An Integrated Water–Energy Vulnerability Index for Irrigated Agricultural Regions

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Abstract.
The growing dependence of irrigated agriculture on both water availability and energy infrastructure has increased the vulnerability of agricultural production systems, particularly under conditions of climate variability, hydrological uncertainty, and rising energy costs. Although the water–energy nexus has been widely investigated, integrated frameworks capable of simultaneously assessing water availability, energy reliability, operational efficiency, and renewable-energy integration at the regional scale remain scarce. This study proposes a diagnostic framework for evaluating water–energy vulnerability in center-pivot irrigation systems through the integration of three dimensions: the Water–Energy Vulnerability Index (WEVI), the Water–Energy Intensity Index (WEI), and the Renewable Flexibility Index (RFI). These dimensions are combined into a Priority Index (PI) to support the prioritization of regions for integrated water-efficiency, energy-efficiency, and decarbonization interventions. Unlike conventional approaches that assess water and energy performance separately, the proposed framework explicitly captures the interactions among water availability, energy infrastructure, pumping requirements, and renewable-energy integration. The methodology combines public meteorological and hydrological datasets with operational information provided by irrigators, including irrigation demand, water-storage capacity, pumping characteristics, energy consumption, contracted electrical power, and grid-reliability indicators. By integrating these variables into a unified analytical structure, the framework enables a comprehensive assessment of the factors affecting the resilience and sustainability of irrigated production systems. A synthetic case study involving three hypothetical irrigated regions representative of southern Brazil was conducted to evaluate the framework. The results demonstrated the ability of the proposed approach to distinguish vulnerability profiles and identify dominant risk factors. Regions characterized by high evapotranspirative demand, limited water availability, reduced storage capacity, and lower pumping efficiency exhibited the highest vulnerability levels, whereas regions with greater storage capacity and stronger alignment between irrigation demand and solar-generation profiles showed higher renewable flexibility and greater decarbonization potential. The methodology also highlighted trade-offs among water security, energy efficiency, and renewable-energy integration, revealing insights not captured by isolated indicators. The proposed framework offers a replicable decision-support tool for prioritizing investments, improving resilience, and promoting sustainable water and energy management in irrigated agriculture.

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Keywords.
Water–energy nexus; Vulnerability assessment; Renewable energy; Center-pivot irrigation.

Introduction

Agricultural irrigation accounts for approximately 70% of global freshwater withdrawals (FAO, 2020). In Brazil, irrigated agriculture has expanded significantly due to the intensification of agricultural production and the growing need to mitigate climate-related risks. Increasing rainfall variability and more frequent water deficits during critical crop growth stages have transformed irrigation from a supplementary practice into a fundamental component of agricultural resilience and productivity.

Center-pivot irrigation has become the dominant mechanized irrigation system in Brazil because of its high application efficiency. However, its operation requires substantial energy for water pumping, creating a strong dependence on both water and energy resources. Consequently, disruptions affecting either resource may compromise irrigation performance and agricultural productivity (Hoff, 2011; Scanlon et al., 2017). The vulnerability of these systems emerges from the interaction among crop water demand, water availability, energy reliability, and operational efficiency.

Research on the water–energy nexus in irrigated agriculture has advanced along three main directions: (i) the conceptual understanding of water–energy interdependencies; (ii) the development of irrigation-performance indicators; and (iii) the integration of photovoltaic systems as a decarbonization strategy. Seminal studies established the foundations of the nexus concept by demonstrating how disruptions in one domain propagate effects into the other (Bazilian et al., 2011; Siddiqi & Anadon, 2011), while later work expanded the framework to include food systems and broader sustainability dimensions (Lucca et al., 2023). At the operational level, studies have shown that water-use and energy-use efficiency in center-pivot systems are strongly influenced by management practices (Brik et al., 2022). In parallel, photovoltaic-powered irrigation has been widely investigated as a pathway to reduce carbon emissions and energy costs (Hadole et al., 2021; Khattak et al., 2024).

Despite these advances, the literature still lacks frameworks capable of simultaneously integrating seasonal climatic variability, local hydrological constraints, energy-supply reliability, and the compatibility between solar-energy generation and crop water demand into a practical decision-support tool. To address this gap, this study proposes an integrated framework for assessing water–energy vulnerability in center-pivot irrigation systems. The framework combines publicly available meteorological and hydrological data with operational information provided by irrigators and structures system assessment into three complementary dimensions: the Water–Energy Vulnerability Index (WEVI), which quantifies the risk of failing to satisfy crop water requirements; the Water–Energy Intensity Index (WEI), which evaluates pumping-energy efficiency; and the Renewable Flexibility Index (RFI), which measures the ability of irrigation systems to accommodate renewable-energy sources without compromising water supply. These dimensions are integrated into a composite Priority Index (PI) that supports the identification and prioritization of regions with the greatest potential benefit from combined water-efficiency, energy-efficiency, and decarbonization interventions. The proposed framework provides a replicable decision-support tool for infrastructure planning, resilience enhancement, and public policy development aimed at improving water and energy security in irrigated agriculture.

Background

Water–Energy Nexus in Irrigated Agriculture

The relationship between water and energy in irrigated agriculture is fundamentally asymmetric: water depends on energy to be extracted, conveyed, and distributed, while energy availability determines whether irrigation can be performed at the appropriate time and intensity (Hoff, 2011; Bazilian et al., 2011). In pumped irrigation systems, this dependency is particularly pronounced because energy consumption is directly proportional to crop water demand, total dynamic head, and motor-pump efficiency (Chiarelli et al., 2026).

In center-pivot irrigation systems, this relationship can be described as a sequence of four interconnected links. The first link is climatic: reference evapotranspiration (ET_0) defines the atmospheric water demand and, consequently, the potential deficit that irrigation must supply (Allen et al., 1998). The second link is hydrological: effective precipitation and water storage capacity in soils and reservoirs modulate the actual deficit, determining the volume of water that must be pumped (AQUASTAT, 2026). The third link is hydraulic: this volume, combined with the characteristics of the water distribution system, translates into an energy requirement for pumping. The fourth link is energetic: the availability, reliability, and cost of electricity determine whether irrigation can be delivered at the required time, intensity, and economic viability. Together, these interconnected links illustrate how climatic, hydrological, hydraulic, and energy-related factors jointly shape the operational performance and vulnerability of irrigated agricultural systems.

Climate Determinants of Irrigation Demand

Irrigation demand is governed by the balance between crop evapotranspiration and the effective precipitation available within the root zone. Reference evapotranspiration (ET_0) represents atmospheric water demand from a well-watered reference surface and is calculated from meteorological variables using the FAO Penman–Monteith method (Allen et al., 1998). Crop evapotranspiration (ETc) is obtained by multiplying ET_0 by the crop coefficient (Kc), which varies throughout the crop cycle according to plant growth and development.

Effective precipitation (Pef) corresponds to the fraction of rainfall available for plant uptake after accounting for losses due to runoff and deep percolation. Crop water deficit is defined as the difference between ETc and Pef and represents the irrigation depth required to maintain optimal productivity (AQUASTAT, 2026). Deficits occurring during critical growth stages, such as flowering and grain filling, can significantly reduce crop yields (Sah et al., 2020).

Seasonal variability in ETc and Pef is a major challenge for irrigation planning and operation. Regions with pronounced wet and dry seasons experience concentrated periods of irrigation demand, requiring greater pumping and water-storage capacity. Consequently, climatic conditions influence both water requirements and the temporal distribution of irrigation demand, directly affecting pumping frequency, energy consumption, and overall irrigation-system vulnerability.

Energy Requirements of Center Pivot Systems

Energy consumption in center-pivot irrigation systems is determined by the interaction among the volume of water pumped, the total dynamic head of the system, and motor-pump efficiency. This relationship is commonly expressed through the specific pumping energy (Es, kWh m^{-3}), which represents the amount of electrical energy required to pump one cubic meter of water under the hydraulic conditions of the system (Barbosa et al., 2018; Brik et al., 2022). Consequently, any increase in irrigation water demand directly translates into higher energy consumption, making water and energy inseparable from an operational perspective.

Recent studies have advanced the characterization of energy performance in irrigated systems through the use of normalized indicators such as energy consumption per applied irrigation depth (ECI, kWh mm^{-1} ha^{-1}) and energy consumption per unit of agricultural production (EFI, kWh kg^{-1}). These metrics enable meaningful comparisons among irrigation systems operating under different hydraulic, climatic, and agronomic conditions. In a comparative case study, center-pivot irrigation exhibited the lowest ECI among the evaluated irrigation technologies (7.03 kWh mm^{-1}

ha^{-1}), highlighting its relatively high energy efficiency per unit of applied water compared with furrow and fixed-sprinkler systems, despite its substantial absolute energy consumption associated with large irrigated areas (Salman et al., 2025).

Electricity pricing structures introduce an additional economic dimension to irrigation-system vulnerability. In Brazil, irrigators operating under time-of-use tariff schemes, such as the Green and Blue tariffs, face significant variations in electricity costs throughout the day and across seasonal periods (ANEEL, 2022). These cost fluctuations can influence pumping schedules and operational decisions, particularly when peak electricity prices coincide with periods of elevated crop water demand. Although energy costs are not explicitly incorporated into the framework proposed in this study, they constitute an important contextual factor that may further constrain irrigation-system operation and should be considered when evaluating water–energy management strategies.

Renewable Energy Integration in Irrigation

The integration of photovoltaic systems into agricultural irrigation has advanced rapidly as a strategy for decarbonization and operational cost reduction, driven by declining solar-panel costs and growing interest in alternatives to diesel-powered and grid-dependent irrigation systems in remote areas (Hilarydoss, 2023). In Brazil, recent large-scale applications have demonstrated this potential. Off-grid photovoltaic systems installed on farms operating multiple center pivots in the Bahia Cerrado region have reduced daily diesel consumption by up to 70%, resulting in substantial reductions in production costs and carbon emissions (Neris, 2024).

From a technical perspective, the feasibility of photovoltaic-powered irrigation depends on the temporal coupling between solar-energy generation and crop water demand. Studies have shown that irrigation loads offer opportunities for flexible pumping schedules that take advantage of periods of high solar generation (Navarro-González et al., 2023; El-Sonbaty et al., 2024). However, synchronizing energy production and irrigation demand remains challenging because solar availability varies with irradiance, whereas crop water requirements are primarily governed by agronomic and climatic conditions (Cervera-Gascó et al., 2023).

The ability of an irrigation system to accommodate solar generation without compromising agricultural productivity, hereafter referred to as Renewable Flexibility, depends on soil water-holding capacity, reservoir-storage capacity, operational flexibility, and the alignment between peak solar generation and peak crop water demand. Systems with greater water-storage capacity can shift pumping operations according to energy availability, whereas systems with limited storage and concentrated irrigation demand are more vulnerable to solar intermittency (Navarro-González et al., 2023; Cervera-Gascó et al., 2023; El-Sonbaty et al., 2024).

This concept of Renewable Flexibility provides the foundation for the Renewable Flexibility Index (RFI) proposed in this work, which quantifies the ability of irrigation systems to integrate renewable energy sources while maintaining adequate water delivery to crops.

Methodology

Overview of the Framework

The proposed framework assesses center-pivot irrigation systems through three complementary dimensions. The Water–Energy Vulnerability Index (WEVI) quantifies the risk of failing to meet crop water requirements, the Water–Energy Intensity Index (WEI) evaluates pumping-energy efficiency, and the Renewable Flexibility Index (RFI) measures the ability of the irrigation system to integrate renewable energy sources without compromising water delivery. These dimensions are combined into a composite Priority Index (PI), which supports the prioritization of regions for integrated water-efficiency, energy-efficiency, and decarbonization interventions.

The framework follows the causal chain described previously: climatic factors determine crop water demand, which defines pumping requirements and, consequently, irrigation energy consumption. The assessment combines publicly available datasets, including meteorological, hydrological, and water-use information, with operational data provided by irrigators, such as pumping-system characteristics, water-storage capacity, energy consumption, electricity tariffs, and power-supply reliability. This approach captures both regional conditions and system-specific operational characteristics.

To enable integration into a single decision-support metric, all sub-indices are normalized to a scale ranging from 0 to 1 and aggregated into the Priority Index using weighted coefficients that reflect the relative importance of vulnerability, energy efficiency, and renewable-integration flexibility.

Data Sources

The proposed framework combines two categories of data. The first category consists of publicly available datasets obtained from governmental agencies. In the Brazilian case study presented in this work, these datasets include historical precipitation and temperature records provided by the National Institute of Meteorology (INMET), reference evapotranspiration (ET_0) estimates calculated using the FAO Penman–Monteith method (Allen et al., 1998), and streamflow records and water-use permit information supplied by the National Water and Basic Sanitation Agency (ANA). Equivalent datasets from other national or regional agencies may be used when applying the framework in different geographic contexts.

The second category comprises operational information provided by irrigators and collected through structured questionnaires and technical field assessments. These data include installed pumping power and hydraulic-system characteristics, irrigated area and crop type, reservoir storage capacity, monthly energy consumption, electricity tariff schemes, and power-supply reliability indicators expressed through the frequency and duration of service interruptions. Although tariff information is collected, it is currently used only for contextual assessment and is not explicitly incorporated into the indices proposed in this work.

The integration of these two data sources enables the framework to capture both the structural conditions of a region and the operational characteristics of individual irrigation systems. This combination provides the level of detail required to evaluate water–energy vulnerability, energy efficiency, and renewable-integration potential while maintaining the flexibility necessary for application at regional scales.

Water–Hydraulic Security Index (WHSI)

The Water–Hydraulic Security Index (WHSI) quantifies the relationship between crop water demand and the effective water availability of the irrigation system, capturing the degree of pressure imposed on available water resources during a given period.

Crop water demand is calculated from the difference between crop evapotranspiration (ETc) and effective precipitation (Pef), converted into a volumetric requirement according to the irrigated area:

$$ETc = ET_0 \times Kc \tag{1}$$

$$Déficit = ETc - Pef \tag{2}$$

$$Demand\ (m^3/day) = Deficit\ (mm/day) \times Area\ (ha) \times 10 \tag{3}$$

where Kc is the crop coefficient, which varies according to crop type and phenological stage (Allen et al., 1998). The factor 10 converts a water depth expressed in millimeters over one hectare into cubic meters.

Since effective precipitation (Pef) is obtained from monthly climatological records, monthly precipitation values were converted to daily averages by dividing by 30 before calculating the irrigation deficit.

Effective water availability is estimated as the sum of the water volume available for abstraction within the watershed during the irrigation period and the useful storage capacity available in reservoirs:

$$Availability = (Available\ Flow \times Operating\ Time) + ReservoirStorage \quad (4)$$

The WHSI is then calculated as:

$$WHSI = Demand\ /\ Availability \quad (5)$$

Lower values indicate greater water security, whereas higher values indicate increasing pressure on available water resources. The classification thresholds adopted in this study are: WHSI < 0.5, indicating high water security; 0.5 ≤ WHSI < 1.0, indicating an attention condition; and WHSI ≥ 1.0, indicating structural risk, where water demand exceeds the effective water availability of the irrigation system.

Water–Energy Vulnerability Index (WEVI)

The Water–Energy Vulnerability Index (WEVI) represents the systemic risk that an irrigation system may fail to deliver the irrigation depth required by crops due to water or energy constraints. The index combines three complementary components: the Water–Hydraulic Security Index (WHSI), calculated in the previous section; the Energy Pressure Index (EPI); and the Interruption Risk (IR) associated with power-supply reliability.

The Energy Pressure Index (EPI) expresses the relationship between the electrical power required to satisfy irrigation pumping demand and the electrical power contracted by the irrigator:

$$EPI = Required\ Power\ /\ Contracted\ Power \quad (6)$$

where *Required Power* is the power needed to pump the demanded water volume under the hydraulic conditions of the system, and *Contracted Power* is the electrical demand contracted from the utility. Values approaching or exceeding 1 indicate that the system operates near or above its contracted electrical capacity, signaling structural energy vulnerability.

The Interruption Risk (IR) quantifies the risk associated with electricity-supply unavailability and is calculated as the complement of power-supply reliability. Let (C_e) denote the electrical reliability of the system, defined as the fraction of time during which the system operates without interruptions over the evaluation period:

$$IR = 1 - C_e \quad (7)$$

Values close to 0 indicate highly reliable electricity supply, whereas values close to 1 indicate frequent or prolonged interruptions. For off-grid systems or systems with fully available on-site generation, IR is assumed to be zero.

To ensure that the vulnerability index remains bounded between 0 and 1, the Water–Hydraulic Security Index is limited as follows:

$$WHSI\_lim = min(WHSI, 1) \quad (8)$$

The Water–Energy Vulnerability Index is then calculated as:

$$WEVI = 1 - (1 - WHSI\_lim)(1 - EPI)(1 - IR) \quad (9)$$

This formulation follows a multiplicative risk-composition approach, ensuring that overall vulnerability increases whenever any component exhibits a high value and remains low only when all components are simultaneously low. In practical terms, the formulation captures the idea that severe vulnerability in a single dimension may be sufficient to compromise irrigation-system performance, even if the remaining dimensions exhibit favorable conditions.

The classification thresholds adopted in this study are: 0.00-0.30, low vulnerability; 0.30-0.60, moderate vulnerability; 0.60-0.80, high vulnerability; and 0.80-1.00, critical or structural vulnerability.

Water–Energy Intensity Index (WEI)

The Water–Energy Intensity Index (WEI) quantifies the efficiency of energy use in irrigation-water pumping operations, capturing operational inefficiencies that may not be evident through conventional performance metrics. The index is expressed through two complementary indicators.

The first indicator, WEI_V, represents the energy intensity per unit volume of water pumped:

$$WEI\_V = E / V \quad (10)$$

where E is the electrical energy consumed during the evaluation period (kWh) and V is the total volume of water pumped (m^3). This metric represents the amount of energy required to pump one cubic meter of water under the operating conditions of the irrigation system.

The second indicator, WEI_D, represents the energy intensity per unit irrigation depth applied over a given area:

$$WEI\_D = E / (Area \times Depth) \quad (11)$$

where *Area* is the irrigated area (ha) and *Depth* is the irrigation depth applied during the evaluation period (mm). The resulting unit is expressed as kWh ha^{-1} mm^{-1}. This metric represents the energy required to apply one millimeter of water over one hectare and enables direct comparisons among irrigation systems operating under different hydraulic and agronomic conditions.

Although both indicators provide useful information regarding pumping efficiency, WEI_D is adopted as the primary energy-performance metric within the proposed framework because it directly relates energy consumption to the irrigation service delivered to crops and allows consistent comparisons across systems of different scales.

Higher WEI values indicate lower energy efficiency and suggest opportunities for improvement through interventions such as hydraulic-system optimization, pump replacement, or operational adjustments.

Renewable Flexibility Index (RFI)

The Renewable Flexibility Index (RFI) quantifies the ability of an irrigated system to accommodate renewable energy sources, particularly photovoltaic generation, without compromising the irrigation depth required by crops. The index measures the operational flexibility available to shift pumping activities toward periods of greater renewable-energy availability. To achieve this objective, the RFI combines three complementary mechanisms: soil-water storage capacity (C_soil), reservoir-storage capacity (C_res), and the temporal alignment between irrigation demand and solar-energy generation (M_solar).

The soil-water storage component (C_soil) represents the autonomy provided by water stored within the crop root zone. Greater amounts of available soil water increase the system's ability to postpone irrigation events without inducing crop water stress. This characteristic is initially quantified through the soil autonomy time (T_soil), defined as the number of days during which the water available in the root zone can satisfy crop evapotranspiration demand without irrigation:

$$T\_soil = (CAD \times Zr) / ETc \tag{12}$$

where CAD is the soil available water capacity (mm m^{-1}), Zr is the effective rooting depth (m), and ETc is crop evapotranspiration (mm day^{-1}).

To enable comparisons among regions, the soil-water storage component is normalized relative to the maximum soil autonomy time observed within the evaluated dataset:

$$C\_soil = T\_soil / T\_soil, max \tag{13}$$

where T_soil,max is the highest soil autonomy time among the evaluated regions. Values close to 1 indicate greater operational flexibility derived from soil-water storage, whereas lower values indicate reduced capacity to postpone irrigation events.

The reservoir-storage component (C_res) represents the ability of reservoirs to store water that can be pumped during periods of higher renewable-energy availability. Analogously to the soil-storage component, an equivalent reservoir autonomy time (T_res) is calculated as the number of days for which the stored water volume can satisfy irrigation demand without additional pumping:

$$T\_res = Reservoir\ Storage / Daily\ Water\ Demand \tag{14}$$

where Reservoir Storage is the useful water volume available in the reservoir (m^3) and Daily Water Demand is the irrigation water demand (m^3 day^{-1}).

The reservoir-storage component is then normalized using a reference flexibility horizon (T_ref):

$$C\_res = min(T\_res / T\_ref, 1) \tag{15}$$

where T_ref represents the maximum postponement period considered operationally acceptable for irrigation management. Values equal to 1 indicate that reservoir storage is sufficient to fully satisfy the adopted flexibility horizon.

The use of different normalization approaches for C_soil and C_res reflects the distinct nature of these flexibility mechanisms. While soil-water storage is evaluated relative to the best-performing region, reservoir storage is evaluated against a predefined operational target. Together, these components represent complementary forms of water storage that increase the ability of irrigation systems to shift pumping operations without compromising crop water requirements.

The temporal alignment component (M_solar) quantifies the degree of coincidence between irrigation-demand peaks and photovoltaic-generation peaks. Higher values indicate better synchronization between irrigation requirements and renewable-energy availability, reducing the need for energy storage or operational rescheduling:

$$M\_solar = 1 - |H\_demand - H\_solar| / 12 \tag{16}$$

where H_demand is the hour of peak irrigation demand and H_solar is the hour of peak solar generation, both expressed in hours of the day. The denominator 12 represents the maximum time difference considered within a daily cycle, ensuring that M_solar remains bounded between

0 and 1.

The Renewable Flexibility Index is calculated as a weighted average of its three components:

$$RFI = 0.30 \cdot C_{soil} + 0.40 \cdot C_{res} + 0.30 \cdot M\_solar \quad (17)$$

Unlike the Water–Energy Vulnerability Index (WEVI), which represents a risk metric and therefore employs a multiplicative composition to capture the effect of the weakest system component, the RFI represents an operational capability that emerges from the combined contribution of multiple flexibility mechanisms. For this reason, an additive weighted formulation was adopted, allowing gradual improvements in flexibility to be reflected even when one component exhibits limited performance.

The weighting coefficients were defined based on engineering judgment regarding the mechanisms that provide operational flexibility in irrigated systems. Reservoir-storage capacity received the highest weight (0.40) because it constitutes the primary active mechanism for decoupling pumping operations from irrigation demand. Soil-water storage capacity and demand-generation alignment received equal weights (0.30 each), representing passive flexibility mechanisms associated with natural water storage in the soil and the temporal compatibility between renewable-energy availability and irrigation requirements, respectively.

The classification thresholds adopted in this study are: 0.00-0.30, low flexibility, indicating strong dependence on energy storage or structural modifications to enable renewable-energy integration; 0.30-0.60, moderate flexibility; 0.60-0.80, high flexibility; and 0.80-1.00, very high flexibility for renewable-energy integration and reduced dependence on fossil-fuel-based energy sources.

Priority Index (PI)

The Priority Index (PI) integrates the three dimensions of the proposed framework into a composite indicator designed to support the identification and prioritization of irrigated regions for integrated water-efficiency, energy-efficiency, and renewable-energy interventions. Rather than measuring vulnerability alone, the PI evaluates the combined potential benefit of intervention by considering water–energy risk, energy-performance improvement opportunities, and renewable-integration capability.

To enable aggregation with WEVI and RFI, which are bounded between 0 and 1, WEI_D was normalized using a reference value of 2.0 kWh ha^{-1} mm^{-1}:

$$WEID, norm = min(WEI\_D/2.0, 1) \quad (18)$$

The reference value of 2.0 kWh ha^{-1} mm^{-1} was selected because it represents the upper bound of the energy-intensity range expected for center-pivot irrigation systems under typical operating conditions, ensuring that the normalized indicator remains bounded between 0 and 1.

The Priority Index is calculated as:

$$PI = 0.45 \cdot WEVI + 0.25 \cdot WEI\_D, norm + 0.30 \cdot RFI \quad (19)$$

where WEVI represents water–energy vulnerability, WEI_D,norm represents the normalized water–energy intensity indicator, and RFI represents renewable-integration flexibility.

The weighting coefficients were defined based on engineering judgment and reflect the relative importance of each dimension in the intervention-prioritization process. The Water–Energy Vulnerability Index (WEVI) receives the highest weight (0.45) because it represents the systemic risk of failing to satisfy crop water requirements, which constitutes the most critical operational consequence in irrigated systems. The Renewable Flexibility Index (RFI) receives an intermediate weight (0.30) because it reflects the system's capacity to accommodate renewable-energy sources and support decarbonization strategies. The Water–Energy Intensity Index (WEI_D) receives a weight of 0.25 because it captures opportunities for energy-efficiency improvements, which, although important, are generally more straightforward to address through targeted technical interventions.

The adopted weighting scheme therefore reflects three complementary objectives: operational resilience (WEVI), renewable-energy integration potential (RFI), and energy efficiency (WEI_D). Consequently, the Priority Index assigns higher scores to regions that simultaneously exhibit elevated vulnerability, significant opportunities for efficiency improvement, and favorable conditions for renewable-energy integration.

Table 1 presents the classification thresholds adopted for the Priority Index. These thresholds represent increasing levels of intervention priority based on the combined assessment of water–energy vulnerability, energy efficiency, and renewable-integration potential. The resulting classification provides an objective criterion to support resource allocation and investment planning in center-pivot irrigation systems.

Table 1. Priority Index classification scheme and operational interpretation.

PI Range	Priority Level	Operational Interpretation
0.00-0.20	Very Low	Low vulnerability and limited immediate benefit from intervention.
0.20-0.40	Low	Improvement opportunities exist, but intervention is not urgent.
0.40-0.60	Medium	Meaningful potential gains in resilience, efficiency, or decarbonization.
0.60-0.80	High	Strong candidate for integrated intervention projects.
0.80-1.00	Very High	High vulnerability, energy inefficiency, and renewable potential.

Results

Study Region Characterization

The case study was conducted using synthetic data representing three hypothetical irrigation regions, referred to as Region 1, Region 2, and Region 3. These regions were designed to represent distinct water–energy vulnerability profiles in center-pivot irrigation systems typical of southern Brazil. The synthetic input parameters were selected based on representative values reported in the literature for irrigated agricultural systems and were chosen to reflect contrasting edaphoclimatic conditions commonly found in three physiographic regions of Rio Grande do Sul: the Campanha Gaúcha (Region 1), Missões (Region 2), and Planalto Médio (Region 3).

Two summer crops widely irrigated by center pivots in southern Brazil were considered: soybean (Kc = 1.15) and maize (Kc = 1.20). Both crops were evaluated during the flowering stage, which corresponds to one of the most water-sensitive phenological phases and is typically associated with peak evapotranspiration demand.

The purpose of this synthetic case study is not to reproduce specific real-world irrigation systems but rather to demonstrate the application of the proposed framework under contrasting climatic, hydrological, hydraulic, and energy conditions. For the Renewable Flexibility Index (RFI), a reference flexibility horizon of T_ref = 1.5 days was adopted, representing the maximum postponement period considered operationally acceptable during highly water-sensitive growth stages such as flowering.

The climatic, soil, hydraulic, and energy-related parameters adopted for each hypothetical region are presented in Table 2.

Table 2. Synthetic input parameters adopted for the hypothetical case study.

Parameter	Region 1	Region 2	Region 3
Reference evapotranspiration, ET_0 (mm day^{-1})	6.5	5.8	5.5
Effective precipitation (mm month^{-1})	60	90	100
Soil available water capacity, CAD (mm m^{-1})	60	130	110
Effective rooting depth – soybean (m)	0.7	0.8	0.8

Effective rooting depth – maize (m)	0.8	1.0	1.0
Irrigated area (ha)	100	100	100
Available flow rate (m³ h⁻¹)	80	150	130
Reservoir storage (m³)	500	2000	1500
Total dynamic head (m)	45	30	35
Pump efficiency (η)	0.65	0.75	0.72
Contracted power (kW)	75	90	85
Electrical reliability (C_e)	0.85	0.95	0.92
Reference flexibility horizon, Tref (days)	1.5	1.5	1.5
Peak irrigation demand hour	14h	13h	13h
Peak solar generation hour	12h	12h	12h

Water–Hydraulic Security Index (WHSI)

The WHSI revealed substantial differences among the three regions. Region 1 exhibited WHSI values of 2.26 for soybean and 2.40 for maize, indicating structural risk, with crop water demand exceeding more than twice the effective water availability of the irrigation system. This result is associated with the combination of high evapotranspiration, low effective precipitation, limited available flow, and reduced reservoir-storage capacity.

Regions 2 and 3 presented WHSI values ranging from 0.65 to 0.71 for both crops, corresponding to the attention category, where crop water demand represents approximately two-thirds of the effective water availability. The results are summarized in Table 3.

Table 3. WHSI results for soybean and maize in the three hypothetical regions.

Region	Crop	ETc (mm/day)	Deficit (mm/day)	Demand (m³/day)	Availability (m³/day)	WHSI	Classification
Region 1	Soybean	7.48	5.48	5480	2420	2.26	Structural Risk
Region 1	Maize	7.80	5.80	5800	2420	2.40	Structural Risk
Region 2	Soybean	6.67	3.67	3670	5600	0.66	Attention
Region 2	Maize	6.96	3.96	3960	5600	0.71	Attention
Region 3	Soybean	6.33	3.00	3000	4620	0.65	Attention
Region 3	Maize	6.60	3.27	3270	4620	0.71	Attention

Water–Energy Vulnerability Index (WEVI)

The WEVI confirmed the critical vulnerability of Region 1, with an index value of 1.00 for both crops. This result is directly associated with WHSI values above 1.0, which, when limited to 1.0 in the multiplicative composition of the index, lead to maximum vulnerability regardless of the remaining components.

Regions 2 and 3 presented WEVI values ranging from 0.74 to 0.79 for both crops, classified as high vulnerability. These results reflect the combination of moderate water pressure, low energy pressure, and relatively high electrical reliability. The EPI results indicate that none of the regions operates close to the contracted power limit, with values ranging from 0.19 to 0.60. Region 1 showed the highest relative energy pressure due to the larger pumping volume required. The results are presented in Table 4.

Table 4. WEVI results for soybean and maize in the three hypothetical regions.

Region	Crop	WHSI (limited to 1)	EPI	IR	WEVI	Classification
Region 1	Soybean	1.00	0.57	0.15	1.00	Critical
Region 1	Maize	1.00	0.60	0.15	1.00	Critical
Region 2	Soybean	0.66	0.19	0.05	0.74	High
Region 2	Maize	0.71	0.19	0.05	0.78	High
Region 3	Soybean	0.65	0.19	0.08	0.74	High
Region 3	Maize	0.71	0.22	0.08	0.79	High

Water–Energy Intensity Index (WEI)

The WEI_D results revealed significant differences in energy efficiency among the evaluated regions. Region 1 presented the highest values, 1.89 kWh ha⁻¹ mm⁻¹ for soybean and 1.88 kWh ha⁻¹ mm⁻¹ for maize, reflecting its greater total dynamic head (45 m) and lower pump efficiency (η = 0.65). Region 2 exhibited the lowest WEI_D values (1.09 kWh ha^{-1} mm^{-1} for both crops), benefiting from a lower total dynamic head (30 m) and higher pump efficiency (η = 0.75). Region 3 presented intermediate values (1.32 kWh ha^{-1} mm^{-1}), consistent with its intermediate pumping head and pump efficiency.

These results indicate that Region 1 offers the greatest potential for gains through energy-efficiency interventions. The results are presented in Table 5.

Table 5. WEI_D results for soybean and maize in the three hypothetical regions.

Region	Crop	Energy Consumption (kWh/day)	Irrigation Depth (mm/day)	WEI_D (kWh ha^{-1} mm^{-1})
Region 1	Soybean	1034	5.48	1.89
Region 1	Maize	1092	5.80	1.88
Region 2	Soybean	400	3.67	1.09
Region 2	Maize	432	3.96	1.09
Region 3	Soybean	397	3.00	1.32
Region 3	Maize	432	3.27	1.32

Renewable Flexibility Index (RFI)

The RFI revealed significant differences in renewable-integration flexibility among the evaluated regions. Unlike the previous formulation, the revised soil-water storage component (C_soil) contributed to distinguishing regional performance. Region 2 exhibited the highest soil-water storage flexibility (C_soil = 1.00), followed by Region 3 (C_soil = 0.89) and Region 1 (C_soil = 0.33), reflecting differences in soil available water capacity, rooting depth, and evapotranspiration demand.

The reservoir-storage component (C_res) remained the primary differentiating factor among regions, ranging from 0.057-0.061 in Region 1 to 0.337-0.363 in Region 2. These results indicate that Region 1 possesses substantially lower storage capacity for decoupling pumping operations from energy availability. Solar-demand alignment (M_solar) was slightly more favorable in Regions 2 and 3 (0.92) than in Region 1 (0.83), due to the smaller difference between peak irrigation-demand and peak solar-generation hours.

The resulting RFI classified Region 1 as having moderate flexibility (RFI = 0.371-0.372), whereas Regions 2 and 3 were classified as having high flexibility (RFI = 0.665-0.721). The results are presented in Table 6.

Table 6. RFI results for soybean and maize in the three hypothetical regions.

Region	Crop	C_soil	C_res	M_solar	RFI	Classification
Region 1	Soybean	0.33	0.061	0.83	0.372	Moderate
Region 1	Maize	0.33	0.057	0.83	0.371	Moderate
Region 2	Soybean	1.00	0.363	0.92	0.721	High
Region 2	Maize	1.00	0.337	0.92	0.711	High
Region 3	Soybean	0.89	0.334	0.92	0.677	High
Region 3	Maize	0.89	0.306	0.92	0.665	High

Priority Index (PI)

The integration of the three sub-indices into the Priority Index (PI) resulted in a clear differentiation among regions. Region 1 obtained the highest PI values for both crops (0.798 for soybean and 0.797 for maize), reflecting the combination of critical water–energy vulnerability, high energy intensity, and moderate renewable flexibility. Regions 2 and 3 obtained PI values ranging from 0.683 to 0.720, all classified as high priority. These results reflect relevant water–energy vulnerability, lower energy intensity, and favorable potential for photovoltaic integration. The final results are summarized in Table 7.

Table 7. Priority Index results for soybean and maize in the three hypothetical regions.

Region	Crop	WEVI	WEI_D (norm.)	RFI	PI	Classification
Region 1	Soybean	1.000	0.943	0.372	0.798	High
Region 1	Maize	1.000	0.943	0.371	0.797	High

Region 2	Soybean	0.733	0.545	0.721	0.683	High
Region 2	Maize	0.777	0.545	0.711	0.699	High
Region 3	Soybean	0.739	0.662	0.677	0.701	High
Region 3	Maize	0.788	0.662	0.665	0.720	High

Discussion

The results of the hypothetical case study demonstrate that the proposed framework can distinguish regions with different water–energy vulnerability profiles and identify the dominant drivers of risk and intervention potential. Region 1 emerged as the most critical case, simultaneously exhibiting maximum water–energy vulnerability (WEVI = 1.00), the highest energy intensity (WEI_D = 1.89 kWh ha^{-1} mm^{-1}), and the lowest renewable flexibility (RFI = 0.371–0.372). This outcome reflects the combined effects of high evapotranspirative demand, low effective precipitation, limited water availability, greater pumping head, lower pump efficiency, and reduced reservoir-storage capacity. These factors reinforce one another and would be difficult to identify comprehensively using isolated indicators.

Regions 2 and 3 exhibited more favorable profiles. Although both remained within the high-vulnerability category (WEVI = 0.74–0.79), they achieved substantially higher renewable flexibility (RFI = 0.665–0.721). The revised soil-storage component (C_soil) contributed to differentiating regional performance, with values ranging from 0.33 in Region 1 to 1.00 in Region 2. Together with greater reservoir-storage capacity and stronger alignment between irrigation demand and solar-generation profiles, these characteristics create favorable conditions for decoupling pumping operations from energy availability. Consequently, Regions 2 and 3 appear particularly suitable for photovoltaic-based decarbonization strategies.

Differences between soybean and maize were small across all evaluated regions and dimensions, with Priority Index variations below 0.02 in all cases. This suggests that the framework is more sensitive to regional characteristics—such as water availability, energy infrastructure, storage capacity, and soil properties—than to crop selection. Because both crops were evaluated during the flowering stage, when water demand is similarly high, regional constraints become the dominant factors influencing system vulnerability and performance.

The Priority Index results further demonstrate the value of integrating vulnerability, efficiency, and renewable-flexibility dimensions into a single decision-support metric. While Region 1 achieved the highest priority scores due to its critical vulnerability and poor operational performance, Regions 2 and 3 also received high-priority classifications because of their combination of remaining vulnerability and strong renewable-integration potential. Although Region 1 exhibited maximum water–energy vulnerability, its final Priority Index remained below the Very High priority threshold (PI < 0.80) because the index also incorporates renewable flexibility and normalized energy intensity, preventing vulnerability alone from determining the final classification. This finding highlights that intervention priority is determined not only by risk exposure but also by the expected benefits achievable through efficiency improvements and decarbonization strategies.

Conclusion

This study proposed a diagnostic framework for quantifying water–energy vulnerability in center-pivot irrigation systems through three complementary dimensions: the Water–Energy Vulnerability Index (WEVI), the Water–Energy Intensity Index (WEI), and the Renewable Flexibility Index (RFI). These dimensions were integrated into a composite Priority Index (PI) designed to support the identification and prioritization of regions for water-efficiency, energy-efficiency, and renewable-energy interventions. The framework combines publicly available datasets with operational information provided by irrigators, enabling the assessment of both regional conditions and system-specific characteristics.

The application of the framework to a synthetic case study representing three physiographic regions of Rio Grande do Sul demonstrated its ability to distinguish vulnerability profiles and identify dominant drivers of risk and intervention potential. Region 1 emerged as the most critical case, exhibiting maximum water–energy vulnerability, the highest energy intensity, and the lowest renewable flexibility. In contrast, Regions 2 and 3 combined moderate vulnerability with strong renewable-integration potential, highlighting favorable conditions for photovoltaic-based decarbonization strategies and intelligent pumping management.

The results demonstrate that vulnerability in irrigated systems is driven by the interaction among water availability, crop demand, energy reliability, pumping efficiency, storage capacity, and renewable-energy integration potential. This multidimensional nature of vulnerability supports the use of integrated assessment frameworks rather than isolated indicators.

From a methodological perspective, the framework contributes by explicitly distinguishing between risk, represented by the multiplicative formulation of the WEVI, and operational capability, represented by the additive formulation of the RFI. It also formalizes renewable flexibility as a diagnostic dimension, incorporating soil-water storage, reservoir-storage capacity, and the temporal compatibility between solar-energy generation and irrigation demand.

Future work should focus on validating the framework with data from real irrigation systems, calibrating the weighting coefficients of the Priority Index, and extending the analysis to capture seasonal variations throughout the crop cycle. Sensitivity and uncertainty analyses are also recommended to strengthen the framework's applicability in operational settings.

Overall, the proposed framework provides a replicable decision-support tool for improving water and energy management in irrigated agriculture. By combining regional-scale public datasets with system-level operational information, it supports intervention prioritization while promoting resilience, energy efficiency, and agricultural decarbonization.

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