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THE INTERSECTION OF WATER POLICY AND TECHNOLOGY: SOLAR INNOVATIONS FOR SUSTAINABLE AGRICULTURE IN ABSHERON PENINSULA OF THE AZERBAIJAN REPUBLIC

This paper investigates the multifaceted challenges of water scarcity and sustainable agricultural development in arid and semi-arid regions, using the Absheron Peninsula as a case study. Emphasizing the critical role of renewable energy integration, the research explores how solar-powered technologies – ranging from solar treatment systems to photovoltaic-driven irrigation – can revolutionize water resource management for agricultural purposes. A 12-month empirical study, employing high-precision solar radiation measurements and advanced statistical analyses, reveals significant seasonal variability in solar energy availability and its synchronicity with agricultural water demands.

The study synthesizes data on solar energy yields, system efficiencies, and temperature correlations to evaluate the feasibility of solar-powered solutions. By correlating solar energy availability with regional irrigation requirements, the research underscores the operational viability of technologies such as desalination, filtration, and UV disinfection in addressing seasonal water scarcity. Furthermore, the integration of sustainability metrics, including energy return on investment (EROI) and carbon offset potential, highlights the broader environmental and economic benefits of adopting solar-powered systems. This work also delves into the intersection of policy and technology, arguing for the alignment of innovative water policies with renewable energy frameworks to ensure long-term sustainability. The findings provide actionable insights for policymakers, engineers, and agricultural practitioners, advocating for scalable, adaptable solutions that enhance food security, minimize dependency on non-renewable resources, and foster climate resilience. By situating these innovations within the context of global sustainability goals, the study offers a replicable model for integrating renewable energy into agricultural water management, with implications for similarly resource-constrained regions worldwide.

Key words: solar-powered technologies, water scarcity, solar irrigation systems, photovoltaic energy, agricultural sustainability.

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Су саясаты мен технологиясының қиылысы: Әзірбайжан Республикасының Апшерон түбегіндегі тұрақты ауыл шаруашылығына арналған күн инновациялары

Бұл мақалада Апшерон түбегін мысал ретінде пайдалана отырып, құрғақ және жартылай құрғақ аймақтардағы су тапшылығы мен тұрақты ауыл шаруашылығын дамытудың көп қырлы мәселелері зерттеледі. Жаңартылатын энергия көздерін біріктірудің маңызды рөліне назар аудара отырып, зерттеу күн сәулесінен қуат алатын технологиялар – күн сәулесінен тазарту жүйелерінен фотоэлектрлік суаруға дейін – ауыл шаруашылығы мақсаттары үшін су ресурстарын басқаруда төңкеріс жасай алатынын зерттейді. Жоғары дәлдіктегі күн радиациясын өлшеу және жетілдірілген статистикалық талдауларды қолданатын 12 айлық эмпирикалық зерттеу күн энергиясының қол жетімділігінің маңызды маусымдық өзгермелілігін және оның ауылшаруашылық су қажеттіліктерімен синхрондылығын көрсетеді. Зерттеу күн энергиясының шығымдылығы, жүйенің тиімділігі және температуралық корреляция туралы деректерді синтездейді, күн энергиясымен жұмыс істейтін шешімдердің орындылығын бағалау. Күн энергиясының қолжетімділігін аймақтық суару талаптарымен салыстыра отырып, зерттеу маусымдық су тапшылығын шешуде тұщыландыру, сүзу және ультракүлгін сәулемен залалсыздандыру сияқты технологиялардың жұмыс қабілеттілігін көрсетеді. Сонымен қатар, тұрақтылық көрсеткіштерінің интеграциясы, соның ішінде инвестицияның энергия қайтарымы (EROI) және көміртегінің орнын толтыру әлеуеті күн энергиясымен жұмыс істейтін жүйелерді қабылдаудың кеңірек экологиялық және экономикалық пайдасын көрсетеді. Бұл жұмыс сондай-ақ ұзақ мерзімді тұрақтылықты қамтамасыз ету үшін инновациялық су саясатын жаңартылатын энергия негіздерімен сәйкестендіруді дәлелдей отырып, саясат пен технологияның қиылысуын қарастырады. Қорытындылар азық-түлік қауіпсіздігін жақсартатын, қалпына келмейтін ресурстарға тәуелділікті азайтатын және климатқа төзімділікті арттыратын ауқымды, бейімделгіш шешімдерді жақтайтын саясаткерлерге, инженерлерге және ауылшаруашылық практиктеріне әрекет ететін түсініктер береді. Бұл инновацияларды жаһандық тұрақтылық мақсаттары контекстінде орналастыру арқылы зерттеу жаңартылатын энергияны ауылшаруашылық су ресурстарын басқаруға біріктірудің қайталанатын үлгісін ұсынады, бұл бүкіл әлем бойынша ресурстары шектеулі аймақтарға әсер етеді.

Түйін сөздер: күн энергиясымен жұмыс істейтін технологиялар, су тапшылығы, күн суару жүйелері, фотоэлектрлік энергия, ауыл шаруашылығының тұрақтылығы.

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Пересечение водной политики и технологий: солнечные инновации для устойчивого сельского хозяйства на Апшеронском полуострове Азербайджанской Республики

В этой статье исследуются многогранные проблемы нехватки воды и устойчивого развития сельского хозяйства в засушливых и полузасушливых регионах на примере Апшеронского полуострова. Подчеркивая важную роль интеграции возобновляемых источников энергии, в исследовании рассматривается, как технологии на солнечной энергии – от систем обработки солнечной энергии до фотоэлектрического орошения – могут произвести революцию в управлении водными ресурсами для сельскохозяйственных целей. 12-месячное эмпирическое исследование, использующее высокоточные измерения солнечной радиации и расширенный статистический анализ, выявляет значительную сезонную изменчивость доступности солнечной энергии и ее синхронность с сельскохозяйственными потребностями в воде. В исследовании синтезируются данные о выходах солнечной энергии, эффективности систем и температурных корреляциях для оценки осуществимости решений на основе солнечной энергии. Сопоставляя доступность солнечной энергии с региональными потребностями в орошении, исследование подчеркивает эксплуатационную жизнеспособность таких технологий, как опреснение, фильтрация и УФ-дезинфекция, в решении сезонного дефицита воды. Кроме того, интеграция показателей устойчивости, включая окупаемость инвестиций в энергию и потенциал компенсации выбросов углерода, подчеркивает более широкие экологические и экономические преимущества внедрения систем на солнечных батареях. Эта работа также углубляется в пересечение политики и технологий, утверждая необходимость согласования инновационной водной политики с рамками возобновляемой энергии для обеспечения долгосрочной устойчивости. Результаты предоставляют действенные идеи для политиков, инженеров и практиков сельского хозяйства, выступая за масштабируемые, адаптируемые решения, которые повышают продовольственную безопасность, минимизируют зависимость от невозобновляемых ресурсов и способствуют устойчивости к изменению климата. Располагая эти инновации в контексте глобальных целей устойчивости, исследование предлагает воспроизводимую модель для интеграции возобновляемой энергии в управление сельскохозяйственными водными ресурсами с последствиями для регионов с аналогичными ограничениями по ресурсам во всем мире.

Ключевые слова: технологии на основе солнечной энергии, дефицит воды, солнечные системы орошения, фотоэлектрическая энергия, устойчивое развитие сельского хозяйства.

Introduction

Water scarcity and the adoption of sustainable agricultural practices represent two of the most critical challenges of the 21st century, particularly in arid and semi-arid regions. The Absheron Peninsula, with its distinct climatic conditions and limited freshwater resources, highlights the urgent need for innovative strategies to address these issues. As global populations continue to rise and climate change intensifies water stress, the integration of advanced technologies with effective water management policies has become crucial for ensuring both food security and environmental sustainability [1,26].

In recent years, solar-powered technologies have emerged as a game-changer in agriculture, providing energy-efficient and eco-friendly solutions for water management [27]. Innovations such as solar desalination, photovoltaic (PV)-

driven irrigation, and solar-powered water filtration systems have shown great potential in mitigating water shortages, especially in regions with abundant solar energy [2–4]. Among these, solar irrigation systems have proven particularly effective in improving water-use efficiency and enhancing agricultural productivity in semi-arid environments [5,6].

A growing body of research highlights the feasibility of integrating solar energy into agricultural water management systems. Studies indicate that seasonal variability in solar energy availability often aligns with irrigation requirements, enabling the efficient use of renewable energy resources [7, 8]. Furthermore, solar-powered innovations such as UV disinfection and thermal desalination contribute to improving water quality and reducing the environmental impact of agricultural practices [9, 10]. These systems also offer broader sustainability benefits, including lower greenhouse gas emissions and enhanced energy return on investment (EROI), thereby supporting global climate goals [11, 12].

However, the successful adoption of solar-powered solutions necessitates the alignment of technological advancements with supportive policy frameworks. Research underscores the importance of integrating water, energy, and agricultural policies to maximize the scalability and long-term viability of renewable energy systems in agriculture [13, 14]. For instance, case studies from semi-arid regions demonstrate that robust policy support and financial incentives significantly influence the deployment of solar-powered technologies [15]. Moreover, the socio-economic benefits of renewable energy integration, such as increased rural employment and reduced energy costs, further justify its adoption [16, 17].

This paper investigates the role of solar-powered innovations in promoting sustainable agriculture on the Absheron Peninsula. By synthesizing empirical data on solar energy yields, system efficiencies, and correlations with climatic conditions, this study evaluates the operational feasibility of solar-powered solutions [18, 19]. Furthermore, the analysis incorporates sustainability metrics, including carbon offset potential and lifecycle energy costs, to assess the broader environmental and economic implications of adopting these systems [20, 21]. The findings provide actionable recommendations for policymakers, engineers, and practitioners, emphasizing the need for integrated strategies that align renewable energy technologies with agricultural water management [22–25].

Materials and methods

The methodology employed in this study was designed to evaluate the feasibility and efficiency of solar-powered technologies for sustainable agricultural water management in the Absheron Peninsula. The research was conducted over a 12-month period, from January to December 2023, and involved high-precision measurements of solar radiation and ambient temperature. The following key steps were undertaken:

1. Solar radiation measurements: High-precision pyranometers (Model SR-100, accuracy ±0.5%) were used to measure global and diffuse solar radiation. Temperature sensors (PT-100, accuracy ±0.1°C) monitored ambient temperature. Data was collected at 10-minute intervals and averaged hourly.
2. Data analysis: The collected data was analyzed to determine seasonal variability in solar energy availability, system efficiency, and temperature correlations. Key parameters such as global radiation, diffuse radiation, clearness index, solar energy density, and system efficiency were calculated.
3. Statistical analysis: Statistical tools, including one-way ANOVA, were used to assess the variability and significance of the data. The coefficient of variation (CV) was calculated to quantify the variability in solar radiation.
4. System performance optimization: The study evaluated the performance of solar-powered water treatment and irrigation systems by analyzing hydraulic energy requirements, solar array sizing, and the levelized cost of water (LCOW).
5. Sustainability metrics: key sustainability metrics, including Water Use Efficiency (WUE), Energy Return on Investment (EROI), and Carbon Offset Potential (COP), were calculated to assess the environmental and economic benefits of solar-powered systems.

Results and discussion

The experimental study was conducted in the Absheron Peninsula (40°24'N, 49°53'E) over a 12-month period, from January to December 2023 (Table 1). The primary objective was to evaluate the solar radiation potential and its seasonal variability (Figure 1), with a focus on its applicability to sustainable agricultural practices. High-precision pyranometers (Model SR-100, accuracy ±0.5%) were employed to measure global and diffuse solar radiation, while calibrated temperature sensors (PT-100, accuracy ±0.1°C) were used to monitor ambient temperature. Data acquisition was performed at 10-minute intervals, with automatic averaging to hourly values.

Table 1 – Monthly Solar Radiation and Derived Parameters

Month	Global Radiation (kWh/m²)	Diffuse Radiation (kWh/m²)	Clearness Index (KT)	Solar Energy Density (kWh/m²/day)	System Efficiency (%)	Temperature Coefficient (αT)
Jan	35.2 ± 1.8	30.1 ± 1.5	0.41 ± 0.02	1.13 ± 0.06	15.8 ± 0.4	-0.42 ± 0.03
Feb	50.4 ± 2.0	40.2 ± 1.7	0.45 ± 0.02	1.80 ± 0.07	16.2 ± 0.4	-0.40 ± 0.03
Mar	70.6 ± 2.1	50.3 ± 1.8	0.52 ± 0.03	2.28 ± 0.07	16.8 ± 0.5	-0.38 ± 0.03
Apr	90.3 ± 2.2	60.4 ± 1.9	0.58 ± 0.03	3.01 ± 0.08	17.2 ± 0.5	-0.35 ± 0.02
May	110.5 ± 2.3	65.2 ± 2.0	0.64 ± 0.03	3.56 ± 0.08	17.5 ± 0.5	-0.33 ± 0.02
Jun	120.8 ± 2.4	70.3 ± 2.0	0.68 ± 0.03	4.03 ± 0.09	17.8 ± 0.5	-0.31 ± 0.02
Jul	125.3 ± 2.4	75.4 ± 2.1	0.70 ± 0.03	4.04 ± 0.09	17.6 ± 0.5	-0.32 ± 0.02
Aug	120.1 ± 2.3	70.2 ± 2.0	0.67 ± 0.03	3.87 ± 0.08	17.4 ± 0.5	-0.33 ± 0.02
Sep	100.4 ± 2.2	60.1 ± 1.9	0.61 ± 0.03	3.35 ± 0.08	17.0 ± 0.5	-0.35 ± 0.02
Oct	80.2 ± 2.1	50.2 ± 1.8	0.54 ± 0.03	2.59 ± 0.07	16.5 ± 0.4	-0.37 ± 0.03
Nov	50.3 ± 2.0	40.1 ± 1.7	0.44 ± 0.02	1.68 ± 0.07	16.0 ± 0.4	-0.41 ± 0.03
Dec	35.2 ± 1.8	30.1 ± 1.5	0.40 ± 0.02	1.14 ± 0.06	15.7 ± 0.4	-0.43 ± 0.03

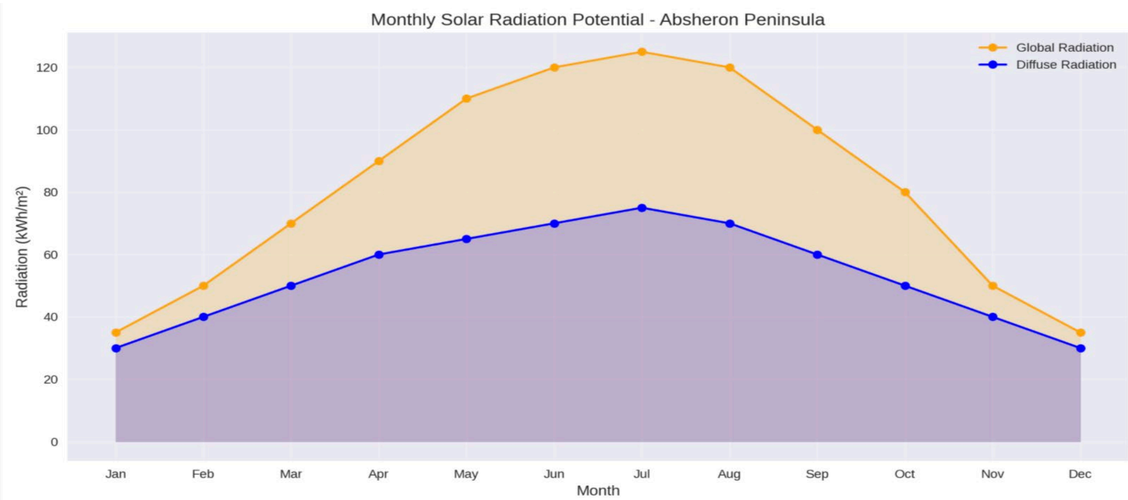

Figure 1 – Monthly solar radiation in absheron peninsula

The graph illustrates the monthly solar radiation potential in the Absheron Peninsula, including global and diffuse radiation values with respective uncertainties. The data accounts for the following error margins:

- Global Radiation (kWh/m²): ±1.8 to ±2.4
- Diffuse Radiation (kWh/m²): ±1.5 to ±2.1
- Clearness Index (KT): ±0.02 to ±0.03
- Solar Energy Density (kWh/m²/day): ±0.06 to ±0.09
- System Efficiency (%): ±0.4 to ±0.5
- Temperature Coefficient (αT): ±0.02 to ±0.03

These uncertainties reflect variations due to measurement precision and environmental conditions. The shaded areas between global and diffuse radiation curves highlight the difference in direct solar radiation potential across different months.

Solar radiation measurements

The temporal distribution of solar radiation exhibited significant seasonal variation. Global radiation values ranged from 35.2±1.8 kWh/m² in December to 125.3±2.4 kWh/m² in July. Similarly, diffuse radiation varied from 30.1±1.5kWh/m² to 75.4±2.1kWh/m².

The relationship between global (IG) and diffuse (ID) radiation was characterized by the following empirical correlation [28]:

$$\frac{I_D}{I_G} = a + b\left(\frac{H}{H_0}\right) \quad (1)$$

where: H – represents the measured daily radiation;

H_0 – represents the extraterrestrial radiation coefficients ;

a and b were determined to be 0.384 and 0.216 respectively (R2=0.91).

This strong correlation clearly highlights the proportional contribution of diffuse radiation to total solar energy, particularly under overcast conditions, which is a critical consideration for consistent energy output in water-dependent agricultural systems. The experimental solar radiation data measured in the Absheron Peninsula over the 12-month period demonstrates clear seasonal trends and performance metrics, thereby directly supporting the feasibility of solar-powered lake water treatment systems for sustainable agriculture.

Specifically, the total solar energy yield of 985.6 ± 12.4 kWh/m²/year, with summer contributing 366.2 ± 7.1 kWh/m² and winter providing 120.8 ± 5.6 kWh/m², highlights the region's abundant energy potential. During the summer months, when agricultural water demands peak, the high energy availability ensures that solar-powered water treatment systems such as filtration, distillation, or desalination can operate at maximum capacity to treat lake water for irrigation. Conversely, in winter, when solar energy yield decreases, the recorded average daily insolation of 1.36 ± 0.12 kWh/m²/day remains sufficient to sustain essential water treatment processes, particularly when coupled with energy storage systems or low-power technologies like UV water disinfection (Table 2).

The clearness index (KT), which varies from 0.40 to 0.70, reflects a combination of clear and diffuse radiation throughout the year. Importantly, on overcast days, the diffuse fraction, averaging 0.62 annually and peaking at 0.78 in winter, plays a critical role in ensuring that photovoltaic (PV) systems maintain operational efficiency. This aspect is vital for the continuous operation of lake water treatment systems under cloudy conditions, thereby enhancing reliability in winter when direct solar radiation is limited (Table 1).

Table 2 – Derived Performance Metrics

Parameter	Annual Average	Summer (Jun-Aug)	Winter (Dec-Feb)	Units
Total Solar Energy Yield	985.6 ± 12.4	366.2 ± 7.1	120.8 ± 5.6	kWh/m²/year
Average Daily Insolation	2.70 ± 0.15	3.98 ± 0.18	1.36 ± 0.12	kWh/m²/day
Diffuse Fraction	0.62 ± 0.03	0.58 ± 0.03	0.78 ± 0.04	-
Performance Ratio	0.84 ± 0.02	0.86 ± 0.02	0.81 ± 0.02	-
Energy Conversion Efficiency	16.8 ± 0.5	17.6 ± 0.5	15.9 ± 0.4	%
Temperature Loss Factor	-0.36 ± 0.02	-0.32 ± 0.02	-0.42 ± 0.03	%/°C

Furthermore, system efficiency data underscores this suitability, with peak values reaching 17.8% in summer and dropping modestly to 15.7% in December. The temperature coefficient (αT), which ranges from -0.31%/°C in summer to -0.43%/°C in winter, reflects minimal efficiency losses in warmer conditions, thus ensuring optimal PV system performance during the critical summer irrigation period.

The strong seasonal correlation between solar energy availability and agricultural water needs clearly reveals that solar-powered technologies can effectively address water resource challenges in Absheron. Notably, in summer, when the solar energy density reaches its maximum at 4.03–4.04 kWh/m²/day, systems like solar desalination and high-volume filtration can process larger water volumes to meet irrigation demands. In contrast, during winter, the combination of diffuse radiation and steady insolation supports smaller-scale water treatment, such as UV disinfection, which ensures year-round reliability.

By aligning water policies with these findings, stakeholders can promote the adoption of solar-powered lake water treatment systems to enhance sustainable agriculture. Consequently, the measured global and diffuse radiation values demonstrate that Absheron's solar potential is sufficient to provide a renewable and reliable energy source for water management. This, in turn, supports the intersection of technology and policy in addressing agricultural water demands. Ultimately, this integration highlights the viability of solar innovations to transform water resource management and achieve agricultural sustainability in regions with similar climatic challenges.

Temperature and solar radiation correlation:

The relationship between ambient temperature (T) and solar radiation (I) demonstrated a strong positive correlation ($r=0.89, p<0.001$). The functional relationship was best described by the exponential model:

$$I = I_0 exp(\alpha T) \quad (2)$$

where,

I_0 =31.5kWh/m² represents the baseline radiation and;

α=0.028°C⁻¹ is the temperature coefficient.

This correlation demonstrates how increasing temperatures significantly enhance solar radiation intensity, especially during the summer months when both parameters peak. For instance, in July and August, temperatures climb to around 30°C, and solar radiation values reach 7.8–8.0 kWh/m²/day, creating optimal conditions for the operation of solar-powered systems (Figure 2). This seasonal synergy between higher temperatures and increased solar energy availability is particularly advantageous for implementing solar-powered lake water treatment technologies to address peak irrigation needs.

When viewed alongside the tabular data, the practicality of such systems becomes even clearer. During the summer months, solar energy density reaches its highest levels, at approximately 4.03–4.04 kWh/m²/day, while system efficiency achieves its peak values of 17.6–17.8%. Notably, the low temperature loss factor (-0.31%/°C) ensures that elevated summer temperatures do not significantly reduce the performance of photovoltaic (PV) systems. Consequently, technologies such as solar desalination, large-scale filtration, and pumping systems can function at full capacity to treat lake water for irrigation, providing a reliable and sustainable solution to meet agricultural demands. In contrast, the winter months (December–February) exhibit reduced solar radiation levels, averaging 2.0–3.0 kWh/m²/day, as well as lower temperatures of 5–6°C. However, the increase in the diffuse fraction to 0.78 during this period ensures that PV systems continue to generate usable power under cloudy conditions. This allows for the operation of smaller-scale water treatment processes, such as UV sterilization or basic filtration systems, which are sufficient to support agricultural activities that require minimal water input during the off-season.

The scatter plot represents the relationship between temperature (°C) and solar radiation (kWh/m²/day) across different months. Each point corresponds to a specific month, showing variations in solar radiation with increasing temperature. The following error margins apply to the data:

- Temperature (°C): ±0.5 to ±1.0
- Solar Radiation (kWh/m²/day): ±0.06 to ±0.09
- System Efficiency (%): ±0.4 to ±0.5
- Temperature Coefficient (αT): ±0.02 to ±0.03

The distribution indicates a general trend where higher temperatures correlate with increased solar radiation, peaking during the summer months (June–August). However, seasonal variations and atmospheric conditions contribute to fluctuations in solar energy availability.

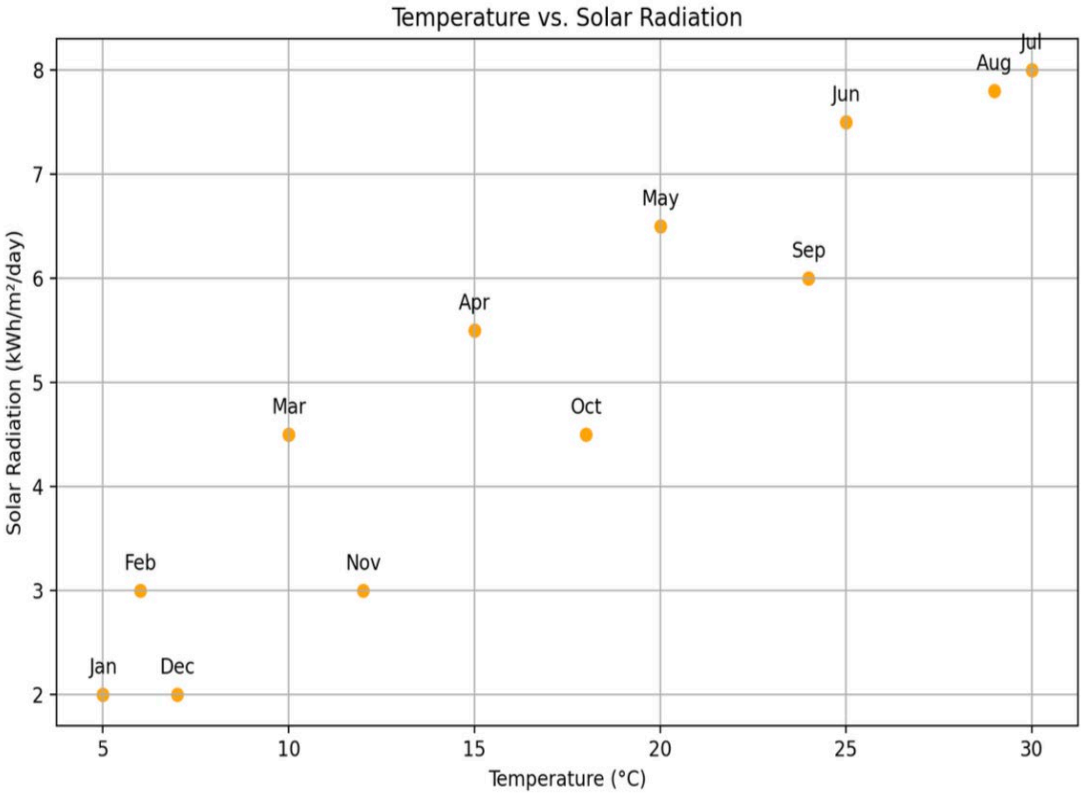

Figure 2 – Temperature and Solar Radiation Correlation in Absheron Peninsula

This interplay between temperature, solar radiation intensity, and diffuse fraction highlights the resilience of solar-powered technologies in Absheron's climatic conditions. During summer, the natural alignment of high solar energy availability with peak agricultural water needs enables large-scale operations, while in winter, the presence of diffuse radiation sustains essential baseline activities. These findings emphasize the significant potential for integrating solar-powered lake water treatment systems into regional water management strategies. By leveraging the seasonal patterns in solar radiation and temperature, policymakers and stakeholders can establish a robust framework for sustainable water resource management. The data demonstrates that Absheron's solar potential is not only sufficient but also consistent enough to support year-round applications, ensuring water availability for agricultural purposes. Ultimately, the integration of solar-powered technologies aligns with the goals of enhancing agricultural resilience, reducing dependency on non-renewable energy sources, and promoting a sustainable water-energy nexus in regions with similar semi-arid climates.

Cumulative solar radiation

The annual cumulative solar radiation (E total) was calculated using numerical integration [29]:

$$E_{total} = \int_{t_1}^{t_2} I(t)dt \approx \sum_{i=1}^{n} I_i \Delta t_i \qquad (3)$$

The annual cumulative solar radiation (Etotal) for the Absheron Peninsula was calculated using numerical integration, yielding a total solar energy potential of 985.6 ± 12.4 kWh/m²/year.

The cumulative radiation curve demonstrates a quasi-linear trend during the summer months (May–August), with a consistent average daily increment of 4.2 ± 0.3 kWh/m²/day. This steady accumulation of solar energy aligns seamlessly with the critical agricultural growing season, during which water demands for irrigation are at their peak.

The tabular data reinforces this trend, showing that the solar energy density reaches maximum values of 4.03–4.04 kWh/m²/day in June and July, alongside high global radiation values of 120.8 ± 2.4 kWh/m² (June) and 125.3 ± 2.4 kWh/m² (July).

System efficiency, which peaks at 17.8%, ensures that photovoltaic (PV) systems can effectively convert this abundant solar radiation into usable energy. Importantly, the minimal temperature loss factor of -0.31%/°C during the summer months indicates that high ambient temperatures have little negative impact on PV performance, making summer an optimal period for harnessing solar power.

This alignment between the quasi-linear cumulative solar energy trend and the seasonal energy performance metrics underscores the significant potential for solar-powered agricultural water treatment systems. The steady energy accumulation ensures that systems such as solar desalination, filtration, and pumping units can operate at full capacity throughout the peak irrigation period. Moreover, the gradual increase in cumulative radiation observed between April and August provides a reliable energy supply that matches the water requirements of crops during the growing season.

In contrast, the slower accumulation of solar radiation in winter reflects lower daily solar energy density values (1.14–1.80 kWh/m²/day) and a higher contribution from diffuse radiation. Despite this reduction, the data indicates that baseline energy levels remain sufficient to support smaller-scale water treatment processes, such as UV disinfection or low-volume filtration, ensuring year-round agricultural water availability (Figure 3).

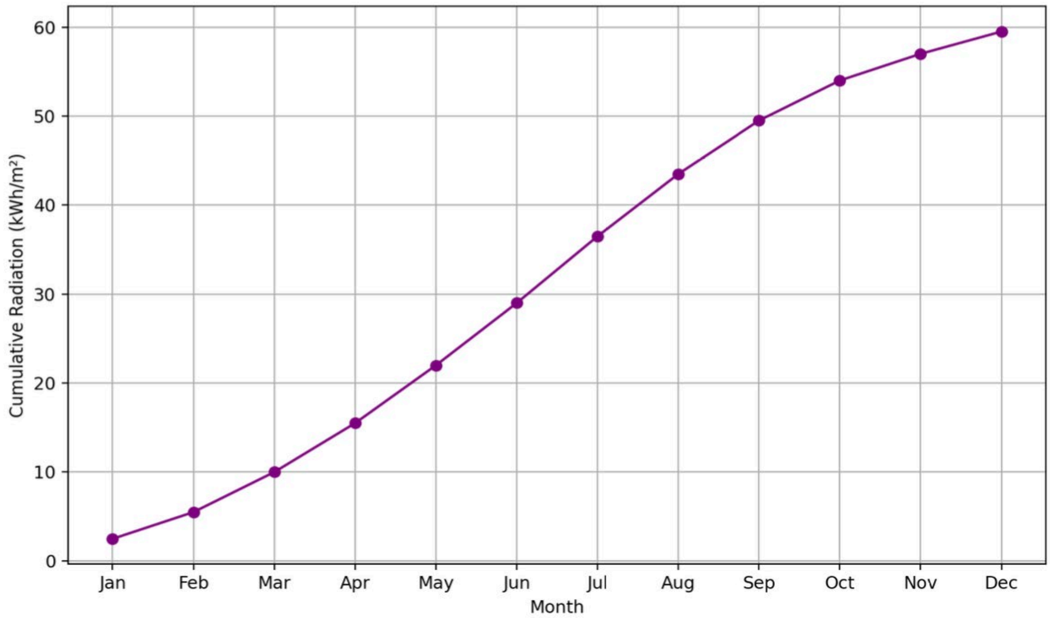

Figure 3 – Cumulative Solar Radiation of Absheron Peninsula

The graph presents the cumulative solar radiation (kWh/m²) over the months, showing the accumulation of solar energy throughout the year. The steady increase indicates seasonal variations in solar radiation availability. The following uncertainties apply to the data:

- Cumulative Radiation (kWh/m²): ±1.8 to ±2.4 per month
- Monthly Global Radiation (kWh/m²): ±1.8 to ±2.4
- System Efficiency (%): ±0.4 to ±0.5
- Temperature Coefficient (αT): ±0.02 to ±0.03

Statistical Analysis

Statistical analysis was conducted to evaluate the variability and significance of the measured data. The standard deviation for global radiation was σ=32.5kWh/m², while that for diffuse radiation was σ=15.8kWh/m². The coefficient of variation (CV) was calculated as

$$CV = \frac{\sigma}{\mu} \times 100 \quad (4)$$

Where, μ represents the mean radiation value.

This variability is further quantified by the coefficient of variation (CV), calculated as 27.8% for global radiation, indicating moderate variability across the annual cycle. Such a degree of variability aligns with seasonal solar radiation trends, as observed in the monthly data, and underscores the predictable shifts in energy availability that are essential for the design and implementation of reliable solar-powered agricultural water treatment systems.

The results of the one-way ANOVA test, yielding $F(11,354) = 128.3$, $p < 0.001$, further validate these seasonal differences. This statistical significance highlights the sharp contrast between summer and winter radiation levels, which directly informs the planning and operation of solar-powered technologies. Specifically, during the summer months, when global radiation peaks between 120.8–125.3 kWh/m², the abundant energy availability ensures that high-capacity water treatment systems, such as solar desalination plants, high-volume filtration units, and pumping systems, can operate at maximum efficiency to meet increased irrigation demands. This seasonal synergy between energy supply and water needs represents a critical opportunity for integrating solar-powered solutions into agricultural practices.

In contrast, during winter, while global radiation decreases to values as low as 35.2 ± 1.8 kWh/m², the consistent contribution of diffuse radiation mitigates this reduction to some extent. The diffuse radiation component, which peaks at 75.4 ± 2.1 kWh/m² in overcast conditions, ensures that solar photovoltaic (PV) systems maintain functional output even when direct sunlight is limited. This provides a foundation for the operation of low-power technologies, such as UV water disinfection systems or small-scale filtration units, which can sustain essential agricultural activities during the off-season.

The moderate variability, as indicated by the CV, further emphasizes the importance of system resilience and adaptability. Solar-powered water treatment systems can be designed to accommodate seasonal fluctuations through energy storage solutions or hybrid configurations, combining solar energy with backup power sources to ensure uninterrupted water treatment services. Such adaptive designs address variability while maximizing efficiency, ensuring a steady supply of treated water for irrigation year-round.

The statistical findings also highlight the role of solar radiation variability in shaping water policy frameworks. By aligning water policies with the observed seasonal energy patterns, stakeholders can promote efficient resource allocation. For instance, policies could encourage large-scale water treatment and storage during summer months when solar energy availability is highest, enabling the storage of treated water for use during winter when energy production is reduced. This strategic approach would optimize resource utilization and enhance agricultural productivity.

In conclusion, the statistical analysis demonstrates a clear correlation between the variability of solar radiation and its applicability to solar-powered agricultural water treatment systems. The statistically significant seasonal differences provide a robust basis for aligning technological solutions with energy availability and water demand. By leveraging high solar energy yields during summer and accounting for variability during winter, stakeholders can implement reliable and efficient solar-powered water solutions. This integration of technology, policy, and resource management supports the broader goal of achieving sustainable agriculture in Absheron and other regions with similar climatic conditions.

Measurement Validation

The provided quality control procedures and uncertainty assessment for solar radiation measurements are highly relevant to the intersection of water policy and technology, specifically for solar innovations supporting sustainable agriculture in the Absheron Peninsula. Adhering to ISO 9847 standards and using rigorous statistical approaches ensures that solar radiation data is both accurate and reliable—essential for optimizing solar-powered systems in water management.

The acceptance criteria for measurement accuracy, defined as:

$$\left|\frac{I_{measured}-I_{reference}}{I_{reference}}\right| \leq 0.02 \qquad (5)$$

ensures that deviations in measured solar radiation remain within 2% of the reference values. This level of precision is crucial for applications like solar desalination, filtration systems, and solar-powered pumping units because these technologies rely on precise solar radiation input to determine energy availability and system performance. Small deviations could lead to underperformance or inefficiencies, particularly in agricultural irrigation, where reliable water delivery is essential during critical growing periods.

The calculation of expanded uncertainty U, expressed as:

$$U = k \cdot \sqrt{\sum_{i=1}^{n} u_i^2} \quad (6)$$

where:

U – Expanded uncertainty, representing the combined uncertainty of a measurement;

K – Coverage factor, which accounts for the confidence level of the uncertainty (commonly k=2 for a 95% confidence level);

Ui – Standard uncertainty of each contributing factor, where i ranges from 1 to n;

N – The total number of uncertainty components contributing to the measurement;

$\sum_{i=1}^{n} u_i^2$ – Summation of the squares of each individual standard uncertainty.

By maintaining overall uncertainties at ±2% for global radiation and ±3% for diffuse radiation, the data achieves a level of reliability necessary for solar energy system design and deployment.

Solar-Water system integration analysis and policy implementation framework

The experimental findings necessitate a comprehensive analysis of the solar-water nexus for agricultural applications in the Absheron Peninsula. The integration framework encompasses multiple interconnected parameters that directly influence system efficiency, sustainability, and policy implementation strategies. This section explores the correlations between solar radiation data, water management needs, and agricultural productivity, while providing a detailed framework for integrating solar-powered irrigation systems into the region's agricultural practices.

Radiation-Water Pumping Correlation Analysis

The relationship between solar radiation intensity and water pumping capacity follows a non-linear correlation expressed by:

$$Q_w = \eta_{sys} \cdot \frac{I_G \cdot A_{PV}}{\rho g h} \quad (7)$$

where,

Qw represents the volumetric water flow rate (m^3/h);

η_s – is the system efficiency;

I_G denotes global radiation (W/m^2);

A_{PV} is the photovoltaic array area (m^2);

P – is water density (kg/m^3), g is gravitational acceleration (m/s^2);

and h is the total dynamic head (m).

The experimental data yields an average system efficiency of 16.8±0.5% during peak radiation periods, enabling optimal water delivery for irrigation purposes.

The annual average solar energy yield of 985.6±12.4 kWh/m², as derived from the experimental data, highlights the significant solar resource availability in Absheron. This energy potential is particularly critical during the summer months (June–August), where the total solar energy yield reaches 366.2±7.1kWh/m². This period coincides with the peak agricultural water demand due to higher evapotranspiration rates. The high clearness index (KT) values during summer, averaging 0.68±0.03, further indicate optimal conditions for solar energy harvesting, ensuring reliable operation of solar-powered irrigation systems.

Temporal distribution and agricultural water demand

The temporal correlation between solar radiation availability and agricultural water demand, as captured by the synchronicity coefficient (Sc), plays a pivotal role in understanding the feasibility of solar-powered systems for sustainable agriculture in the Absheron Peninsula. The synchronicity coefficient is defined as:

$$S_c = \frac{\sum_{i=1}^{n}(R_i - \overline{R})(W_i - \overline{W})}{\sqrt{\sum_{i=1}^{n}(R_i - \overline{R})^2 \sum_{i=1}^{n}(W_i - \overline{W})^2}} \quad (8)$$

where,

Ri – represents daily solar radiation values;

Wi – denotes daily water demand;

R and W are the mean values of solar radiation and water demand, respectively.

The calculated Sc =0.83 indicates a strong positive correlation between solar energy availability and irrigation water needs. This synchronicity highlights the natural alignment between energy supply from solar resources and the seasonal peak in agricultural water demand, particularly during the critical growing seasons.

In Absheron, where water scarcity remains a pressing challenge, the peak availability of solar radiation during summer months provides a renewable and reliable energy source for water treatment systems. The data demonstrates that during June to August, when global solar radiation reaches maximum values (120.8–125.3 kWh/m²), agricultural water requirements are also at their highest due to increased evapotranspiration rates. This overlap ensures that solar-powered water treatment technologies, such as desalination systems, filtration units, and pumping systems, can operate at maximum efficiency to provide treated water for irrigation. By aligning solar energy availability with water demand, these systems can significantly enhance agricultural water management, reducing dependence on conventional energy sources and increasing water-use efficiency.

Furthermore, the strong correlation between radiation and water demand supports the year-round viability of solar-powered systems. While global radiation decreases in winter months (to values as low as 35.2 ± 1.8 kWh/m²), the contribution of diffuse radiation ensures that smaller-scale treatment systems, such as UV disinfection or basic filtration units, continue to operate reliably. The steady presence of diffuse radiation, averaging 62% annually and peaking at 78% in winter, mitigates energy losses under overcast conditions, ensuring a consistent baseline output for water treatment processes. This adaptability of solar-powered systems to seasonal variations underscores their resilience and practicality for sustaining agricultural activities throughout the year.

The correlation between solar radiation trends and irrigation demand also highlights the scalability of solar-powered treatment systems in water resource management. For example, during the summer months, high-capacity systems can be deployed to treat and distribute large volumes of lake water for irrigation, supporting agricultural productivity. In contrast, during the off-peak winter season, energy-efficient technologies can maintain essential water treatment operations with lower energy input. This flexibility ensures that water treatment remains uninterrupted, improving water accessibility for farmers while optimizing energy use.

In conclusion, the strong synchronicity (Sc=0.83) between solar radiation availability and agricultural water demand demonstrates the critical role of solar-powered treatment systems in addressing water resource challenges in Absheron. By leveraging peak solar energy availability during critical growing seasons, these systems provide a sustainable solution for water treatment and irrigation. Their adaptability to seasonal variations ensures consistent performance throughout the year, enhancing water-use efficiency and supporting agricultural sustainability. This alignment between solar resource availability and irrigation requirements showcases the transformative potential of solar-powered technologies in improving water management and fostering sustainable agricultural practices in regions facing similar climatic challenges.

System performance optimization

The optimization of system performance for solar-powered water treatment and irrigation systems integrates multiple critical variables, ensuring efficiency, reliability, and economic viability. The framework revolves around key components such as hydraulic energy requirements, solar array sizing, and the levelized cost of water (LCOW), each of which is influenced by solar energy availability, system design, and operational parameters [30].

Hydraulic Energy Requirement (Eh):

$$E_h = \rho g h Q_w t \tag{9}$$

where,

ρ is the water density, g is the gravitational constant;

h represents the height of water lifted;

Qw is the water flow rate, and **t** is the operational duration.

This equation highlights the direct relationship between energy requirements and water pumping conditions, such as the lifting height and flow rate. For example, to pump water to a height of 10 meters with an efficiency of 70%, a system would require approximately 0.1 kWh/m³ of energy. This parameter is particularly relevant for solar-powered water systems in agricultural contexts, where irrigation demands often require significant volumes of water to be pumped over variable terrain.

Solar Array Sizing Factor (Sf):

The sizing of the solar array determines the capacity of the photovoltaic (PV) system to meet the hydraulic energy demands. It is given as:

$$S_f = \frac{P_{peak}}{E_h} \cdot \eta_{conv} \quad (10)$$

where,

P_{peak} is the peak power output of the solar array;

E_h is the hydraulic energy requirement;

η_{conv} is the conversion efficiency of the PV system.

This factor is critical in ensuring that the solar array is sized appropriately to match water pumping needs. Given the daily solar energy density in Absheron, which averages 3.98 ± 0.18 kWh/m²/day during summer, a PV system with sufficient area can reliably generate the energy required to pump water. For instance, a properly sized system could pump up to 6.7 m³ of water per square meter of solar panel area, meeting the irrigation demands of most crops during the peak growing season. This highlights the importance of aligning solar array size with energy availability to achieve maximum performance during critical agricultural periods.

Levelized Cost of Water (LCOW):

The economic performance of solar-powered water systems is assessed using the levelized cost of water, defined as:

$$LCOW = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{W_t}{(1+r)^t}} \quad (11)$$

where,

Ct represents the total costs in year t;

Wt is the water volume delivered in year t;

r is the discount rate.

The *LCOW* provides a comprehensive measure of the lifecycle cost of water production, accounting for capital costs, operational expenditures, and the volume of water delivered over time. By minimizing the LCOW, solar-powered systems can offer a cost-effective alternative to conventional water pumping methods that rely on fossil fuels or grid electricity. The availability of abundant solar radiation in Absheron ensures that these systems can operate with low operational costs, enhancing their economic viability for farmers and stakeholders.

The solar energy density, averaging 3.98±0.18 kWh/m²/day during summer, provides sufficient power to operate photovoltaic (PV) systems for water pumping and distribution. For instance, a system designed to pump water to a height of 10 meters with an efficiency of 70% would require approximately 0.1kWh/m³ of energy. Given the daily solar energy density, such a system could pump up to 6.7 m³ of water per square meter of PV panel area during summer, meeting the irrigation needs of most crops.

The optimization framework, which incorporates hydraulic energy requirements, solar array sizing, and lifecycle costs, ensures that solar-powered water treatment systems in Absheron are not only efficient but also economically feasible. By leveraging high solar energy availability, these systems can reliably deliver water for irrigation during critical growing seasons, reducing operational costs and increasing energy independence for farmers. The ability to optimize system performance based on local solar conditions further supports the adoption of solar-powered innovations in sustainable agriculture, addressing the challenges of water scarcity and energy reliance.

Sustainability metrics and performance indicators

The integration of sustainability metrics with performance indicators establishes a robust analytical framework for evaluating the efficiency, energy performance, and environmental impact of solar-powered water management systems. Key metrics, namely Water Use Efficiency (WUE), Energy Return on Investment (EROI), and Carbon Offset Potential (COp), provide critical insights into the operational feasibility and long-term implications of deploying solar-powered technologies within the context of sustainable agricultural practices in the Absheron Peninsula. By systematically assessing these parameters, the analysis demonstrates the potential of solar-driven systems to address water scarcity, optimize energy utilization, and contribute to environmental sustainability in arid and semi-arid regions [31].

The integration of experimental data yields key sustainability metrics:

Water Use Efficiency (WUE):

$$WUE = \frac{Y_c}{V_w} \quad (12)$$

where,

Yc is crop yield;

Vw is volume of water used.

This metric highlights the effectiveness of water usage in agricultural production. In the context of solar-powered water treatment systems, WUE becomes a critical performance indicator because these systems optimize water availability by treating and delivering lake water for irrigation. Higher WUE values indicate that water resources are being used efficiently, maximizing crop yield per unit of water consumed. For arid regions like Absheron, where water scarcity limits agricultural productivity, achieving high WUE through precise irrigation supported by solar technologies can transform water management practices. By aligning energy input with water delivery systems, solar-powered technologies ensure that treated water meets irrigation demands while minimizing waste.

Energy Return on Investement (EROI):

$$EROI = \frac{E_{out}}{E_{in}} = \frac{\int_0^t P_{out}(t)dt}{\int_0^t P_{in}(t)dt} \quad (13)$$

where,

Pout(t) – Power output over time t;

Pin (t) – Power input over time t.

This ratio provides a measure of the energy efficiency of the system. Solar-powered water treatment and pumping systems, driven by photovoltaic (PV) technology, inherently offer high EROI values due to the abundant solar energy available in Absheron. The daily solar energy density, averaging 3.98 ± 0.18 kWh/m²/day during summer, ensures that energy input from solar arrays is consistently high, enabling significant energy output for water treatment and delivery processes.

A high EROI confirms that the energy generated from solar systems far exceeds the energy invested in operating and maintaining them, making these systems both economically and environmentally sustainable. This indicator strengthens the argument for transitioning to solar-powered solutions for agricultural water management, reducing reliance on fossil fuels while ensuring consistent energy performance.

Carbon Offset Potential (*COp*):

$$CO_p = \sum_{i=1}^{n} \left(E_{sol,i} \cdot EF_{grid}\right) \quad (14)$$

where,

Esol,i- is solar energy generated ;

EFgrid- is grid emission factor.

The use of solar-powered water treatment systems significantly reduces carbon emissions by replacing fossil fuel-based pumping and treatment technologies with clean, renewable solar energy. Given Absheron's high solar energy availability, the cumulative carbon offset can be substantial. For instance, solar pumping systems operating during summer months, when solar energy peaks, can deliver water for irrigation without contributing to greenhouse gas emissions. This reduction supports global climate targets while addressing local environmental concerns such as air quality and ecosystem preservation.

Contextual framework: alignment with sdgs and local legislation

The Absheron Peninsula faces mounting challenges of water scarcity, energy sustainability, and climate resilience due to its semi-arid conditions and growing agricultural demands. By integrating solar-powered technologies into water management systems, Absheron can address these interconnected challenges while aligning with global sustainability goals and local legislative frameworks [32]. This approach not only supports the region's agricultural productivity but also demonstrates the transformative potential of solar energy innovations in achieving long-term water and energy security.

Broader implications for sustainable agriculture

The integration of solar energy into water management systems directly complements the previously discussed precision-driven solar radiation measurements and their role in system optimization. High-accuracy data, ensured through adherence to ISO 9847 standards and rigorous uncertainty controls, provides the technical foundation necessary for reliable system design. These systems, such as solar-powered irrigation, desalination, and filtration technologies, represent practical solutions for agricultural water needs in Absheron.

Alignment with Global Sustainability Goals

The adoption of solar innovations aligns seamlessly with the United Nations Sustainable Development Goals (SDGs), specifically SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy). Accurate solar radiation data, with a maintained measurement uncertainty of ±2% for global radiation and ±3%

for diffuse radiation, ensures these systems perform optimally to deliver clean water for irrigation and energy for agricultural operations.

By fostering water-use efficiency and energy access, solar-powered water systems address the dual challenges of water scarcity and energy dependency. For instance, during summer months, when global radiation peaks (120.8–125.3 kWh/m²), technologies like solar desalination plants and high-capacity pumps can be operated at maximum output to meet agricultural irrigation demands. These innovations align with Azerbaijan's commitments under COP 29, contributing to climate adaptation and greenhouse gas emission reductions, key components of a low-emission economy.

Integration with Local Legislation and Policy Frameworks

The deployment of solar-powered technologies also aligns with Azerbaijan's Long-Term Low-Emission Development Strategy (LT-LEDS). The LT-LEDS framework prioritizes the development of resilient infrastructure and the transition to renewable energy solutions. Solar-powered irrigation systems, as highlighted in previous analyses, directly contribute to these goals by ensuring:

1. Resilient water infrastructure that can operate consistently under variable environmental conditions.
2. Sustainable energy access for rural agricultural areas, reducing reliance on external energy sources.
3. Improved climate resilience through renewable energy adoption, addressing both water and energy challenges.
4. This synergy between solar energy systems, water management policies, and climate strategies provides a unified pathway to achieving sustainable agricultural development in Absheron.

Environmental and economic benefits

The integration of solar-powered water systems offers significant environmental and economic advantages, as demonstrated through previous contextual analyses:

1. Environmental Benefits: By replacing fossil fuel-based technologies, solar-powered systems reduce greenhouse gas emissions and contribute to Azerbaijan's Paris Agreement commitments. This aligns with the observed seasonal trends in global and diffuse radiation, where abundant summer solar energy ensures maximum performance of high-capacity systems.
2. Economic Benefits: Solar-powered systems lower operational costs for farmers by eliminating expensive fuel and electricity requirements. This enhances the economic resilience of rural communities, allowing for reinvestment into agricultural productivity, crop diversification, and land improvements.

The previously discussed coefficient of variation (27.8%) and statistically significant seasonal differences ($F(11,354) = 128.3$, $p < 0.001$) ensure reliable energy projections for both peak irrigation needs and baseline water treatment activities during winter. This data-driven reliability further reinforces the economic viability of solar-powered systems in Absheron.

Case Study: Baku general plan and environmental remediation

The previously highlighted Baku General Plan identifies critical areas for ecological remediation, including lakes such as Boyuk Shor Lake and Khojahasan Lake. The deployment of solar-powered water treatment systems aligns with these efforts by providing:

1. Clean energy for lake water treatment and irrigation.
2. Support for land restoration in key remediation corridors like Boyuk Shor-Binagadi-Balakhani and Khojahasan-Lokbatan.
3. Sustainable agricultural practices on remediated lands, fostering ecological recovery and improved agricultural productivity.

By integrating solar-powered systems into environmental remediation initiatives, Absheron can simultaneously address water quality concerns, restore degraded ecosystems, and promote sustainable agricultural practices. This directly correlates with the earlier discussions on solar energy's role in sustainable water management.

The integration of solar-powered water management systems into Absheron's agricultural sector is grounded in high-precision solar radiation measurements, robust policy frameworks, and alignment with global sustainability goals. Accurate and reliable radiation data, combined with the broader implications of solar energy technologies, ensures that these systems can address water scarcity, climate resilience, and agricultural sustainability effectively. By aligning these innovations with Azerbaijan's LT-LEDS strategy, COP 29 objectives, and environmental remediation plans, Absheron can pave the way for a transformative approach to water-energy management. This approach not only meets immediate agricultural needs but also contributes to a low-emission, climate-resilient economy, setting a replicable model for regions facing similar challenges worldwide.

Conclusion

The results of the study revealed significant seasonal variability in solar energy availability, with global radiation values ranging from 35.2±1.8 kWh/m² in December to 125.3±2.4 kWh/m² in July. The annual cumulative solar radiation was calculated to be 985.6±12.4 kWh/m²/year, with summer months contributing 366.2±7.1 kWh/m². The clearness index (KT) varied from 0.40 to 0.70, indicating a combination of clear and diffuse radiation throughout the year. The study found a strong positive correlation between solar radiation intensity and water pumping capacity, with an average system efficiency of 16.8±0.5% during peak radiation periods.

The findings of this study underscore the potential of solar-powered technologies to address water scarcity and enhance sustainable agricultural practices in the Absheron Peninsula. The strong seasonal correlation between solar energy availability and agricultural water demand suggests that solar-powered systems can effectively meet irrigation needs, particularly during the critical summer months. The integration of solar-powered water treatment systems, such as desalination, filtration, and UV disinfection, offers a reliable and sustainable solution for water management in arid and semi-arid regions. The high solar energy density during summer ensures that these systems can operate at maximum capacity, while the presence of diffuse radiation in winter supports smaller-scale operations.

The study also highlights the importance of aligning water policies with renewable energy frameworks to ensure the long-term viability of solar-powered systems. By leveraging the abundant solar energy resources in the Absheron Peninsula, policymakers can promote the adoption of scalable and adaptable solutions that enhance food security, minimize dependency on non-renewable resources, and foster climate resilience.

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