspiration during the dry season. Based on these calculations, irrigation flow rates, required pumping power, and the optimal capacity of the photovoltaic system are determined through hourly simulations of solar radiation and ambient temperature.

2. Materials and Methods

The incorporation of smart irrigation systems powered by photovoltaic solar energy has been identified as a viable alternative to reduce water-pumping energy costs, improve the energy autonomy of production units, and decrease emissions associated with fossil-fuel use. Thus, this study draws on the work of Rodríguez and Vidal y Gamboa [8,11], who designed and implemented small-scale solar drip irrigation systems based on the phenology of jalapeño pepper cultivation in Cosamaloapan, Veracruz, using the Penman-Monteith method to estimate evapotranspiration. Based on this reference, the same Penman-Monteith method, as well as the CROPWAT software, is used to estimate evapotranspiration and water requirements. Subsequently, the[9] Irrigation and photovoltaic systems are evaluated under different climatic conditions in Mexico. This analysis is performed for native corn and bean crops in 3 selected locations with different climates and soil conditions: Veracruz, Chiapas and Jalisco.

2.2. Selected locations

As mentioned, in this study, three pilot plots were selected, and monitoring systems were installed. This will allow future studies to validate the assumed theoretical variables and adjust their values using this data. Table 1 shows the geographical locations of the study sites.

Table 1. *Location of the installations selected.*

Location name	Town	Latitud	Longitud
Rancho YIK	Emiliano Zapata, Chiapas	16.553555	-92.926633
La Barca	Jalisco	20.235194	-102.59086
Rancho Casa Blanca	Acayucan, Veracruz	18.016778	-95.035556

The calculation of irrigation and pumping needs considered planting 1 hectare of land during the dry season with a drip irrigation system, and the coverage of irrigation water needs using well water at a depth of 40 meters.

2.2. Methodology description

For calculating crop irrigation demands and scheduling, the single-coefficient methodology proposed in the FAO Manual 56 [9]and in the FAO CROPWAT simulation software, version 8.0 [10], was used. Figure 1 shows a diagram of the methodology employed.

The meteorological data required to calculate reference evapotranspiration were obtained from validated satellite-based sources, such as the National Renewable Energy Laboratory [11]. The aforementioned meteorological data allow us to obtain the water and pumping requirements for each crop plot, enabling us to determine the energy needs and size the PV system. Subsequently, a comparative analysis of energy consumption is performed, comparing average indices with the potential savings achievable through a more precise analysis.

Finally, a comparative analysis is also conducted with other irrigation technologies, such as sprinklers, to compare energy consumption.

In parallel, the assessment of the energy resource was carried out by analyzing solar irradiance data at high temporal resolution, which enabled estimation of the equivalent solar hours and the energy available for the photovoltaic system. This information was subsequently coupled with the energy demand derived from water requirements, allowing a direct correspondence to be established between the availability of solar energy and the water-pumping needs throughout the agricultural cycle.

Unlike previous approaches, such as the one proposed by [8] Rodríguez-Chiunti in which system sizing is based on average conditions or static water demand scenarios, the methodology developed in this work incorporates a dynamic representation of both water demand (through ET_c per phenological stage) and the energy resource (through hourly irradiance), allowing for more precise sizing that is adaptable to variable climatic conditions. This methodological integration improves the estimation of required power, optimizes the size of the photovoltaic system, and allows for the evaluation of more energy- and water-efficient operating strategies.

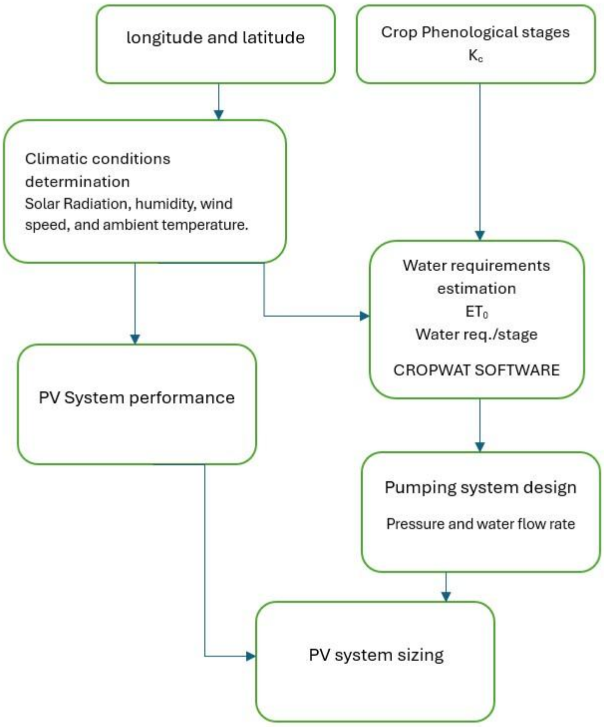

Figure. 1. *Methodology diagram*

2.2.1. Water requirement determination

Evapotranspiration is a simultaneous process through which a cultivated area loses water through evaporation from the soil and transpiration from the foliage. To determine its value, it is first necessary to determine the evapotranspiration of a reference crop, in this case, grass (ET_0) without water restrictions. For calculating ET0, the FAO proposes the Monteith method [9], which determines the evapotranspiration index for a given location, based on climatic conditions, using the following equation:

$$ET_0 = \frac{0.408\Delta(R_N - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{1}$$

Where:

ET_0= Reference Evapotranspiration (mm).

R_n= Net solar radiation on the crop surface (MJ/m^2).

G= Albedo radiation (MJ/m^2).

T= Mean temperatura at 2 m high (°C).

u_2= Wind velocity (m/s).

$e_s - e_a$=Vapor pressure deficit(kPa).

Δ= slope of the vapor pressure curve(kPa)

γ=psychometric constant(kPa)

Solar radiation, relative humidity, wind speed, and temperature values were obtained from satellite data via the NSRDB platform [12] considering the CONUS region for the year 2024. Using this data, the CROPWAT program, which already includes the aforementioned model, was applied to each location listed in Table 1. This software also allows determination of irrigation requirements based on phenological stages and crop yield coefficients, as well as on precipitation and soil moisture retention. This enables a more precise estimate of water requirements at each stage of plant growth.

For the present work, the phenological stages and crop coefficients for maize proposed by [13] were considered, which are described in Table 2. For the bean, crop coefficients and phenological stages were also determined based on what was proposed by FAO [14] and are shown in Table 3.

Table 2. *Phenological stage and crop coefficient for a typical intermediate variety of corn [13]*

Phenological Stage	Crop coefficient (Kc)	Average duration
Emergence	0.3	12
4 leaves	0.4	34
8 leaves	0.85	37
12 leaves	0.98	14
Bloom	1.12	13
Corn ear growth	1.25	15
Aqueous grain	1.2	17
Milky grain	1.1	11
Doughy grain	1	11
Dented grain	0.85	7
Maturity	0.3	8
Harvest	0.2	11
TOTAL		

Table 3. *Phenological stage and crop coefficient for a typical intermediate variety of bean [14]*

Phenological Stage	Crop coefficient (Kc)	Average duration
Initial	0.4	20
Crop development	0.4-1.15	30
Mid season	1.15	40
Late season	0.35	20
TOTAL		110

Regarding rainfall, the periods with the lowest precipitation in 2024, as reported by CONAGUA (2026) for a meteorological station near the analyzed location, were considered. This was done to analyze water requirements under the most unfavorable conditions and avoid undersizing the system.

The aforementioned data are fed into the program, enabling a more precise determination of water requirements at each growing season and phenological stage.

With the determined water requirements, the irrigation flow rate for each phenological stage can be obtained. To determine the maximum flow rate, the average water requirement will not be considered, but rather the water requirement during the most critical period, since this ensures that the water needs in the other periods are met.

2.2.2. Energy pumping calculation

To size the pumping system, determine the required flow rate. For this purpose, the phenological stage with the highest water demand, presented in Tables 4 and 5, was adopted as the design condition. A drip irrigation system was considered because it uses water more efficiently and requires lower pressure and flow rates, thereby reducing energy consumption and, consequently, the PV system.

Table 4. *Water requirements for maize in the different locations. [14]*

Etapa	**Kc**	**Stage Duration (Days)**	**Period**	**Rancho Yik Chiapas**		**Acayucan Veracruz**		**La barca Jalisco**	
				Water Req. mm/day	Water Req /stage	Water Req. mm/day	Water Req /stage	Water Req. mm/day	Water Req /stage
Emergence	0.3	12	1-12 Oct	1.61	19.32	1.83	21.96	0.75	9
4 leaves	0.4	34	12 Oct-15Nov	1.79	60.86	2.3	78.2	2.65	90.1
8 leaves	0.85	37	15Nov-22Dec	3.80	119.14	2.79	103.23	3.10	114.7

12 leaves	0.98	14	22Dec-13Jan	3.49	53.2	2.32	32.48	2.88	40.32
Bloom	1.12	13	13-26 Jan	3.55	47.32	3.28	42.64	2.82	36.66
Corn ear growth	1.25	15	26 Jan-11Feb	3.61	55.8	3.47	52.05	2.83	42.45
Aqueous grain	1.2	17	11Feb-28Feb	3.62	58.14	3.37	57.29	2.94	49.98
Milky grain	1.1	11	28Feb-11Mar	3.41	34.54	2.43	26.73	2.84	31.24
Doughy grain	1	11	11Mar-22Mar	3.14	33.22	1.82	20.02	2.71	29.81
Dented grain	0.85	7	22Mar-2April	3.01	19.95	2	14	2.53	17.71
Maturity	0.3	8	2April-9April	2.83	21.12	2.34	23.6	2.34	18.72
Harvest	0.2	11	9April-20april	1.8	19.69	1.9	20.9	1.95	21.45
				Total	542.3	Total	503	Total	504.01

Table 5. *Water requirements for beans in the different locations. [14]*

Etapa	Kc	Stage Duration (Days)	Period	Rancho Yik Chiapas		Acayucan Veracruz		La barca Jalisco	
				Water Req. mm/day	Water Req /stage	Water Req. mm/day	Water Req /stage	Water Req. mm/day	Water Req /stage
Initial	0.4	9	1-9 Oct	1.61	14.5	0.40	3.6	0.75	3.6
Initial	0.4	10	9-19 Oct	1.55	15.5	1.59	15.9	2.65	4.6
Development	0.53	10	19-29 Oct	2.13	21.3	1.86	18.6	3.1	14.7
Development	0.79	11	29 Oct-9Nov	2.50	27.5	1.76	19.4	2.88	22.6
Development	1.04	10	10Nov-20Nov	3.42	34.2	2.44	24.4	2.82	27.9
Med	1.15	10	21Nov-1Dec	3.64	36.4	2.64	26.4	2.83	29.7
Med	1.15	10	2-12Dec	3.49	34.9	2.42	24.2	2.94	27.6
Med	1.15	10	13-23 Dec	3.34	33.4	2.19	21.9	2.84	25.8
Final	1.15	11	23 Dec-2 Jan	3.39	37.3	2.59	28.5	2.71	28.9
Final	0.89	10	3-13 Jan	2.63	26.3	2.40	24	2.53	20.8
Final	0.89	9	13-22 Jan	1.47	13.2	1.48	13.3	2.34	10.8
				Total	294.5	Total	220.2	Total	217

Gravity irrigation was not considered because, although it has very low energy consumption, its water use efficiency is very low, barely 50%, while drip irrigation has an efficiency of 90 to 95%. This undoubtedly translates into a very significant saving in the amount of water applied and electricity used. Furthermore, this system allows for the injection of other inputs (fertilizers, herbicides, insecticides, etc.), significantly improving their efficiency and enabling the use of lower, more controlled doses. This indirectly reduces environmental impacts [15]. On the other hand, an irrigation system widely used in corn cultivation is sprinkler irrigation, which offers advantages such as simpler installation; however, it suffers evaporation losses and is less efficient than drip irrigation. This method is not considered in this study, but a comparison of energy consumption is presented at the end.

Thus, the literature suggests that sprinkler irrigation requires less frequent, larger applications, while drip irrigation uses smaller, more frequent applications because the system wets only a fraction of the soil volume and aims to maintain relatively stable moisture in the root zone near the emitter. The FAO describes localized irrigation as a method of applying small volumes at frequent intervals, with the frequency ranging from every 2–4 days initially to even daily under conditions of higher evaporative demand [16].

Irrigation scheduling was based on the water balance approach proposed by the (See Table 6). Intervals of 4–6 days were defined for initial stages, 3–4 days during vegetative development, and 1–2 days during critical stages of higher evaporative demand, thus ensuring a continuous water supply to the root zone and minimizing crop water stress.

Table 6. *Drip irrigation scheduling for maize and beans [16]*

Maize		**Beans**	
Stage	Drip Irrigation Scheduling Days	**Stage**	Drip Irrigation scheduling Days
Emergence	6	Initial	3
4 leaves	5	Development	3
8 leaves	4	Medium	2
12 leaves	3	Final	2
Bloom	3		
Corn ear growth	3		
Aqueous grain	2		
Milky grain	2		
Doughy grain	2		
Dented grain	3		
Maturity	5		
Harvest	6		

These irrigation schedules are used to calculate the required flow rate during the critical stage. For the calculation of pumping requirements, a well of 40 m depth and average head losses of 20 m along the entire irrigation pipe of the plots considered were considered. These considerations are theoretical; however, they can be adjusted to actual data measured in the plots. The pumping power was determined with eq. (2):

$$P = \frac{\rho g Q H}{\eta} \tag{2}$$

Where: Q is the water flow rate, H is the total height, considering losses, and η is the pump efficiency.

2.2.3. PV System determination

The methodology used to determine the power output of a photovoltaic panel throughout the year is based on a performance model that accounts for actual weather conditions and solar geometry. The process begins with input data from NREL [10], where the global horizontal irradiance (GHI) values in W/m² and the ambient temperature were filtered and prepared at a temporal resolution of 30 minutes over 365 days. This data enabled calculation of the cosine of the solar incidence angle, a critical factor that varies with the day and time and affects the irradiance incident on the module. Using the aforementioned data, the photovoltaic cell temperature (Tc) was estimated, correcting the ambient temperature based on the GHI and the cell characteristic factor (S in °C/W/m²). Finally, the instantaneous power delivered by the module was calculated by adjusting the nominal peak power (Ppeak) using the module's temperature factor and the actual conditions (GHI and Tc) relative to the standard test conditions (STC). This procedure was applied iteratively to the entire database to obtain the complete annual power profile. For this project, the most common photovoltaic modules on the market, with a power output of 550 W, were considered.

3. Results

The analysis presented here demonstrates the need to use the actual water requirements of crops as the basis for sizing the pumping and PV systems. As mentioned previously, this article uses the critical condition as the basis: the highest daily water requirement per stage, as described in Table 4 for corn and Table 5 for beans, multiplied by the irrigation interval, prioritizing the most critical stages: the initial and development stages.

Based on the criteria described above, for maize, the critical condition of “8 leaves” is used for the 3 locations. For this critical condition, the design flow rate per hectare was estimated under a drip-irrigation scheme, as shown in Table 7.

***Table 7.** Drip irrigation scheduling for maize and beans*

Location	Irrigation interval (days)	Water Vol. per Day (m³/ha·día)	Water Vol. per aplication (m³/ha·día)
Rancho Yik, Chiapas	4	38.0	152.0
Acayucan, Veracruz	3	27.9	111.6
La Barca, Jalisco	4	31	124.0

Subsequently, two alternative irrigation time intervals were considered to meet the daily water requirement: 6 and 8 hours. With these irrigation intervals, the flow rate and power requirements shown in Table 8 can be determined. It can be observed that, even when considering the same type of crop and the same size of land, there is a significant variation in the flow rate and pumping power required for each location. Thus, for an irrigation period of 6 hours, the highest flow rate occurs in Rancho Yik, Chiapas, with a value of 25.33 m3/h, while the lowest value is in Acayucan Veracruz with 11.57 m3/h. These differences are due to the soil and climatic conditions of each analyzed location.

***Table 8.** Maize water flow and power requirement*

Location	Water flow required for irrigation (m³/ha)	Volume rate 6h (m³/h)	Power requirement 6h (kW)	Volume rate 8h (m³/h)	Power requirement 8h (KW)
Rancho Yik, Chiapas	152.0	25.33	6.90	19.00	5.18
Acayucan, Veracruz	111.6	18.6	5.06	14.00	3.8
La Barca, Jalisco	124.0	20.67	5.63	15.50	4.22

Using the same criteria as for maize, the critical irrigation stages for beans were determined for each location. These were the third stage of development for Chiapas and Veracruz, and the first stage for Jalisco. For this critical condition, the water requirements per application were estimated (see table 9) and the flow rates, also considering 6 and 8 hours of irrigation period, as well as the power; these results are shown in table 10.

***Table 9.** Drip irrigation scheduling for beans*

Location	Irrigation interval (days)	Water Vol. per Day (m³/ha·día)	Water Vol. per aplication (m³/ha·día)
Rancho Yik, Chiapas	3	34.2	102.6
Acayucan, Veracruz	3	24.4	73.2
La Barca, Jalisco	3	21.3	93.0

***Table 10.** Beans water flow and power requirement*

Location	Water flow required for irrigation (m³/ha)	Volume rate 6h (m³/h)	Power requirement 6h (KW)	Volume rate 8h (m³/h)	Power requirement 8h (KW)
Rancho Yik, Chiapas	102.6	17.1	4.66	12.8	3.5
Acayucan, Veracruz	73.2	12.2	3.32	9.15	2.5
La Barca, Jalisco	93.0	15.5	4.22	11.63	3.16

Subsequently, the number of PV modules required to supply the pumping system's power and the photovoltaic panel's nominal power (550 W) was calculated, taking into account temperature losses and module efficiency. Under this criterion, the systems for maize ranged from 7 to 16 modules (see figure 2), while for beans they ranged from 5 to 11 modules (see figure 3), depending on location and daily operating window. It can be observed that, although the same head losses, depth of the water body, and dimensions of the plot were considered, the amount of energy required and, therefore, the amount of PV modules required is different. For example, in the case of maize, Rancho Yik, Chiapas, has the most unfavorable situation, requiring 16 modules for 6 h of irrigation, while La Barca has a power requirement of 5.63 kW, representing only 13 modules. These results show the importance of making an accurate estimate based on satellite, climatic and soil parameters.

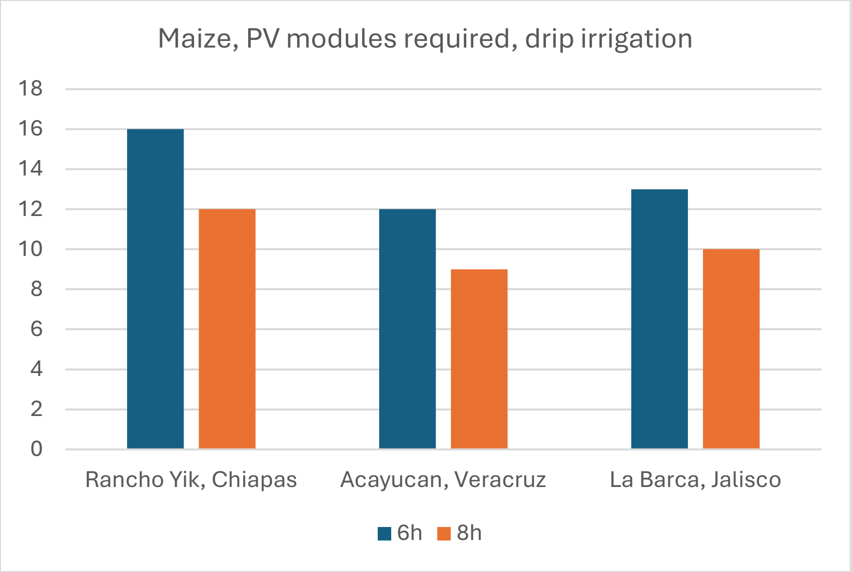

Figure. 2. *PV modules required for the drip irrigation of 1 hectare of maize, for the three locations*

Finally, a comparison is made of the power required and the need for PV modules for the typical system used for the irrigation of maize and beans in Mexico, which has a water and energy consumption of approximately 20% more and a drip irrigation system. This comparison is shown in Figure 4. (FAO, 1989).

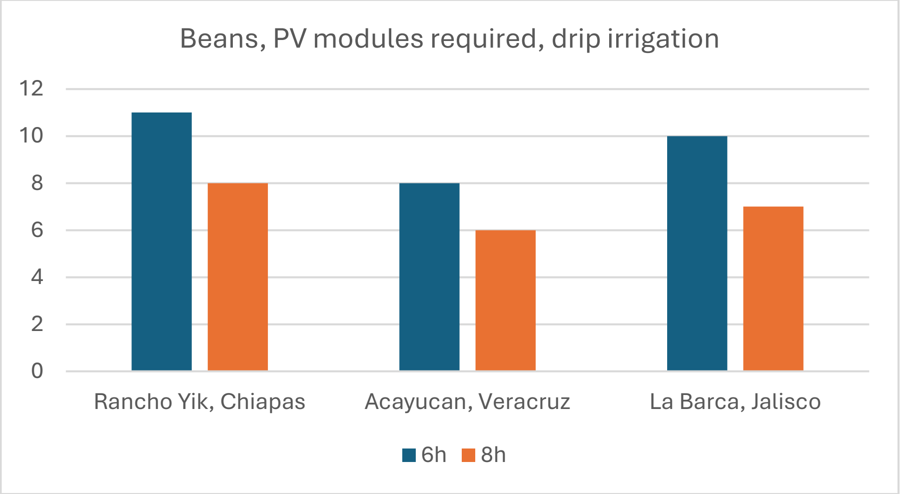

Figure. 3. *PV modules required for the drip irrigation of 1 hectare of beans, for the three locations*

It can be observed that energy consumption is higher, due to the greater pumping pressure required and the volume of water; this significantly increases the size of the PV system, and consequently the area of land that this system will occupy and which, in a way, competes with the cultivated land.

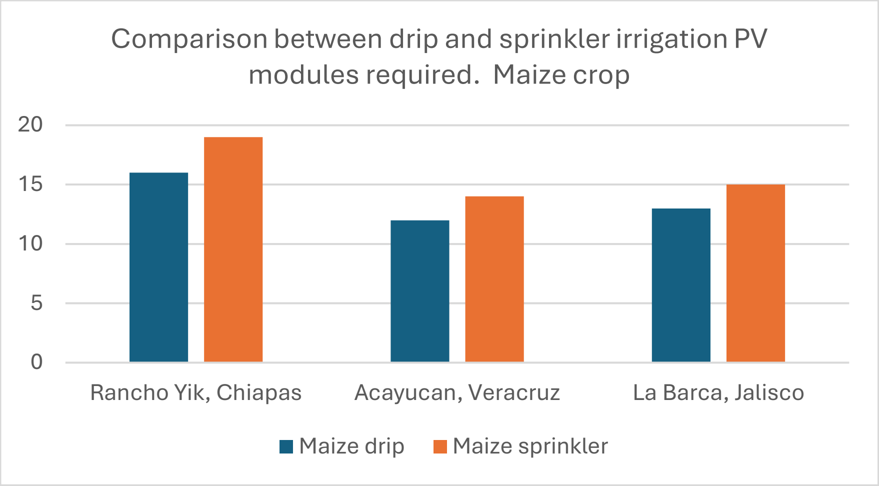

Figure. 4. *Comparison of PV modules required for the drip and sprinkler irrigation of 1 hectare of maize, for the three locations*

Conclusions

This study presents a methodology for designing agrivoltaic irrigation systems by integrating crop water requirements and solar energy availability across different climatic conditions in Mexico. The approach combines the FAO Penman–Monteith method, including crop coefficients for each phenological stage, with a photovoltaic performance model based on high-resolution climatic data.

The results show that estimating water demand from phenological stages yields more accurate irrigation requirements, directly affecting the calculation of flow rates and pumping power. For the cases analyzed, pumping power requirements range from 3.22 to 6.9 kW per hectare, depending on location and irrigation scheduling, which is an affordable value for small farmers. These differences result in photovoltaic system sizes ranging from 5 to 16 modules.

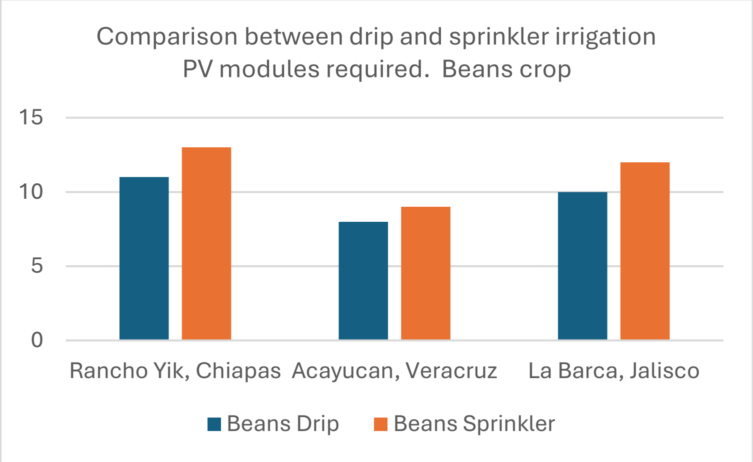

Figure. 5. *Comparison of PV modules required for the drip and sprinkler irrigation of 1 hectare of beans, for the three locations*

The analysis also shows that, even under the same design conditions in terms of cultivated area, well depth, and head losses, energy requirements vary significantly due to climatic and soil conditions. This confirms the importance of considering site-specific parameters in the design of photovoltaic irrigation systems, instead of relying on simplified or average-based approaches.

In conventional irrigation system design, average flow values are frequently used as a general criterion for preliminary sizing. Typical values reported in the literature range from 5 to 7 m³/h per hectare [17], assuming continuous operation (24h). However, the results obtained in this study show that, when irrigation is applied within limited daily operating periods and based on peak crop water demand, the required flow rates can exceed those estimated using average values. This indicates that the use of generalized flow criteria without considering local climatic conditions and crop development stages may lead to under-dimensioning of pumping systems or inefficient water application.

In addition, the comparison between irrigation technologies indicates that drip irrigation requires lower flow rates and pumping power than sprinkler systems, which leads to smaller photovoltaic systems and more efficient use of both water and energy.

Overall, the proposed methodology provides a practical tool for estimating water and energy requirements for irrigation systems under different climatic conditions. Its application can support the design of more efficient systems adapted to local conditions. Furthermore, it can be adapted to include accurate information on nearby water sources, such as reclaimed water from nearby communities, and to calculate pumping power and energy requirements.

For future work, validating the estimated evapotranspiration and water requirements against field data is recommended to refine the model and improve its applicability under real operating conditions.

Acknowledgments

The authors express their gratitude to the Project “Decision Matrix for Technology Selection and the Design of Agricultural Irrigation System Models for Small and Medium-Sized Maize and Bean Producers in Mexico,” sponsored by the SECIHTY with the Sembrando Vida Program

References

[1] Gobierno de México. Energía para el Campo en Materia de Energía Eléctrica de Uso Agrícola 2025. https://www.gob.mx/agricultura/colima/articulos/programa-especial-de-energia-para-el-campo-en-materia-de-energia-electrica-de-uso-agricola-peua-352368#:~:text=Las%20y%20los%20participantes%20deber%C3%A1n,30%20de%20noviembre%20de%202023.&text=Copia%20del%20%C3%BAltimo%20recibo%20de,legal%20(s%C3%B3lo%20personas%20morales). (accessed March 11, 2026).

[2] Robles-Lecona E., Gutiérrez-Martínez V., Zamora-Cárdenas E. Prospect of photovoltaic solar systems for agricultural irrigation in the state of Guanajuato, MEXICO. Agrociencia 2025:1–16. https://doi.org/10.47163/agrociencia.v59i8.3420.

[3] Guevara M, Manzini F, Sánchez-Juárez A. Technical and economic analysis for the implementation of photovoltaic systems in agricultural zones of Mexico City: A case study. Energy for Sustainable Development 2025;87:101743. https://doi.org/10.1016/j.esd.2025.101743.

[4] Muhsen DH, Khatib T, Nagi F. A review of photovoltaic water pumping system designing methods, control strategies and field performance. Renewable and Sustainable Energy Reviews 2017;68:70–86. https://doi.org/10.1016/j.rser.2016.09.129.

[5] Mahmoud IM, Ashraf A, Hatem A, Abdellatif SO, Ghali HA. Pre-sizing online tool for photovoltaic water pumping system: development, testing, validation, and evaluation. Discover Sustainability 2024;5:15. https://doi.org/10.1007/s43621-024-00198-2.

[6] RATEDPOWER. PVSys. Software 2026. https://ratedpower.com/compare/pvsyst/ (accessed April 18, 2026).

[7] Maity R, Sudhakar K, Razak AA. Agri-solar water pumping design, energy, and environmental analysis: A comprehensive study in tropical humid climate. Heliyon 2024;10:e39604. https://doi.org/10.1016/j.heliyon.2024.e39604.

[8] Rodríguez Chiunti MÁ, Vidal Gamboa A. Diseño de un sistema de riego solar fotovoltaico para la evaluación de la fenología en chile jalapeño. Tendencias En Energías Renovables y Sustentabilidad 2022;1:150–7. https://doi.org/10.56845/terys.v1i1.150.

[9] R. Allen LPDR and MS. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. 1998.

[10] FAO. CROPWAT COMPUTER PROGRAM. Software 1992. https://www.fao.org/land-water/databases-and-software/cropwat/en/ (accessed April 18, 2026).

[11] Rodríguez-Flores JM, Medellín-Azuara J, Valdivia-Alcalá R, Arana-Coronado OA, García-Sánchez RC. Insights from a Calibrated Optimization Model for Irrigated Agriculture under Drought in an Irrigation District on the Central Mexican High Plains. Water (Basel) 2019;11:858. https://doi.org/10.3390/w11040858.

[12] NATIONAL LABORATORY OF THE ROKIES. NSRDB: National Solar Radiation Database. Database 2025. https://nsrdb.nlr.gov/data-viewer (accessed April 18, 2026).

[13] Ritchie S, Hanway J, Benson G. How a corn plant develops. Special report. Ames: 1992.

[14] FAO. Bean Crop Information. Land and Water 2026. https://www.fao.org/land-water/databases-and-software/crop-information/bean/en/ (accessed April 17, 2026).

[15] Bahena-Delgado G, Broa-Rojas E, Vázquez-Sánchez J, Morales-Soto M, Delgado-Escobar I, Sainz-Aispuro M. SUSTENTABILIDAD DEL AGUA EN LA PRODUCCIÓN DE MAÍCES CRIOLLOS EN XALOSTOC, MORELOS, MÉXICO. Agricultura, Sociedad y Desarrollo 2009;6:197–205.

[16] Prins K, Heibloem M. Irrigation Water Management. FAO TRAINING MANUAL 1989. https://www.fao.org/4/t7202e/t7202e00.htm#Contents (accessed April 18, 2026).

[17] FAO. CROP WATER INFORMATION. Land & Water Database 2025.