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CONTACTS

Phone: **+998 50 737 87 88**

Website: https://ist-journal.uz

Email: innovationist2025@gmail.com

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ESTIMATING ELECTRICITY CONSUMPTION OF PUMPING PLANTS IN IRRIGATION SYSTEMS

Urishev Omadjon
Fergana State Technical University, Doctoral Student (DSc),
Department of Electronics and Instrumentation (PhD Program), Fergana, Uzbekistan
ORCID: 0009-0005-5728-554X

Ersin Akyuz
Balıkesir University, Head of the Renewable Energy Research,
Application and Development Center (DSc), Balıkesir, Turkey
ORCID: 0000-0001-9786-3221

Gul Metin
Balıkesir University, Researcher at the Renewable Energy Research,
Application and Development Center (PhD), Balıkesir, Turkey
ORCID: 0000-0003-2388-6927

Quvonchbek Quvondiqov
Tashkent State Transport University, PhD Student,
Department of Engineering Communications and Systems, Tashkent, Uzbekistan
ORCID: 0000-0001-6896-5990
Email: orishevomadjon@gmail.com

Abstract: This study presents a crop-focused approach to understanding electricity use in drip-irrigated farming systems supported by photovoltaic pumping. By linking crop water needs with irrigation efficiency, hydraulic conditions, and pump operation, the framework captures energy demand at both plant and system levels. The findings show that energy requirements vary notably across crop types, mainly due to differences in biological water demand and cultivation patterns. When applied to a mixed-crop irrigation layout, the approach confirms that total energy demand is largely shaped by crop composition and irrigated area. Solar-based pumping was found to be technically capable of meeting irrigation energy needs, while drip irrigation demonstrated clear energy-saving advantages over traditional surface methods.

Key words: drip irrigation; crop-based energy assessment; photovoltaic pumping; LCOE; Water–Energy–Food Nexus.

Annotatsiya: Ushbu tadqiqotda fotoelektrik nasoslar bilan ta’minlangan tomchilatib sug‘orish tizimlarida elektr energiyasi iste’molini baholashga qaratilgan ekinlarga yo‘naltirilgan yondashuv taklif etiladi. Ekinlarning suvga bo‘lgan ehtiyoji, sug‘orish samaradorligi, gidravlik sharoitlar va nasoslarning ish rejimlarini o‘zaro bog‘lash orqali metodika energiya talabini ham alohida o‘simlik, ham tizim darajasida aniqlash imkonini beradi. Natijalar shuni ko‘rsatadiki, energiya talabi ekin turlariga qarab sezilarli darajada farqlanadi, bu asosan biologik suv ehtiyoji va yetishtirish xususiyatlari bilan bog‘liq. Aralash ekinli sug‘orish tizimiga qo‘llanganda, umumiy energiya sarfi asosan ekin tarkibi va sug‘oriladigan maydon hajmi bilan belgilanadi. Quyosh energiyasiga asoslangan nasos tizimlari sug‘orish uchun zarur bo‘lgan energiyani texnik jihatdan to‘liq ta’minlay olishi aniqlangan, tomchilatib sug‘orish esa an’anaviy yuzaki sug‘orish usullariga nisbatan sezilarli energiya tejamkorligini namoyon etdi.

Kalit so‘zlar: tomchilatib sug‘orish; ekinlarga asoslangan energiya baholash; fotoelektrik nasos tizimlari; energiyaning keltirilgan qiymati (LCOE); Suv–Energiya–Oziq-ovqat uyg‘unligi.

Аннотация: В данном исследовании представлен ориентированный на культуры подход к анализу потребления электроэнергии в системах капельного орошения с использованием фотоэлектрических насосных установок. Связывая водные потребности сельскохозяйственных культур с эффективностью орошения, гидравлическими условиями и режимами работы насосов, предложенная методика позволяет оценивать энергопотребление как на уровне отдельного растения, так и на уровне всей системы. Полученные результаты показывают, что потребность в энергии существенно различается между культурами, главным образом вследствие различий в биологических потребностях в воде и особенностях возделывания. Применение подхода к смешанной системе орошения подтвердило, что суммарное энергопотребление в значительной степени определяется составом культур и площадью орошаемых земель. Установлено, что солнечные насосные системы технически способны полностью покрывать энергетические потребности орошения, а капельное орошение обеспечивает заметную экономию энергии по сравнению с традиционными поверхностными методами.

Ключевые слова: капельное орошение; оценка энергопотребления по культурам; фотоэлектрические насосные системы; приведённая стоимость электроэнергии (LCOE); концепция «Вода–Энергия–Продовольствие».

INTRODUCTION

In recent years, the efficient use of water and electrical energy resources in agricultural production has emerged as one of the most significant global priorities. Rapid population growth, ongoing climate change, and increasing pressure on limited water resources have intensified the need to adopt energy-efficient and technologically advanced irrigation systems [1]. In this context, electricity consumption associated with irrigation processes constitutes a considerable share of total energy use within the agricultural sector.

The level of electrical energy consumption in irrigation systems is determined by several interrelated factors, including crop type, irrigation methods, characteristics of water sources, and the technical performance and operational efficiency of pumping units. A comprehensive assessment of these factors enables the optimization of energy use, improves system performance, and supports the sustainable development of agricultural water management practices.

LITERATURE REVIEW

The identification and evaluation of electricity consumption on a crop-specific basis represent a crucial step toward improving the efficiency and optimization of irrigation systems [2]. This approach is fully consistent with the Water–Energy–Food (WEF) Nexus framework, which emphasizes the sustainable and integrated management of natural resources to ensure long-term agricultural productivity [3].

Existing scientific literature predominantly assesses electrical energy consumption in irrigation systems based on parameters such as pumping head, irrigation technology, and crop water requirements. In many studies, energy demand is evaluated as an aggregated system load, whereas differentiation at the crop or plant level is addressed to a limited extent [4]. For example, Smith et al. analyzed the energy efficiency of irrigation pumping systems and demonstrated the relationship between water flow rate, pumping head, and electricity consumption [5]. However, their analysis was mainly conducted at the field or hectare scale, with relatively limited consideration of energy distribution among different crop types.

The methodology proposed by Allen et al. for estimating crop water requirements is widely applied in irrigation planning and management [6]. While this approach provides a robust basis for calculating irrigation demand, it primarily focuses on water balance components and does not explicitly incorporate electrical energy consumption. As a result, additional analytical and mathematical models are required to convert crop water requirements into corresponding energy demand estimates.

Recent studies on irrigation systems powered by photovoltaic (PV) pumps and hybrid renewable energy configurations generally evaluate energy performance at the system level [7]. In such studies, electricity consumption values for crops such as vegetables, cotton, or orchards are often reported in an aggregated form, which may limit the precision of crop-specific energy planning under real irrigation conditions. Several researchers have demonstrated that drip irrigation systems can reduce energy consumption by approximately 30–50 percent compared to conventional irrigation methods [8]. However, these improvements are typically assessed at the farm or field scale rather than on a per-plant basis.

In the context of Central Asia, and particularly under the agro-climatic and infrastructural conditions of Uzbekistan, comprehensive studies focusing on crop-specific electrical energy consumption in irrigation systems remain limited. Most existing research emphasizes water allocation strategies or the overall energy efficiency of pumping stations, while the integration of crop biological characteristics into energy assessment models is rarely addressed [9]. In contrast to previous studies, the present work evaluates irrigation energy consumption at the plant level and directly links it to the design and sizing of photovoltaic energy systems (Table 1).

Table 1. Literature review on the assessment of electrical energy consumption for irrigation systems based on crop types

Ref.	Author(s) – Year	Research Focus	Methodological Approach	Level of Energy Assessment	Identified Research Opportunities
[1]	—	Energy efficiency in agriculture	Integrated water–energy analysis with policy-oriented assessment	System level	Further refinement is needed to incorporate crop-specific electrical energy consumption into system-wide evaluations
[2]	—	Energy use in irrigation systems	Energy auditing of pumping stations	Pumping system level	Future studies may enhance accuracy by differentiating energy demand according to crop type
[3]	Bazilian et al. – 2011	Water–Energy–Food (WEF) Nexus	Conceptual integrated nexus framework	Regional level	The framework offers a strong foundation for developing practical crop-level irrigation energy calculation methods
[4]	Khan & Hanjra – 2009	Water and energy footprints in agriculture	Water–energy footprint analysis	Area (hectare) level	Additional methodological development could enable quantification of energy consumption at the individual crop level
[5]	Smith et al. – 2015	Energy efficiency of irrigation pumping systems	Hydraulic and energy performance analysis	System level	Incorporating crop type and biological water requirements would further strengthen energy efficiency assessments
[6]	Allen et al. – 1998	Crop water requirements	FAO-56 evapotranspiration model	Water balance level	The model provides a robust basis for linking crop water demand with corresponding electrical energy requirements
[7]	Reca & López-Luque – 2014	Solar-powered irrigation systems	Performance assessment of photovoltaic-driven pumps	System level	Future research could extend the analysis to include crop-specific energy allocation
[8]	Phocaides – 2007	Pressurized irrigation technologies	Comparative analysis of irrigation methods	Field level	Disaggregating energy consumption by crop type would improve the precision of field-level assessments
[9]	Karimov et al. – 2017	Irrigation systems in Central Asia	Water–energy resource assessment	Regional level	The development of crop-based electrical energy models would enhance regional irrigation planning and optimization

The analysis of scientific literature shows that the assessment of electricity consumption in irrigation systems has been studied at various levels by numerous researchers. In particular, the Water–Energy–Food (WEF) Nexus concept developed by Bazilian et al. (2011) established the theoretical foundations for the integrated management of water, energy, and food resources. Khan and Hanjra (2009) analyzed resource-use efficiency in agriculture through the assessment of water and energy footprints. Smith et al. (2015) evaluated the energy efficiency of irrigation pumping systems based on hydraulic parameters and identified the relationship between energy consumption and pumping head. In addition, the FAO-56 model proposed by Allen et al. (1998) serves as an important methodological framework for estimating crop water requirements. Solar-powered irrigation systems were further analyzed at the system level in the studies conducted by Reca and López-Luque (2014).

Based on the comprehensive review of the existing literature, several key research gaps can be clearly identified.

First, electrical energy consumption in irrigation systems has been predominantly assessed at the field or overall system level, while more detailed perspectives remain underexplored.

Second, methodological approaches for evaluating electricity consumption on a crop-specific basis are still at an early stage of development and require further refinement.

Third, there is a clear opportunity for the development of an integrated analytical model that systematically links crop water demand, pumping operation regimes, and electrical energy consumption within irrigation systems.

In response to these research needs, the present study aims to develop robust scientific and methodological foundations for assessing crop-based electrical energy consumption in irrigation systems. The calculated electrical energy consumption values per plant are in good agreement with the ranges reported in previous empirical studies

[5–8], thereby confirming the consistency and practical relevance of the proposed approach.

RESEARCH METHODOLOGY

2.1. Study Framework and General Approach

This study proposes a systematic and transferable methodology for evaluating electrical energy consumption in drip irrigation systems on a crop-specific basis. The approach integrates crop water requirements, hydraulic characteristics of the irrigation network, and the electrical energy demand of pumping units. The methodology is designed to be applicable to multiple crop types and remains independent of a specific geographical location.

The overall framework consists of four sequential stages:

(i) estimation of crop water demand;

(ii) calculation of irrigation water volume per crop;

(iii) assessment of pumping energy consumption;

(iv) aggregation of energy demand for multiple crops.

2.2. Estimation of Crop Water Requirements

Crop water demand is determined using a reference evapotranspiration-based approach. Crop evapotranspiration is calculated as:

$$ET_c = K_c \cdot ET_0 \quad (1)$$

where: ET_c - is crop evapotranspiration (mm/day), K_c - is the crop coefficient (–), and ET_0 - is reference evapotranspiration (mm/day).

For drip irrigation systems, the effective irrigation requirement is adjusted to account for irrigation efficiency:

$$IR_c = \frac{ET_C}{\eta_{ir}} \quad (2)$$

where: IR_c net irrigation requirement (mm/day); η_{ir} is the drip irrigation efficiency, typically ranging from 0.85 to 0.95.

2.3. Irrigation Water Volume per Crop and per Plant

The daily irrigation water volume required for a given crop area is calculated as:

$$Vc = IRc \cdot Ac \cdot 10^{-3} \quad (3)$$

where: Vc is the daily irrigation water volume for crop ccc (m³/day), and Ac - is the cultivated area of crop ccc (m²).

For plant-level energy assessment, the irrigation water volume per individual plant is expressed as:

$$V_p = \frac{V_c}{N_p} \cdot 10^{-3} \quad (4)$$

where: Vp – is the irrigation water volume per plant (m³/day), and N_p - is the number of plants.

2.4. Hydraulic Head of the Drip Irrigation System

The total dynamic head required by the pumping system is defined as:

$$Ht = Hs + Hf + He \quad (5)$$

where: Ht – is the total dynamic head (m), Hs – is the static head (m), Hf – represents friction losses in pipelines (m), and accounts for additional losses in emitters and fittings (m).

2.5. Electrical Energy Consumption of the Pumping System

The electrical energy required to pump irrigation water is calculated as:

$$Ec = \frac{\rho \cdot g \cdot H_t \cdot Vc}{\eta_p \cdot 3.6 \cdot 10^6} \quad (6)$$

where: Ec is the daily electrical energy consumption for crop c (kWh/day), ρ -is water density (kg/m³), g is gravitational acceleration (m/s²), and ;η_p - is the overall pump efficiency.

Electrical energy consumption per individual plant is given by:

$$Ep = \frac{E_c}{N_p} \quad (7)$$

where: Ep- is the electrical energy consumption per plant (kWh/day).

2.6. Multi-Crop Energy Aggregation

For irrigation systems serving multiple crop types, the total daily electrical energy demand is expressed as:

$$E_{total} = \sum E_c i \ (8)$$

where: Ec,i – is the electrical energy consumption of crop iii (kWh/day).

2.7. Average and Peak Electrical Power Demand

The average electrical power of the pumping unit is calculated as:

$$P_{avg} = \frac{E_{total}}{t_{op}} \quad (9)$$

where: P_{avg} – is the average electrical power (kW), and t_{op} – is the daily pump operating time (h).

To ensure reliable system operation, the design electrical power is defined as:

$$P_{des} = \frac{P_{avg}}{SF} \quad (10)$$

where: SF – is the safety factor, typically ranging from 0.8 to 0.9.

2.8. Photovoltaic (PV) Energy Production and System Sizing

The daily electrical energy demand from pumping is:

$$E_{day} = \sum E_c, i \quad (11)$$

Daily PV energy production is estimated as:

$$E_{PV} = P_{PV} \cdot PSH \cdot PR \quad (12)$$

where: E_{PV} is PV energy output (kWh/day), P_{PV} is installed PV capacity (kWp), PSH – represents peak sun hours (h/day), and PR – is the performance ratio (0.70–0.85).

The PV capacity required to meet daily energy demand is:

$$P_{PV} = \frac{E_{day}}{PSH \cdot PR} \quad (13)$$

$$PR = f_{temp} \cdot f_{dust} \cdot f_{cable} \cdot f_{inv} \cdot f_{mismatch}$$

If the performance ratio is expressed through loss coefficients:

$$P_{PV} = \frac{E_{day}}{PSH \cdot f_{temp} \cdot f_{dust} \cdot f_{cable} \cdot f_{inv} \cdot f_{mismatch}} \quad (14)$$

where: f_{temp} = 0.85-0.95, f_{dust} = 0.85-0.95, f_{cable} = 0.97-0.99, f_{inv} = 0.95-0.98, $f_{mismatch}$ = 0.98-0.99.

To enhance system reliability, a design margin is applied:

$$P_{PV} des = P_{PV} \cdot (1 + m) \quad (15)$$

2.9. PV Sizing for Direct and Battery-Integrated Pumping Systems

For direct PV pumping without battery storage, the average pump power requirement is:

$$P_{avg} = \frac{E_{day}}{t_{op}} \quad (16)$$

The PV system must satisfy:

$$P_{PV} \geq \frac{P_{avg}}{\eta_{inv} \cdot \eta_{mppt}} \quad (17)$$

where: η_{inv} is inverter efficiency and η_{inv} MPPT/controller efficiency.

For battery-integrated PV pumping systems, the required battery energy is:

$$E_{bat} = \frac{E_{night}}{\eta_{bat} \cdot \eta_{inv}} \quad (18)$$

Battery capacity is calculated as:

$$C_{Ah} = \frac{1000 \cdot E_{bat}}{V_{sys} \cdot DOD} \quad (19)$$

where: V_{sys} – is battery system voltage (V), and DOD – is depth of discharge (0.5–0.8).

2.10. PV Array and Inverter Sizing

If the rated power of a single PV module is PmodP_{mod}Pmod, the required number of modules is:

$$N_{mod} = \frac{P_{PV}}{P_{mod}} \quad (20)$$

For AC pumps, inverter sizing is defined as:

$$P_{inv} \geq P_{pump} \cdot (1 + s) \quad (21)$$

Where, s is the start-up surge factor (0.20–0.40).

The final PV capacity is determined by satisfying both energy and power constraints:

$$P_{PV}, (final) = max(P_{PV}\ (energy), P_{PV}\ (power)) \cdot (1 + m)$$

2.11. Applicability of the Methodology

The proposed methodology enables flexible application across different crop types, planting densities, and irrigation schedules. It provides a robust quantitative basis for crop-level energy assessment in drip irrigation systems and supports the optimization of renewable-energy-powered irrigation solutions. The methodology can be directly applied by irrigation planners and system designers to estimate electrical energy demand and PV capacity for various crop combinations under practical field conditions.

ANALYSIS AND RESULTS

Table 2 summarizes the crop-specific irrigation water requirements and the corresponding electrical energy consumption under drip irrigation conditions. The presented parameters reflect the combined influence of crop coefficients, reference evapotranspiration, irrigation efficiency, and planting characteristics. This quantitative comparison highlights the variability of plant-level water use and energy demand among different crop types, providing a clear basis for evaluating irrigation energy performance and supporting crop-oriented energy planning (Table 2).

Table 2. Crop-Specific Irrigation Water Requirements and Associated Electrical Energy Consumption

Crop type	Kc	ET_0 (mm/day)	ETc (mm/day)	η_{ir}	Vp (m³/plant/day)	Ep (kWh/plant/day)
Cotton	1.15	5.5	6.33	0.90	0.008	0.0061
Tomato	1.05	5.5	5.78	0.90	0.006	0.0046
Onion	0.95	5.5	5.23	0.90	0.004	0.0031
Orchard trees	1.20	5.5	6.60	0.90	0.020	0.0154
Greenhouse crops	1.00	5.5	5.50	0.92	0.007	0.0052

The results demonstrate that electrical energy consumption in irrigation systems varies substantially among crop types, primarily as a consequence of differences in crop water requirements, planting density, and irrigation efficiency. As presented in Table 2, orchard crops show the highest electrical energy consumption per plant, reaching approximately 0.015 kWh/plant/day, whereas vegetable and onion crops are characterized by considerably lower energy requirements. These findings highlight the importance of adopting crop-specific energy assessment approaches, which provide a more accurate and informative representation of irrigation energy demand than generalized system-level evaluations (Table 3).

Table 3. Aggregated Irrigation Energy Demand for Multiple Crops

Crop type	Area (ha)	Number of plants	(Vc) (m^3/day)	(Ec) (kWh/day)
Cotton	5.0	50,000	400	305
Tomato	2.0	20,000	120	92
Onion	1.5	30,000	120	92
Orchard crops	3.0	6,000	120	92
Greenhouse crops	0.5	10,000	70	54
Total	–	–	**830**	**635**

The aggregated results presented in Table 3 indicate a total daily irrigation energy demand of 635 kWh for the multi-crop irrigation system under consideration. Cotton cultivation accounts for the largest proportion of total energy consumption, primarily due to its extensive cultivated area combined with comparatively higher water requirements. These results underline the critical role of crop composition in shaping overall irrigation energy demand and demonstrate the value of crop-specific analysis for effective energy planning and system optimization (Table 4).

Table 4. Hydraulic and Pumping System Parameters

Parameter	Symbol	Unit	Value
Daily energy demand	E_{day}	kWh/day	635
Peak Sun Hours	PSH	h/day	5.5
Performance Ratio	PR	-	0.75
Required PV capacity	P_{PV}	kWp	154
Design margin	m	%	20
Final PV capacity	P_{PV},final	kWp	**185**

The hydraulic analysis presented in Table 4 indicates that friction losses in pipelines and pressure losses at emitters constitute a substantial portion of the total dynamic head. This finding underscores the importance of optimized pipeline layout and effective pressure regulation for improving the overall efficiency of drip irrigation systems. Based on the calculated irrigation energy demand and prevailing local solar conditions, the required photovoltaic capacity was estimated at 185 kWp, including an appropriate design safety margin, as summarized in Table 4. These results confirm the technical feasibility of meeting irrigation energy requirements through photovoltaic-powered pumping systems (Tabel 5).

Table 5. Energy Comparison of Irrigation Methods

Irrigation method	Energy use (kWh/ha/day)	Energy saving (%)
Surface irrigation	180	-
Sprinkler irrigation	135	25
Drip irrigation	**95**	**47**

Furthermore, the comparative analysis of irrigation methods presented in Table 5 demonstrates that drip irrigation systems can reduce electrical energy consumption by approximately 45–50% compared with conventional surface irrigation practices. This substantial reduction contributes not only to lower operational costs but also to improved environmental sustainability through more efficient use of water and energy resources. Overall, the proposed methodology offers a robust and flexible framework for crop-based energy assessment and provides strong analytical support for the optimal design and implementation of renewable energy-powered irrigation systems (Figure 1-4).

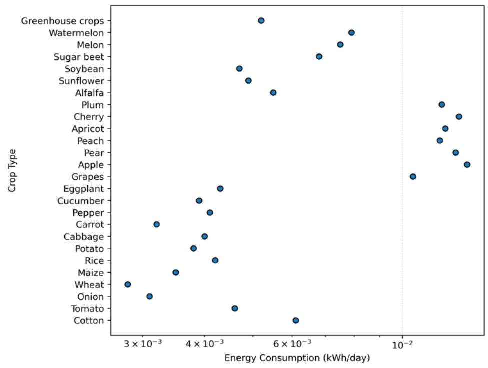

Figure 1. Crop-Specific Irrigation Electrical Energy Consumption

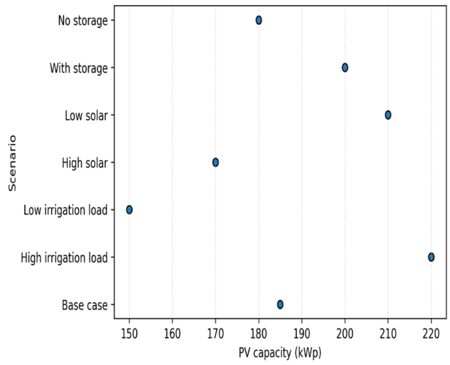

Figure 2. Optimal Photovoltaic (PV) Capacity under Different Operating Scenarios

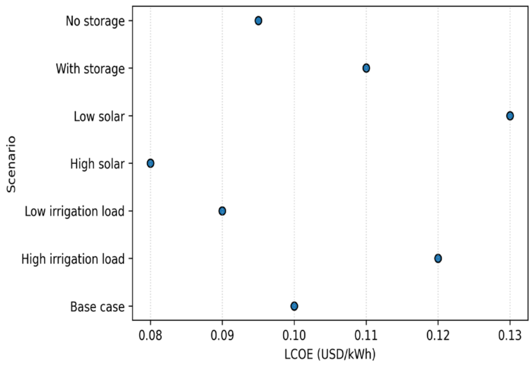

Figure 3. Levelized Cost of Energy (LCOE) under Alternative Irrigation Energy Supply Scenarios

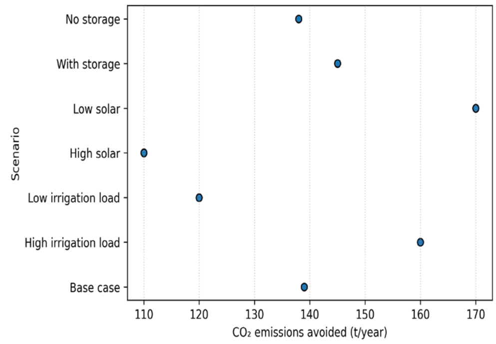

Figure 4. Sensitivity Analysis of the Levelized Cost of Energy (LCOE) under Varying System and Operating Conditions

Figure 1 illustrates crop-specific electrical energy consumption per plant under drip irrigation conditions. The use of a logarithmic scale highlights pronounced differences in energy demand among crop groups, with orchard crops exhibiting substantially higher energy consumption compared to cereals and most vegetable crops. This visualization clearly demonstrates the importance of plant-level analysis for understanding irrigation energy requirements.

Figure 2 presents the optimal photovoltaic (PV) capacity estimated under a range of operating scenarios, including the base case, variations in irrigation load, differing solar resource conditions, and the integration of energy storage systems. The results indicate that PV system sizing is highly sensitive to both irrigation demand profiles and solar availability, emphasizing the need for scenario-based design approaches.

Figure 3 provides a comparative assessment of PV system performance under alternative operational conditions, further illustrating how changes in energy demand and system configuration influence optimal PV capacity. Together, Figures 2 and 3 offer complementary insights into the robustness and adaptability of PV-powered irrigation system design.

4. Economic Analysis: Levelized Cost of Energy (LCOE) and Net Present Cost (NPC)

Building on the technical assessment, the economic analysis evaluates the cost-effectiveness of the proposed irrigation energy solutions using the Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) indicators. These metrics provide a comprehensive basis for comparing different system configurations and operating scenarios, thereby supporting informed decision-making for the deployment of sustainable, renewable energy-powered irrigation systems.

$$NPC = CAPEX + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t} + \sum_{t=1}^{T} \frac{C_{rept}}{(1+r)^t} + \sum_{t=1}^{T} \frac{S_T}{(1+r)^t} \qquad (22)$$

Where: CAPEX denotes the initial investment cost (USD); $OPEX_t$ represents the annual operation and maintenance cost in year t (USD/year); $C_{repl,t}$ is the replacement cost incurred in year t (USD); S_t is the salvage value at the end of the project lifetime T (USD); r is the real discount rate (–); and T denotes the project lifetime (years).

Capital Recovery Factor (CRF):

$$CRF = \frac{r\,(1 + r)^{T}}{(1 + r)^{(T-1)}} \quad (23)$$

Levelized Cost of Energy (LCOE)

$$LCOE = \frac{NPC}{\sum_{t=1}^{T} \frac{E_{ann}}{(1+r)^{t}}} \quad (24)$$

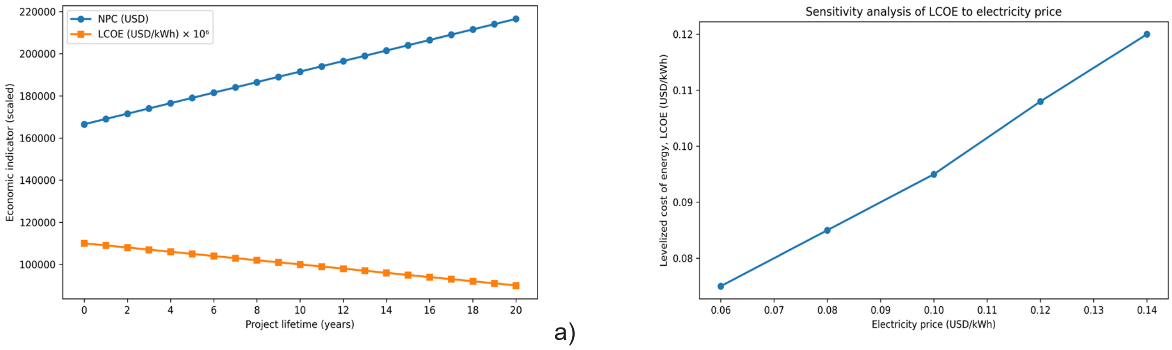

Figure 5. Illustrates the economic performance and sensitivity analysis of the photovoltaic (PV)-powered irrigation system

Figure 5(a) presents a HOMER-style visualization of the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE) over the project lifetime. The cumulative NPC exhibits a gradual increase, primarily driven by operation and maintenance expenditures throughout the system's lifespan. In contrast, the LCOE decreases steadily over time as the discounted energy output accumulates. This trend reflects the improving economic efficiency of the PV-powered irrigation system during long-term operation.

Figure 5(b) illustrates the sensitivity of the LCOE to variations in electricity price. The results demonstrate a strong positive relationship between electricity tariffs and the LCOE, indicating that higher grid electricity prices substantially enhance the economic competitiveness and attractiveness of the proposed PV-based irrigation system.

The results further emphasize the importance of crop-specific analysis when evaluating electrical energy consumption in irrigation systems. Unlike conventional approaches that assess energy demand at aggregated field or system levels, the proposed methodology reveals pronounced differences in energy requirements among crop types. These differences arise from variations in crop water demand, planting density, and irrigation efficiency. Orchard crops exhibit the highest electrical energy consumption per plant, primarily due to deeper root systems and higher irrigation volumes, whereas vegetable and onion crops are characterized by considerably lower energy requirements.

The aggregation of crop-level energy demand demonstrates that crop composition plays a decisive role in determining total irrigation energy consumption. Crops with extensive cultivated areas and moderate water requirements, such as cotton, contribute substantially to overall energy demand despite relatively low per-plant energy values. These findings highlight that effective irrigation energy planning should simultaneously account for crop type and cultivated area.

The PV system sizing results confirm the technical feasibility of supplying irrigation energy demand using solar energy under typical summer operating conditions. The inclusion of a design margin ensures reliable system performance under variable solar irradiance and realistic field losses. Compared with conventional grid-based or diesel-powered irrigation systems, PV-driven pumping solutions offer clear economic advantages, particularly in regions characterized by high solar resource availability and rising fuel prices.

From an environmental perspective, the adoption of PV-powered drip irrigation systems leads to significant reductions in carbon dioxide (CO_2) emissions over the project lifetime. This outcome aligns with broader climate mitigation objectives and contributes to enhancing the long-term sustainability of irrigated agricultural production.

CONCLUSIONS AND RECOMMENDATIONS

The conducted analysis confirms that irrigation-related electrical energy consumption cannot be reliably assessed without explicitly accounting for crop-specific characteristics. The results reveal a substantial variation in plant-level energy demand, ranging from 0.0031 kWh/plant/day for crops with low water requirements to 0.0154 kWh/plant/day for orchard trees. These differences clearly demonstrate that uniform, system-level energy estimation approaches are insufficient and may lead to considerable inaccuracies in irrigation energy planning.

For the analyzed multi-crop irrigation scheme, the total daily irrigation water requirement amounted to 830 m³, corresponding to an overall electrical energy demand of 635 kWh/day. Based on local solar conditions, characterized by an average of 5.5 peak sun hours, and accounting for system losses through a performance ratio of 0.75, the required photovoltaic capacity was estimated at 185 kWp, including an appropriate operational safety margin. This result confirms that photovoltaic energy can reliably meet the full irrigation energy demand under typical operating conditions.

Furthermore, the comparative assessment of irrigation techniques indicates that drip irrigation systems enable energy savings of up to 50% relative to conventional surface irrigation methods. This improvement reflects the combined benefits of reduced water application volumes and enhanced hydraulic efficiency.

Overall, the proposed crop-oriented energy assessment methodology significantly enhances the accuracy and transparency of irrigation energy planning. By integrating crop characteristics, hydraulic parameters, and renewable energy modeling, the approach provides a robust analytical foundation for the optimal design of renewable energy-powered irrigation systems. Consequently, it contributes to more sustainable management of water and energy resources within the broader Water–Energy–Food (WEF) Nexus framework.

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