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Canal-top photovoltaic systems on the Qush-Tepa Canal: a model for energy–water synergy

Hameedullah Zaheb [a,b,*], Mohammad Shahab Sharifi [b,*], Mohammad Shafi Sharifi [c], Abdul Ghayoor Shokory [d], Atsushi Yona [a]

[a] Graduate School of Engineering and Science, University of the Ryukyus, 1 Senbaru, Okinawa 903-0213, Japan
[b] Department of Energy Engineering, Faculty of Engineering, Kabul University, Kabul 1006, Afghanistan
[c] Department Electrical and Electronics Engineering, Faculty of Engineering, Kabul University, Kabul 1006, Afghanistan
[d] Department of GIS, Faculty of Engineering, Avicenna University, Kabul 1006, Afghanistan

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ABSTRACT

Amid chronic energy shortages, severe water scarcity, and limited land availability for utility-scale solar installations, Afghanistan urgently needs integrated solutions that address its interlinked resource challenges. This study presents the first comprehensive techno-environmental and economic assessment of a Canal-Top Photovoltaic (CTPV) system on Afghanistan's ambitious Qush-Tepa irrigation canal; offering an innovative blueprint for sustainable energy-water synergy in arid and conflict-affected regions. The proposed system would cover 20 % of the canal area (5,712 m^2), with first-hand data sourced from primary data sources, online databases, published research, and Sentinel-2 satellite imagery. This study employs and introduces the Integrated Techno-Economic-Environmental Assessment (ITEEA) approach, incorporating SAM software, the Evaporation Coefficient Method (ECM), and cost-benefit analysis to evaluate the viability of CTPV deployment on the Qush-Tepa canal. The CTPV system is designed with an installed capacity of 836 MW and using a base-case capacity factor of 20 %, the system is capable of generating approximately 1,465 GWh annually, with a sensitivity range of 1,318–1,684 GWh corresponding to capacity factors of 18–23 %. Furthermore, the system reduces water evaporation by approximately 20 %, conserving about 445 million m^3 of water and yielding water-saving benefits valued at approximately USD 200 million over 25 years. Land-use savings contribute an additional USD 118 million to the total benefits. The initial investment required is approximately USD 1.08 billion, with project economics evaluated over a 25-year lifetime using a base discount rate of 12 % and sensitivity analysis across 8–16 %. Under favorable financing and performance scenarios, the system demonstrates positive economic returns, while results remain sensitive to capacity factor and discount rate assumptions. These findings validate the technical feasibility, economic potential, and long-term sustainability of the project, highlighting its capacity to address Afghanistan's energy and water scarcity challenges. Policymakers are strongly encouraged to integrate CTPV deployment into national energy and water strategies, as it presents a transformative solution with high return on investment and multi-sectoral impact.

1. Introduction

Afghanistan faces significant challenges in meeting its energy demands due to a severe power shortage, which has far-reaching implications for the nation's development [1]. The energy deficit has led to widespread disruptions in daily life, negatively affecting industries, healthcare services, and educational institutions. Domestic energy production, while gradually increasing, remains inadequate to meet the growing demands of the population, with renewable sources such as hydropower and solar energy accounting for only a small fraction of the total energy consumption [2]. Furthermore, the lack of infrastructure and investment in the energy sector has compounded the issue, leaving vast portions of the country, particularly rural and remote areas, without access to reliable electricity [3]. This energy crisis has stifled economic growth, hindered essential services, and exacerbated existing inequalities, perpetuating a cycle of poverty and underdevelopment.

* Corresponding authors.
E-mail addresses: hameedzaheb@gmail.com (H. Zaheb), shahabsharifi7@gmail.com (M.S. Sharifi).

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Addressing this critical issue requires innovative solutions that leverage Afghanistan's abundant natural resources, such as solar energy, to achieve energy independence and sustainability while fostering long-term socio-economic progress [4].

While heavily relying on imported electricity, Afghanistan has the potential to produce over 222,000 MW of electricity by using solar energy, which could reduce dependence on imports and make the country energy self-sufficient. Solar power is becoming more widespread: solar parks have been established in several cities, and in 2020, Afghanistan's energy administration commissioned 72 solar projects worth $345 million. The country's renewable energy resource potential exceeds 300,000 MW, with over two-thirds of this potential from solar energy, supported by nearly 300 sunny days annually [5]. This untapped resource holds immense economic and social significance, including strengthening energy security, creating employment opportunities, supporting productive sectors, and mitigating climate change [6,7].

To address constraints such as land availability, innovative renewable energy solutions have been explored, including Floating Photovoltaic (FPV) and Canal-Top Photovoltaic (CTPV) systems [8]. These technologies not only optimize land use but also provide environmental benefits such as reduced evaporation and improved efficiency from natural cooling [9,10].

Early experiments with FPV began in Japan in 1999 [11], and the idea soon gained international attention. In the early 21st century, canal-top solar projects were piloted in India, a country with both electricity shortages and severe evaporation losses, followed by large-scale systems in Gujarat and California [9]. Installing solar panels on canals reduces land consumption, preserving agricultural and ecological spaces. For example, a study in California showed that 15 % of the state's agricultural land is dedicated to solar projects—land that could be preserved if non-conventional spaces like canals were utilized [12].

Research has also shown that shading water bodies with PV panels can significantly reduce water evaporation. In India, covering 30 % of the Narmanda canal could conserve up to 90 billion liters of water annually [13]. Additionally, the natural cooling effect of water bodies lowers PV module temperatures, improving efficiency, reducing thermal stress, and lowering maintenance costs [14]. The availability of nearby water also simplifies dust removal, an important advantage in arid regions such as northern Afghanistan [15].

CTPV systems possess several thermodynamic, structural, and operational characteristics that distinguish them from both land-mounted and floating PV configurations. First, the presence of flowing water beneath the PV arrays creates a localized cooling micro-climate that reduces module operating temperature and can improve energy yield by 2–5 % depending on climate and design conditions [14,16]. The continuous air movement above the canal surface enhances convective heat dissipation, mitigating thermal stress and improving long-term module reliability relative to ground-mounted systems in arid regions. Second, structural design constraints over canals typically require lower tilt angles, longer spans, corrosion-resistant support structures, and linear array geometries, which influence irradiance capture and cabling losses in ways not observed in floating PV (FPV) systems [17,18]. Unlike FPV systems, which rest on buoyant pontoons, CTPV installations must accommodate canal hydraulics, maintenance access, and load distribution across non-uniform embankments, resulting in different capital cost structures and performance behaviors. Furthermore, CTPV systems provide dual benefits by simultaneously generating electricity and reducing evaporation losses, an increasingly important consideration for water-stressed countries [19,20].

Despite these advantages, CTPV technology presents structural and operational challenges. Canal-spanning support structures must withstand currents, wind, and dust storms while accommodating thermal expansion [17,18]. Electrical wiring requires careful insulation to prevent corrosion and ensure accessibility for maintenance [19]. To address these, researchers recommend lightweight materials, waterproof connectors, and remote monitoring through smart sensors [11]. Regular cleaning remains a challenge but can be improved with automated devices such as robots, brushes, and drones.

Environmental concerns also need consideration. Shading may disrupt aquatic ecosystems by affecting photosynthesis, oxygen levels, and hydrodynamics [20,21]. Structural debris, installation noise, or maintenance activities may also disturb aquatic life [22].

Large-scale initiatives further demonstrate the potential of CTPV [23]. The Gujarat Canal Solar Power Project, launched in 2012 with a $2.2 million pilot, now targets 2,200 MW of capacity with 10 % canal coverage, saving 20 billion liters of water annually. Similarly, California's Project Nexus, launched in 2021, aims for 13 GW by 2026, conserving 63 billion gallons of water annually [21].

Afghanistan also presents opportunities for adopting CTPV. The Qush-Tepa Canal, currently under construction in northern Afghanistan, is designed to divert water from the Amu Darya to irrigate 550,000 ha and impact over 60,000 households [24,25]. Given its scale and strategic significance, the canal represents a promising site for integrating CTPV systems.

Despite international demonstrations of CTPV systems, no study has undertaken a high-resolution, canal-scale techno-economic and environmental assessment for Afghanistan or comparable fragile economies (water-scarce, climate-sensitive, and infrastructure-limited regions). This research presents the first integrated evaluation of a CTPV system for the Qush-Tepa Canal using a combined System Advisor Model (SAM)–based generation simulation, the Evaporation Coefficient Method (ECM), and a bottom-up economic model. Unlike prior studies, this work quantifies energy yield, water savings, land-use avoidance, and financial performance for a large-scale canal corridor in an arid, infrastructure-limited context. The analysis provides evidence-based insights on system feasibility under conditions of high solar irradiance, severe water scarcity, and limited grid connectivity, conditions typical of fragile and conflict-affected regions. By establishing a replicable, data-driven assessment framework, this study contributes new methodological and contextual knowledge to the literature on CTPV deployment in developing countries.

This study bridges these gaps by analyzing the techno-economic and environmental impacts of installing CTPV systems on the Qush-Tepa Canal. It contributes in several ways:

1. Demonstrates feasibility of CTPV in addressing dual challenges of energy shortages and water scarcity.
2. Highlights co-benefits for water conservation and sustainable irrigation.
3. Establishes profitability through cost-benefit analysis, including avoided land-acquisition costs.
4. Tailors' CTPV application to Afghanistan's unique context, creating a replicable model for similar regions.
5. Provides insights for policymakers and investors, encouraging sustainable energy adoption.

Finally, this study evaluates the potential of installing CTPV systems on 20 % of the Qush-Tepa Canal surface, assessing energy generation, water conservation, and economic feasibility. This dual approach seeks to enhance Afghanistan's renewable capacity and mitigate water scarcity, contributing to sustainable development.

1.1. Site profile of the Qush-Tepa canal

Along with dozens of national projects, the Qush Tepe Canal, which has recently started, is one of the most fundamental and vital projects in the country, with a length of 285 km (excluding sub-canals), a top width of 125 m, a bed width of 85 m, a water depth of 6.5 m, and a canal depth of 8 m. The irrigation capacity of the canal is 650 cubic meters per second, which can irrigate 550,000 ha of fresh and barren land ready for cultivation. The initiation and implementation of the Qush Tepe project enrich agricultural products and, on the other hand, directly provides employment opportunities for skilled and unskilled people. The project started at 2022 and is expected to be completed on 2028. The completion and implementation of the above-mentioned project will take about 6 years, which are divided into the following three phases:

1) The first phase, 108 km long, starts in Kaldar and ends in Neckah, Daulat Abad district of Balkh province, as shown in Fig. 1.
2) The second phase is 177 km long, which starts from Neckah and ends in Andkhoi district of Faryab province.
3) The third phase is the distribution of sub-canals.

The canal system includes several segments with varying lengths and costs. The Main Canal Lined is 285 km long, costing $185,116,271.34. The exact location of Qush-Tepa canal's intake is at Kaldar with coordinates of Lat 37.079 and Lng 67.788; the orientation map of the main and sub-canals are shown in Fig. 1.

The flow duration curve of the amu Darya is shown in Fig. 2.

The canal system consists of several sections with varying lengths and discharge rates. The main canal has a length of 285 km, with a discharge rate of 950.82 m^3/s. The branch canal measures 105.932 km in length and has a discharge of 332.480 m^3/s. The secondary canal is 308.847 km long with a discharge of 42.36 m^3/s. The average discharge rate for the tertiary canal is 3.5 m^3/s, while the quaternary canal has a discharge rate of 0.15 m^3/s.

This study explores the techno-economic feasibility of CTPV systems on the Qush-Tepa Canal, a major irrigation canal in Afghanistan. Qush-Tepa Canal is exposed to high solar radiation and suffers from significant water losses due to evaporation. The installation of CTPV systems on the canal could potentially reduce water losses by reducing evaporation [25] while also generating renewable energy. This could provide a win–win solution for both water conservation and renewable energy generation in the region. Further research is needed to determine the exact benefits and costs of such a system. The satellite imagery of the Qush-tepa canal has been carried out using the Open-Source Hub by utilizing the Sentinal-2 satellite for the imagery (Fig. 3).

2. Materials and methods

This study adopts an integrated, multi-method research design combining structured interviews, satellite imagery analysis, simulation modeling, and mathematical calculations to evaluate energy generation, evaporation reduction, economic feasibility of a CTPV system on the Qush-Tepa Canal and proposes a novel framework for replicability and scalability. Given the limited availability of public data during the canal's construction phases, detailed interviews with engineers from the National Development Corporation (NDC) were conducted. The interviews, guided by a comprehensive questionnaire, collected data across seven thematic areas, including canal dimensions, flow rates, sediment management, and irrigation plans. These insights were further enriched using Sentinel-2 satellite imagery to monitor construction progress and capture precise geographic details of the canal layout. This integrated approach ensured robust data acquisition, addressing key knowledge gaps and enabling a thorough analysis of the CTPV system's potential impacts on energy and water resources in Afghanistan.

A comprehensive literature review containing studies from 2017 to 2023 provided sufficient information, including an overview of the Qush-Tepa canal, effects of CTPV on water canals, and techno-economic outputs from similar systems, such as India's Gujarat and California's Nexus project. For data analysis, two complementary methods were used: simulation through the System Advisor Model (SAM) and mathematical calculations. SAM, a widely recognized techno-economic tool developed by the National Renewable Energy Laboratory (NREL), was selected for its ability to model renewable energy systems and provide detailed financial insights, including cash flow, energy costs, and payback periods. Since the Qush-Tepa Canal is vast, designing a CTPV system for its entire length would not be economically feasible; therefore, following international best practices, 20 % of the canal was selected, specifically the portion crossing Mazar-i-Sharif, as it offers higher solar energy potential and has more available weather data for accurate system optimization and efficiency analysis. To simulate the performance of the proposed CTPV system, the selected portion was analyzed using SAM based on Typical Meteorological Year (TMY) data. The meteorological inputs, including global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), ambient temperature, and wind speed, were sourced from the National Solar Radiation Database (NSRDB). The NSRDB TMY dataset provides long-term, site-specific hourly weather data derived from satellite observations and ground-based measurements and is widely used for utility-scale photovoltaic performance assessment. The use of TMY data ensures that the simulated energy yield represents a statistically typical long-term climatic condition rather than short-term interannual variability. Temperature effects on photovoltaic module performance were explicitly incorporated using the SAM thermal and electrical performance framework. Module operating temperature was calculated using SAM's NOCT-based thermal model, which estimates cell temperature as a function of ambient air temperature, plane-of-array irradiance, and

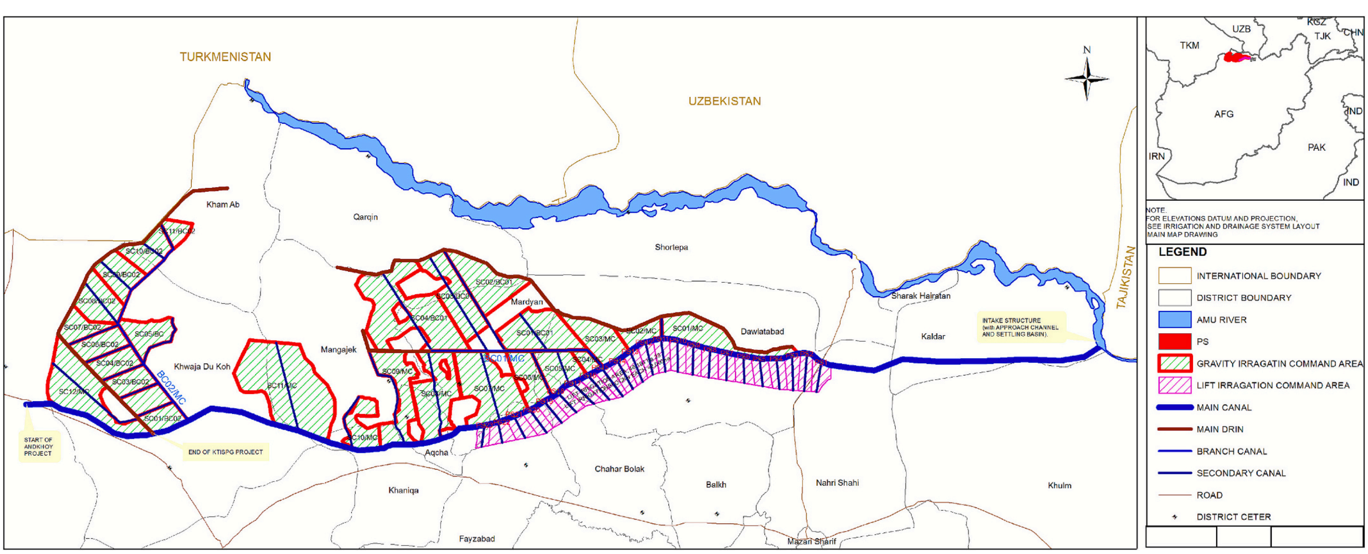

Fig. 1. Project command area of the Qush-Tepa Canal and its associated sub-canals, illustrating the geographic extent and irrigation coverage of the canal network.

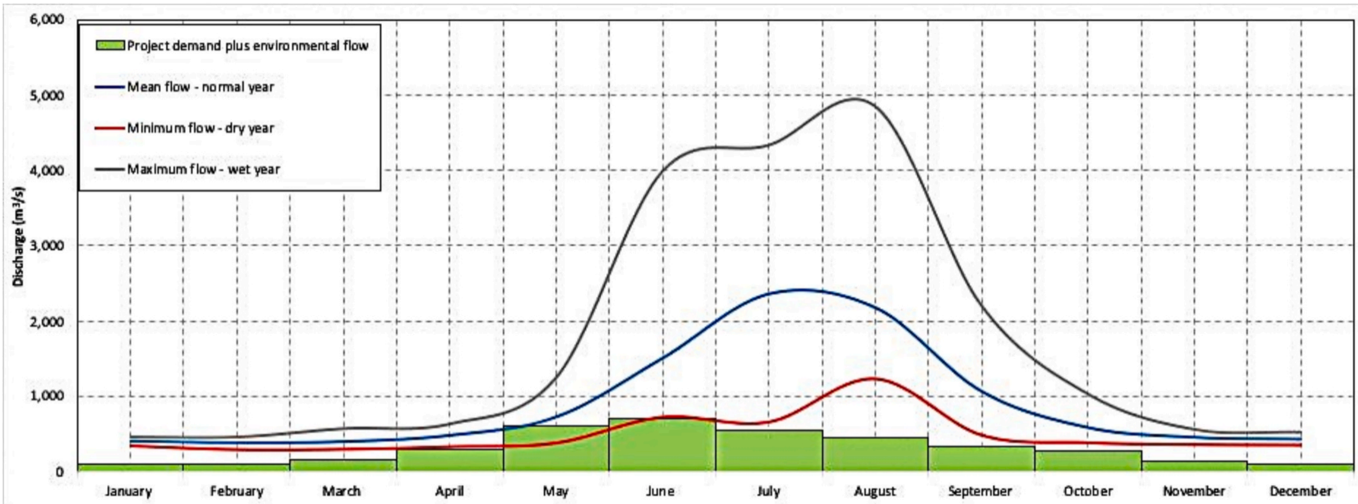

Fig. 2. Flow duration curve (FDC) of the Amu Darya River, representing the variability and reliability of river discharge over the recorded period.

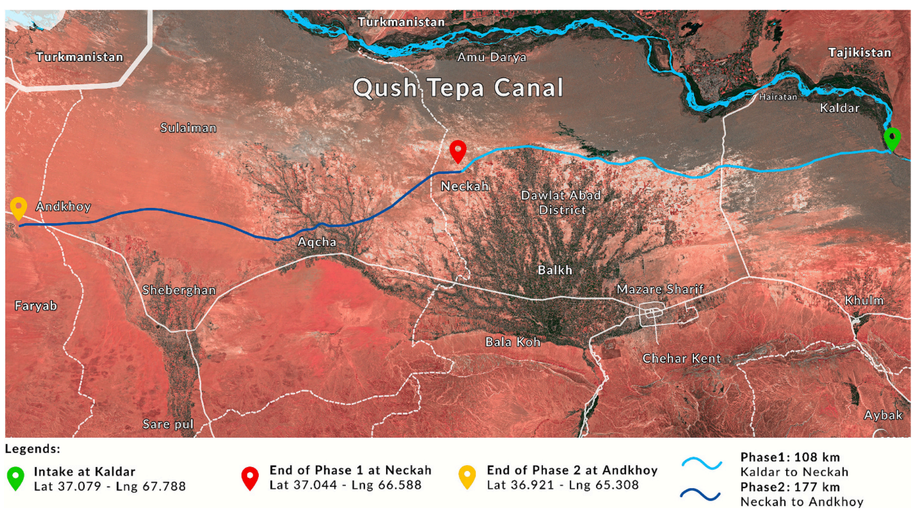

Fig. 3. Mapping of the first and second phases of the Qush-Tepa Canal using Sentinel-2 satellite imagery, highlighting the canal's spatial development and alignment.

wind speed. The nominal operating cell temperature (NOCT) approach accounts for convective and radiative heat transfer without requiring explicit user-defined U-values. The resulting cell temperature was then used to correct module power output through the manufacturer-specified temperature coefficient of power, applied internally by SAM's performance model.

The outputs from SAM provided critical insights, such as hourly and annual energy generation, the impact of temperature on system efficiency, and visualizations of performance trends over time.

The PV system configuration in SAM was defined using a fixed-tilt layout representative of canal-top deployment. The array geometry (tilt, azimuth, and row spacing), module and inverter selections, and balance-of-system (BOS) assumptions were specified in SAM to compute plane-of-array irradiance, temperature-corrected module output, inverter conversion, and total AC energy yield. Table 1 summarizes the complete system design inputs used in the simulation, and Table 2 reports the modeled system losses and gains applied to the annual energy output.

To ensure the accuracy of the simulation results, the findings were verified using a mathematical formula for daily energy output estimation, offering robust validation of the results:

$$E = A \times r \times H \times PR \tag{1}$$

Table 1
SAM input configuration for the proposed CTPV system (fixed-tilt).

Category	Parameter	Value used in this study
Array geometry	Tilt angle (°)	0
	Azimuth (°)	180° facing-south
	Row spacing / GCR	0.4 m
	Tracker	None (fixed-tilt)
PV module	Module type / technology	Crystalline-silicon (mono-Si) 550 w
	Nameplate efficiency	19 %
Inverter	Inverter type	Central inverter architecture
	DC/AC ratio (ILR)	1.34
	Inverter efficiency	97 %
Electrical design	DC wiring voltage	1500 DC
	AC collection voltage	MV
BOS / Interconnection	Step-up transformer/ substation	Included (grid interconnection via Charbolak)

where E is the energy output in Kilowatt-hours (kWh), A is the total solar panel area in square meters (m^2), r is the solar panel yield or efficiency in percentage (%), H is the annual average solar radiation on tilted panels in Kilowatt-hours per square meter (kWh/m^2), and PR is the performance ratio (typically between 0.5 and 0.9, with a default value of

Table 2
System losses and gains used in yield calculation.

Loss / gain category	Definition	International default value
Soiling	Dust/soiling on modules	**2 %**
Shading	Near/far shading & self-shading allowance	**3 %**
Mismatch	Module/string mismatch	**2 %**
Wiring	DC + AC ohmic wiring losses	**2 %**
Connections	Connector/contact losses	**0.5 %**
LID	Light-induced degradation (initial)	**1.5 %**
Availability	Scheduled/unscheduled downtime	**3 %**
Total system loss	Combined	**≈14 %**

0.75).

To evaluate the system's potential for water savings and to quantify evaporation reduction from the canal, the Evaporation Coefficient Method (ECM) was applied. The ECM was selected for its computational efficiency, ease of application, and its ability to deliver consistent and reliable results across varying hydrological conditions. Given the scale and scope of the Qush-Tepa Canal project, this method offers a practical and effective approach for estimating evaporation losses, aligning well with the study's objectives and ensuring clarity in interpretation and replication of results. This method calculates water loss based on key parameters including air temperature, humidity, wind velocity, and the surface area of the water body. Its simplicity and adaptability made it an ideal choice for estimating the impact of CTPV installations on water evaporation in the resource-constrained setting of this study.

$$g_s = \Theta \times A \times (x_s - x)/3600 \quad (2)$$

where g_s is amount of evaporated water per second (kg/s), Θ is (25 + 19 V) and is evaporation coefficient (kg/m^2/h), V is velocity of air above the water surface (m/s), A is water surface area (m^2), x_s is maximum humidity ratio of saturated air at the same temperature as the water surface (kg H_2O in kg Dry Air), and x is humidity ratio air (kg H_2O in kg dry air).

The maximum saturation humidity ratio in air x_s is the ratio of the mass of water vapor to the mass of dry air when the air is saturated ($M_{DA(Sat)}$) with water vapor at a given temperature and pressure.

$$x_s(atgivenTandP) = \frac{M_{watervapor}}{M_{DA(Sat)}} \quad (3)$$

To find the humidity ratio in air (x):

$$x = 0.62198p_w/(p_a - p_w) \quad (4)$$

where x is the humidity ratio, p_w is the partial pressure of water vapor, and p_a is the atmospheric pressure of moist air.

Hence, to calculate the reduction in water evaporation, with 20 percent of the canal covered with CTPV, assuming the water temperature and weather data to remain constant and only change in exposed areas of the canal to sunlight. Therefore, the ECM was formulated for both cases (as shown in Fig. 4, pre- and post-CTPV installation, and the results were analyzed.

The CTPV capital cost was derived using a component-based benchmark adjustment approach rather than a uniform scaling of total CAPEX. First, the baseline utility-scale fixed-tilt PV CAPEX was taken as 1.15 USD/W_{DC}, obtained from the NREL Annual Technology Baseline (ATB 2024) cost of 1.56 USD/W_{AC}, converted to a DC basis using the ATB inverter loading ratio (ILR ≈ 1.34) [26].

The relative cost shares of major PV system components were adopted from the International Energy Agency (IEA) utility-scale PV investment cost structure, which reports representative global shares for modules, mounting structures, electrical balance-of-system (BOS), inverters, and installation and soft costs [27]. These shares were applied to the NREL benchmark to obtain a component-wise baseline CAPEX.

Consistent with the canal-top PV literature, only the mounting and structural subsystem was adjusted to reflect canal-top deployment conditions. Multiple studies report that canal-top systems require 2–3 times higher structural and mounting costs than ground-mounted PV due to long-span elevated supports, corrosion-resistant materials, and canal-embankment anchoring, while module, inverter, and soft costs remain largely unchanged [22,28]. Accordingly, a 2.5× multiplier was applied exclusively to the mounting-structure component, while all

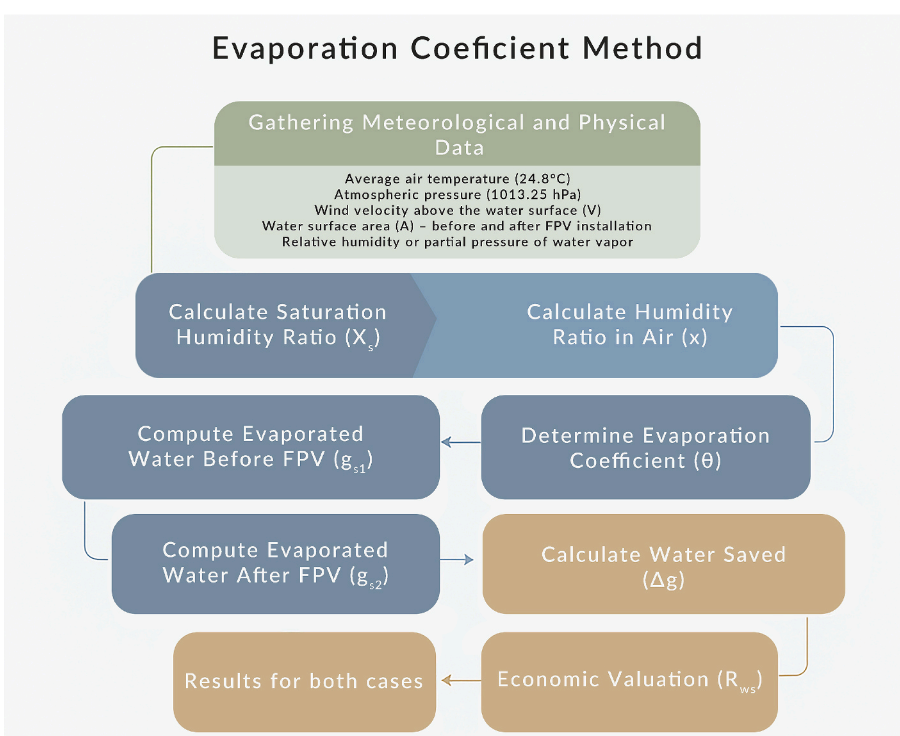

Fig. 4. Flowchart of the ECM used for this study.

other components were retained at their baseline values (Table 3).

Using this component-level adjustment yields a modified CTPV benchmark CAPEX of 1.254 USD/W_{DC}, which is adopted in the subsequent economic analysis. As the proposed CTPV system requires grid interconnection to regional load centers via the Charbolak substation, additional infrastructure in the form of a step-up substation and associated transmission cabling is required. Based on consultations with DABS experts, the combined cost of these grid-connection components is estimated at approximately USD 25 million, equivalent to 29.9 USD/kW. This cost is explicitly included in the economic analysis, resulting in an updated total capital expenditure of 1.283 USD/W.This approach avoids overstating total costs while explicitly accounting for the canal-top–specific structural premium.

The operation-expenditures OPEX vary largely from 0$/kW to 40 $/kW as per NREL ATB 2024, but as stated by Ramasamy et al. [29] in a report by NREL, the O&M costs of utility scale PV systems is 24$/$kW_{AC}$-yr ($18.5/kW_{DC}-yr) in 2022, which can be divided into system-related expenses ($14.4/$kW_{AC}$-yr), property-related expenses ($5.4/$kW_{AC}$-yr), and administration-related expenses ($2.4/$kW_{AC}$-yr).

Using this approach, the capital cost was calculated to provide insights into the system's economic viability, particularly in Afghanistan's context, where cost efficiency is critical for large-scale renewable energy adoption. The capital cost is calculated adopting the following equation:

$$C_{total} = P_{installed} \times C_{benchmark} \quad (5)$$

where C_{total}, $P_{installed}$, and $C_{benchmark}$, shows total installed system cost, total installed capacity and benchmark cost per W. Hence, and the installation cost per kWh was derived as:

$$C_{total/kWh} = C_{total}/P_{installed} \quad (6)$$

To assess the economic viability, levelized cost of energy (LCOE) was calculated using:

$$LCOE = Inv_0/(Q \times PVF_{i,T}) \quad (7)$$

where Inv_0 indicates the initial investment or total installed cost of the system, Q shows annual production and $PVF_{i,T}$ shows the present value factor. In addition to the conventional LCOE, an environmentally adjusted LCOE and Payback Time in Monetary Terms (PBTM) were evaluated to account for monetizable environmental co-benefits associated with canal-top PV deployment. Water conservation benefits from reduced evaporation and land-use benefits from avoided land occupation were quantified and treated as annual monetary credits. The environmentally adjusted LCOE was computed by subtracting these credits from the annualized cost stream, while PBTM was defined as the first year in which cumulative discounted net monetary benefits, including electricity revenues and environmental co-benefits, offset total project costs, using the same discount rate and project lifetime assumptions as the base economic analysis.

$$LCOE_{env} = \frac{\sum_{t=0}^{T} \frac{(C_t B_t)}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (8)$$

$$PBTM = \min\left\{ t : \sum_{k=0}^{t} \frac{(R_k + B_k - C_k)}{(1+r)^k} \geqslant 0 \right\} \quad (9)$$

where $B_t = B_t^{water} + B_t^{land}$, representing water-saving and land-saving benefits, respectively. And is electricity sales revenue in year k, B_k is total monetized co-benefit (water + land), and C_k is total cost (CAPEX/OPEX) in year k

Annual energy production was calculated based on a base-case capacity factor (C_p) of 20 % and the installed system capacity (Cap). To account for uncertainty in performance assumptions, a sensitivity analysis was conducted by varying the capacity factor by ± 2 % (i.e., 18–22 %), reflecting the typical range for fixed-tilt utility-scale photovoltaic systems under high-irradiance conditions

$$Q = Cap \times Cp \times 8760 \quad (10)$$

The economic analysis adopts discount rates consistent with international practice for utility-scale renewable energy projects in developing and high-risk economies. World Bank assessments indicate that financing costs for utility-scale infrastructure projects in developing countries typically fall in the range of 12–18 %, reflecting elevated country, currency, and policy risks [30]. Accordingly, a base-case discount rate of 12 % is adopted in this study. To evaluate the sensitivity of project profitability to financing conditions, a sensitivity analysis is conducted using discount rates of 8 %, 10 %, 12 %, 14 %, and 16 %, allowing assessment of economic robustness under both concessional and market-based financing scenarios.

The profitability of the investment and cash flow for each year is evaluated by adopting NPV equation:

$$NPV = -Inv_0 + (p_e - c_{var}) \times Q \times PVF_{i,T} \quad (11)$$

where p_e is the energy price per unit, and C_{var} is the variable cost per unit. A cost-benefit analysis for saved water was conducted using an estimated irrigation water price of $0.15–0.45/$m^3$ (as per World bank (WB) [31,32]), and land savings were estimated based on the local price of $20.7/$m^2$.

The methodology adopted in this study provided a comprehensive framework for evaluating the energy, environmental, and economic impacts of CTPV installations on the Qush-Tepa canal. By integrating structured interviews, satellite imagery, and simulation tools, the research captured a multidimensional perspective on the feasibility and benefits of the proposed system. The flowchart in Fig. 5 visually summarizes the study's workflow, detailing the progression from research design and data collection to analysis and result interpretation. This structured approach ensured that each aspect of the study—energy yield estimation, water conservation analysis, and economic evaluation—was systematically addressed, offering a holistic understanding of the CTPV system's potential in similar contexts globally.

Table 3
Component-wise capital cost breakdown for CTPV systems derived from the NREL ATB benchmark [26] and IEA cost shares [27], with structural cost adjustment.

Component	IRENA Share (%)	NREL Cost Benchmark of 1.15 ($/w)	Modified Capex for CTPV ($/w)
PV modules	34 %	0.391	0.391
Mounting structures	6 %	0.069	0.173
Electrical BOS	12 %	0.138	0.138
Inverters	5 %	0.058	0.058
Freight	1 %	0.012	0.012
Other	22 %	0.253	0.253
Installation & soft costs	20 %	0.230	0.230
Modified Benchmark for this study			1.254

3. Results

3.1. Power generation yield

The analysis of power generation potential was conducted using SAM based on following meteorological data and system design parameters:

SAM Findings show that the proposed CTPV system has an installed capacity of approximately 836 MW. Annual energy generation was simulated based on standard photovoltaic modules with 19 % conversion efficiency, accounting for a total system loss of 14 %, which includes wiring losses, module mismatch, shading, soiling, degradation,

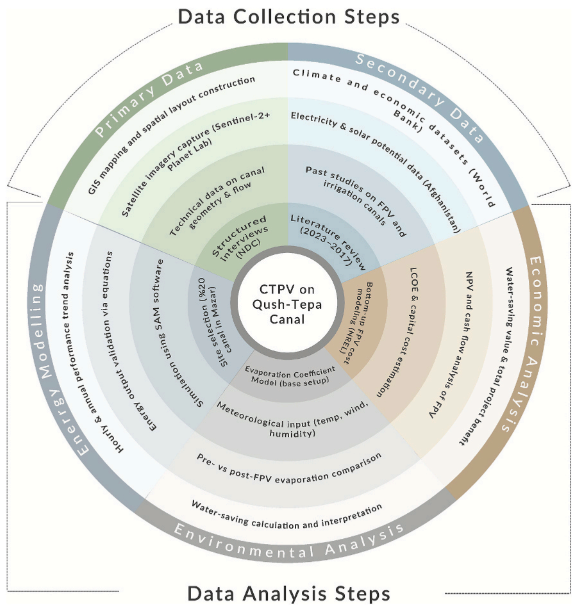

Fig. 5. Research design flowchart illustrating the methodological framework and sequential steps undertaken throughout the study.

and grid-connection losses. Temperature-related efficiency losses were also explicitly incorporated through SAM's performance modeling to ensure realistic output estimates.

Using a base-case capacity factor of 20 %, the simulated annual electricity generation is 1,464,672 MWh (≈1,465 GWh). To reflect uncertainty in system performance and site-specific conditions, a sensitivity analysis was conducted by varying the capacity factor. Under a lower-bound capacity factor of 18 %, annual generation decreases to 1,318,205 MWh, while a higher-bound capacity factor of 23 % yields an annual output of 1,684,373 MWh (≈1,684 GWh). These results demonstrate the proportional relationship between capacity factor and annual energy yield and provide a realistic performance envelope for fixed-tilt canal-top photovoltaic systems operating in high-irradiance environments.

Fig. 6 indicates the weather parameters considered for this design, extracted from the available weather stations in Mazare-Sharif and mapped for the area under study in Fig. 7, while Fig. 8 shows irradiance mapping throughout the Qush-Tepa Canal's portion that is crossing Mazar-e Sharif to identify the most suitable location for CTPV installation. Fig. 8 the monthly energy output of the designed CTPV system. The highest generation capacity is in June, which is mid-summer and has the highest solar radiation. After June, July and May have the highest energy output, respectively. February, November, January, and December have the lowest generation yield since they occur in winter, which has the lowest solar radiation, and of course, cloud effects are also considered in the analysis.

Fig. 9 illustrates the daily energy output of the CTPV system across the year, mapped against the hours of energy generation. During most of the year, the system generates power for approximately 4 h daily (10:00 A.M. to 2:00P.M.), while in summer, extended daylight hours increase generation to 9 h per day (7:00 A.M. to 4:00P.M.). The dark blue segments represent zero energy production during nighttime, while lighter blue to green shades correspond to early morning and late evening production, ranging from 167,231 kWh to 418,077 kWh. Peak generation, indicated by yellow and orange shades, occurs during mid-day hours, reaching values between 501,692 kWh and 836,154 kWh. These patterns highlight the system's enhanced productivity during summer, driven by higher solar radiation and longer daylight hours,

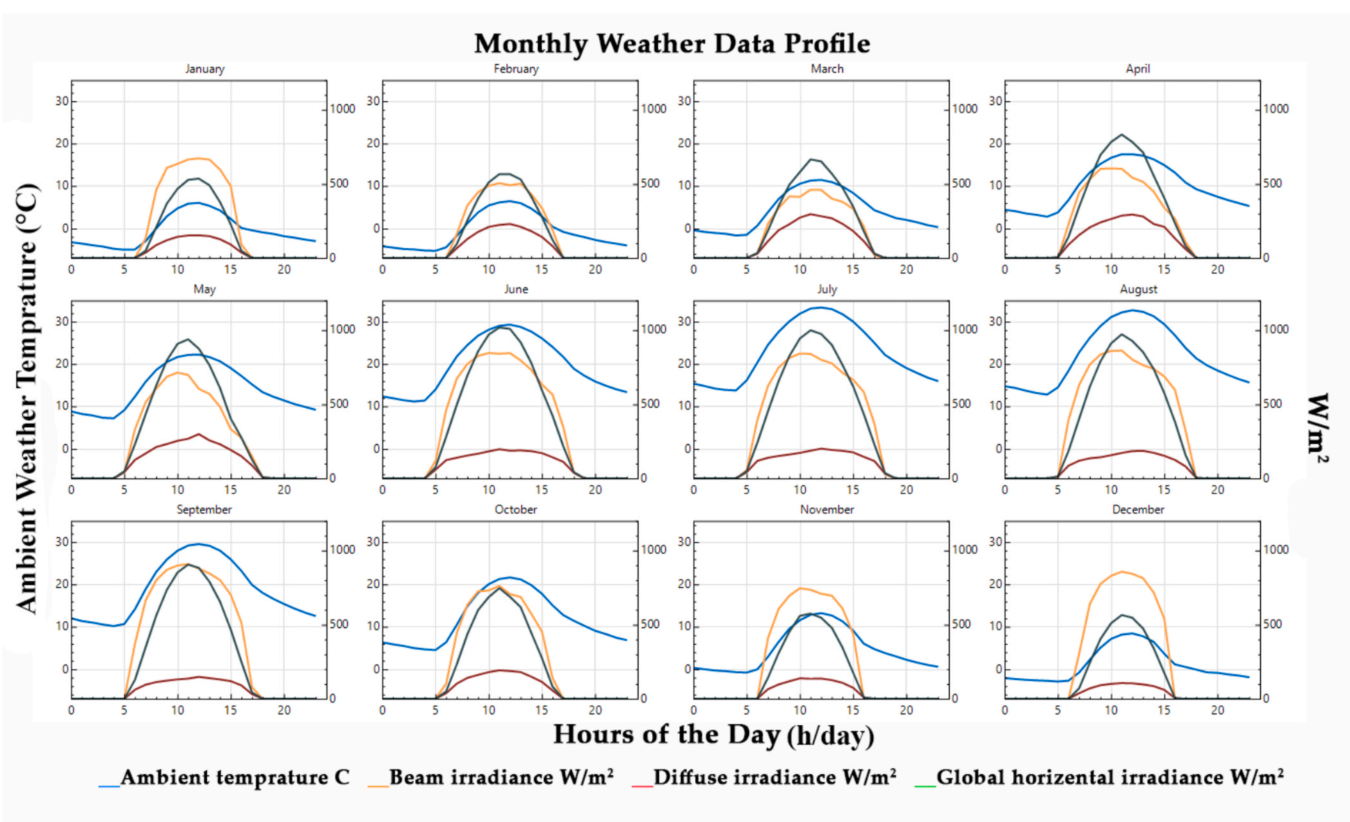

Fig. 6. Monthly weather data profile (Blue: Ambient temperature °C, Orange: Beam irradiance W/m^2, Red: Diffuse irradiance W/m^2, Green: Global horizontal irradiance W/m^2).

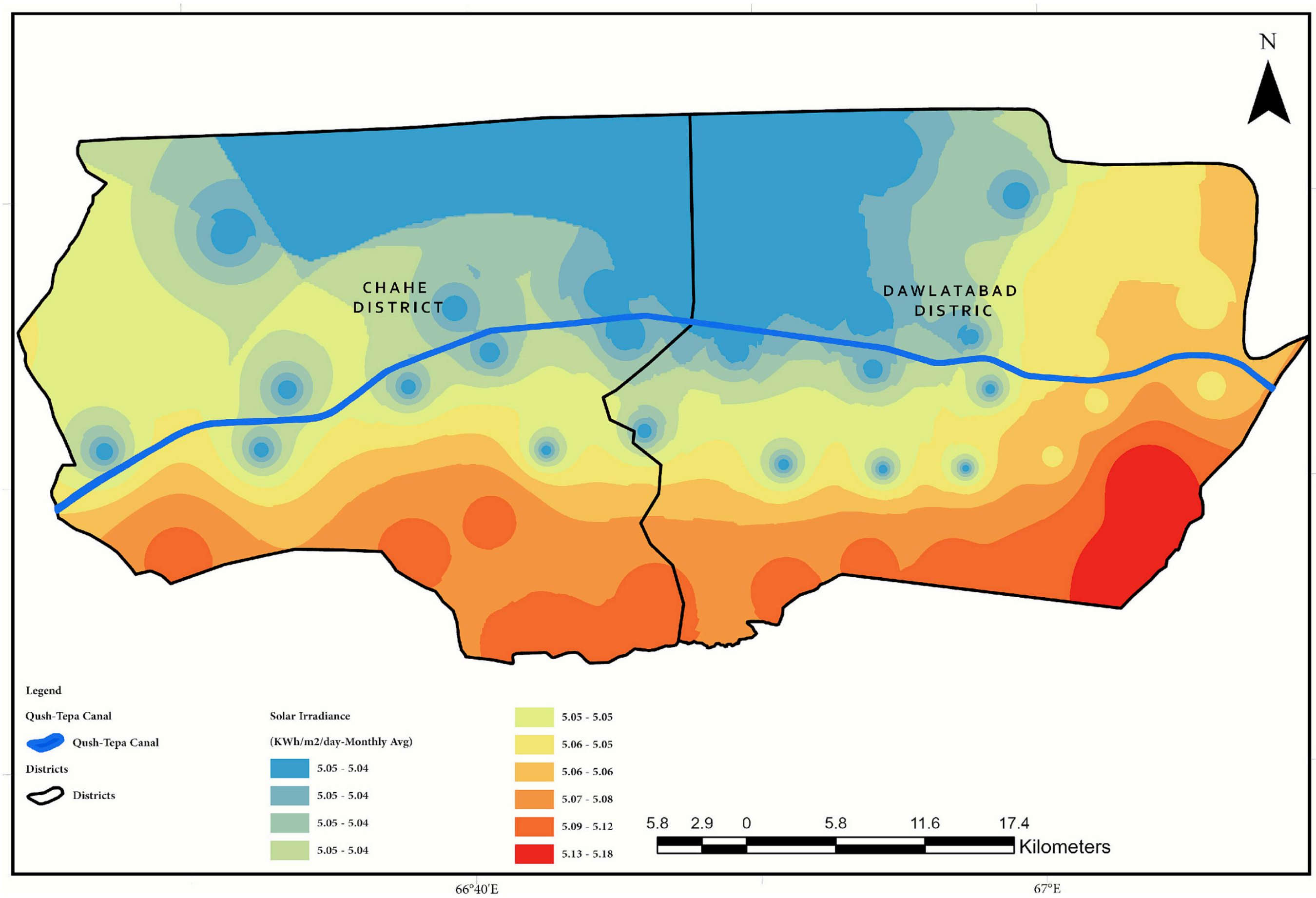

Fig. 7. Irradiance mapping throughout the Qush-Tepa Canal's portion that it crossing Mazar-e Sharif.

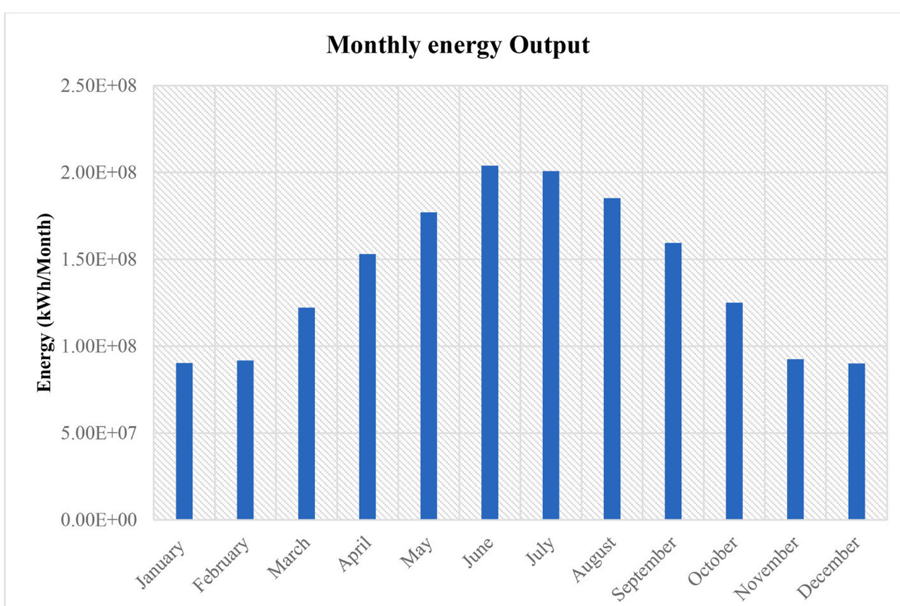

Fig. 8. Monthly energy output of the CTPV system covering 20% of the main canal's surface area.

demonstrating its potential to meet seasonal energy demands efficiently. This variability underscores the importance of optimizing the system's capacity to maximize energy output during peak periods, which is critical for Afghanistan's renewable energy strategy.

Fig. 10 shows the amount of energy generated from the CTPV system versus hours of the year. The average hourly energy generation from the system is 200 MWh. The gaps in between the bars indicate nighttime hours and cloudy days. The peak energy generation from the system

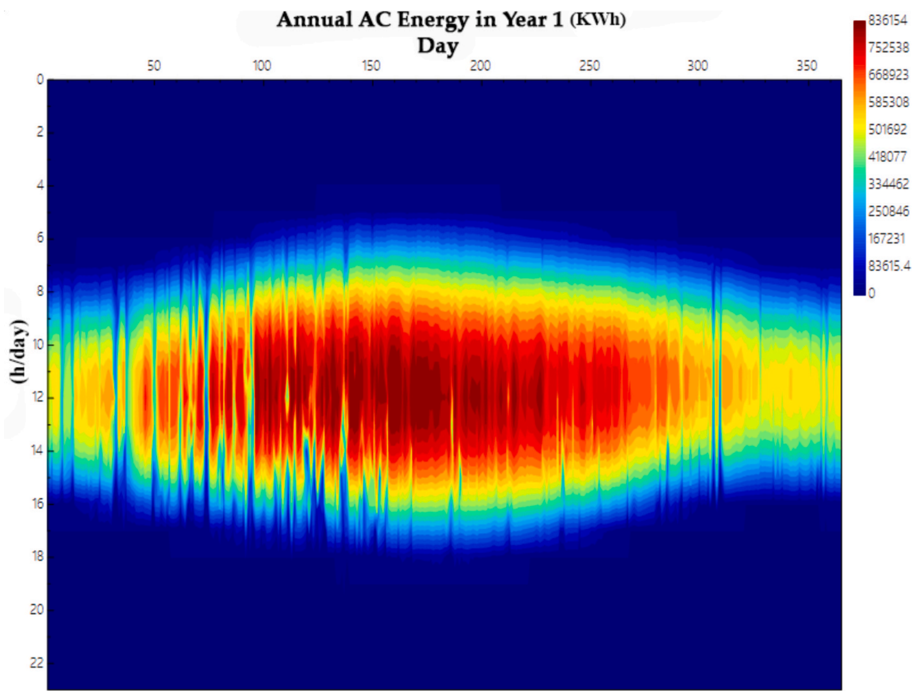

Fig. 9. Daily energy output of the CTPV system throughout the year, compared with daily available sunlight hours.

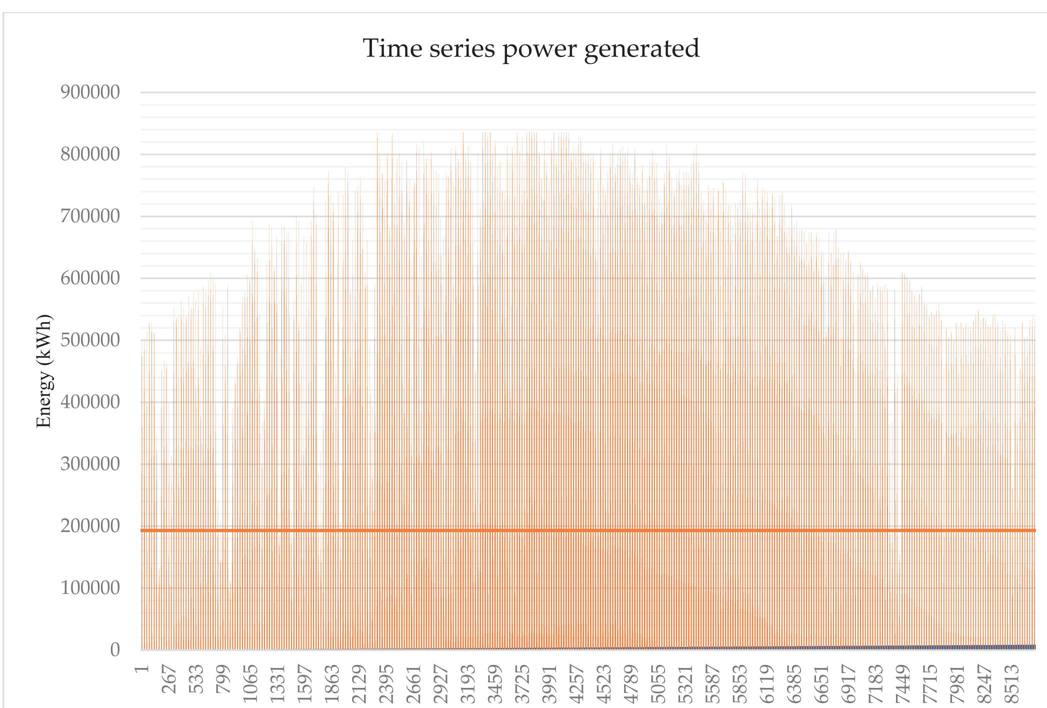

Fig. 10. Time series of power generation from the CTPV system, showing hourly energy generation versus hours of the year.

occurs in summer, which has the highest solar radiation, and it happens to be about 840 MWh. Fig. 11 indicates the system's hourly energy generation for 12 months of the year, showing the high and low generation capacity due to different times of the month and year.

Using Eq. (1), the output of the simulation is verified indication 2,883 MWh/day of energy generation daily.

From the mathematical calculation, the daily power generation from the CTPV system is found to be 4,883 MWh/day, with an average of six available solar hours daily. This result is very close to the result achieved through the simulation output of SAM software, which thereby confirms the output of the software.

3.2. Spatial planning and grid integration of CTPV system on Qush-Tepa canal

A geospatial assessment was undertaken to validate the feasibility of deploying the proposed CTPV system along a selected stretch of the Qush-Tepa Canal in northern Afghanistan. Fig. 12 illustrates the spatial

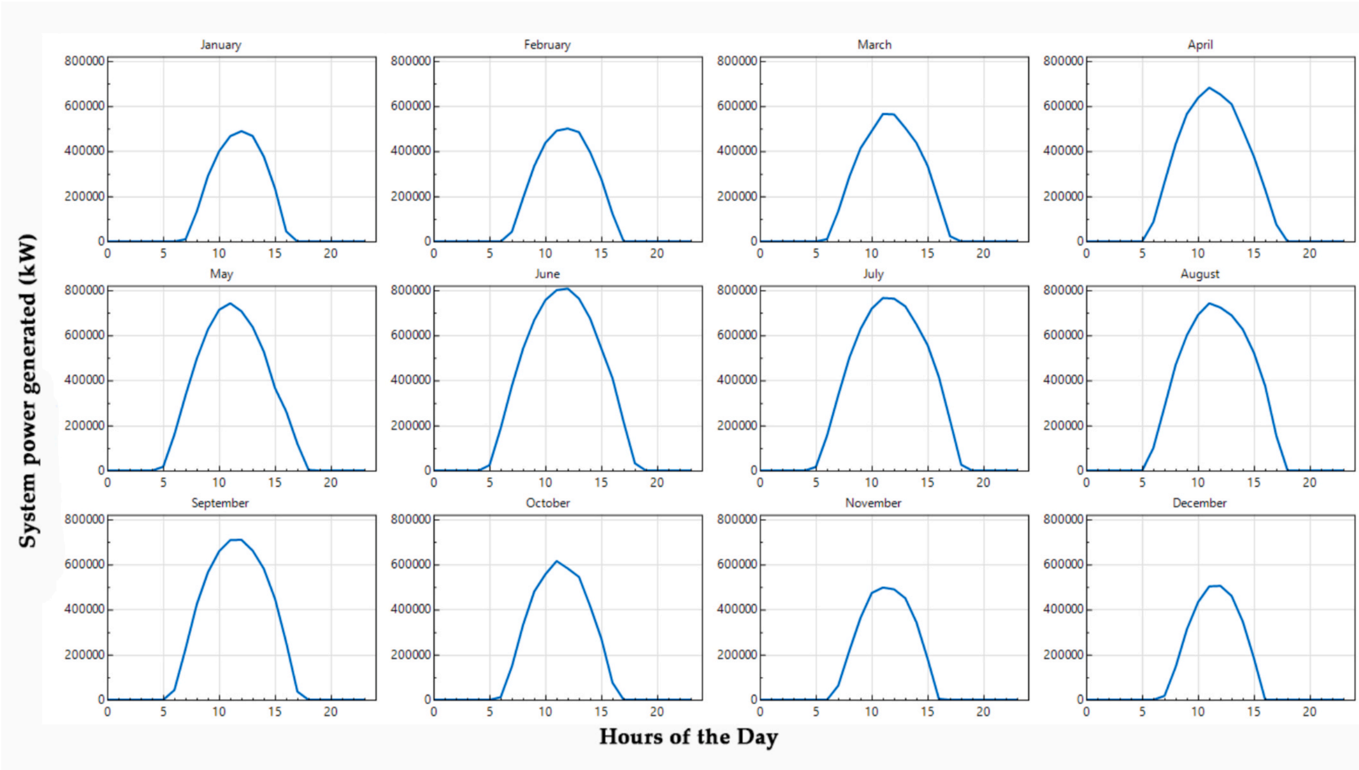

Fig. 11. Hourly power generation curve of the CTPV system, segmented by month, illustrating the variation in energy output throughout the year.

configuration of the canal segment traversing Chahe and Dawlatabad districts in Balkh province, overlaid with key infrastructural, agricultural, and electrical features. The analysis integrates high-resolution land use classification with grid network data, offering a multidimensional site-selection strategy aligned with energy-water-land co-benefits.

The canal segment, outlined in blue, passes through high-density agricultural zones (indicated in green), interspersed with village clusters (red dots) and the nearest grid interconnection point to the proposed CTPV installation is the Charbolak 220/20 kV substation, located at an approximate distance of 22.3 km from the canal-top system alignment. The grid connectivity potential is further enhanced by the proximity to the Mazar-i-Sharif New Substation (220/110/20 kV, 3 × 50 MVA) and planned extensions along the eastern corridor, enabling future scalability and energy evacuation to regional demand centers.

The spatial layout also emphasizes logistical and socio-economic advantages: a nearby secondary highway (olive line) facilitates equipment transport and long-term maintenance access; adjacent built-up areas and villages provide opportunities for localized rural electrification; and the corridor's integration into Afghanistan's broader power development scheme suggests potential alignment with national energy planning and donor-supported electrification programs.

This integrated GIS-based mapping enabled strategic siting of the floating PV arrays with minimal land-use conflict, optimized transmission routing, and efficient energy-water-agriculture synergy. The spatial methodology demonstrated here may be generalized for other canal corridors with comparable topography, transmission infrastructure, and development potential across Central and South Asia.

3.3. Water saving

Using the ECM, considering an average temperature of 24.8 °C, an average pressure of 1,013.25 hPa, and an area of 28,560,000 m^2, the total water evaporation of the main canal was estimated at approximately 28,891 m^3/h under the given climatic conditions. After covering 20 % of the canal surface with floating solar panels, the evaporation reduced to about 23,113 m^3/h, resulting in an hourly water saving of 5,778 m^3. With an average of 3,085 sunny hours per year, the system can save around 17.8 million m^3 of water annually. Over its projected 25-year lifetime, the total conserved water amounts to nearly 445 million m^3.

3.4. Economic analysis of the system

The economic performance of the proposed CTPV system was evaluated under three capacity factor scenarios (18 %, 20 %, and 23 %) to reflect uncertainty in system performance. For the 18 % capacity factor case, the total initial investment is estimated at USD 1.07 billion, yielding an annual electricity output of 1,318,204.8 MWh and corresponding annual sales revenue of approximately USD 124.8 million, assuming a unit electricity price of USD 94.66/MWh (LCOE of 0.094 $/kWh). After accounting for expected annual variable costs of USD 15.47 million, the variable cost ratio (Cvar) is estimated at 11.73 %.

Under the base-case capacity factor of 20 %, with annual electricity generation increasing to 1,464,672.0 MWh. This results in annual sales revenue of approximately USD 156.7 million at an electricity price of USD 106.97/MWh (LCOE of 0.106$/kWh), while variable costs remain unchanged. The corresponding variable cost ratio declines to 10.56 %, reflecting improved operational efficiency with higher energy yield.

In the upper-bound scenario (23 % capacity factor), annual electricity generation reaches 1,684,372.8 MWh, producing annual sales revenue of approximately USD 193.4 million at a unit price of USD 114.80/MWh (LCOE of 0.114$/kWh). With the same expected variable costs of USD 15.47 million, the variable cost ratio further decreases to 9.18 %, indicating enhanced economic performance driven by higher utilization of installed capacity. Overall, the results demonstrate that increases in capacity factor substantially improve revenue generation and cost efficiency, underscoring the strong sensitivity of project economics to system performance assumptions.

Table 4 presents the sensitivity of the CTPV project's net profit at

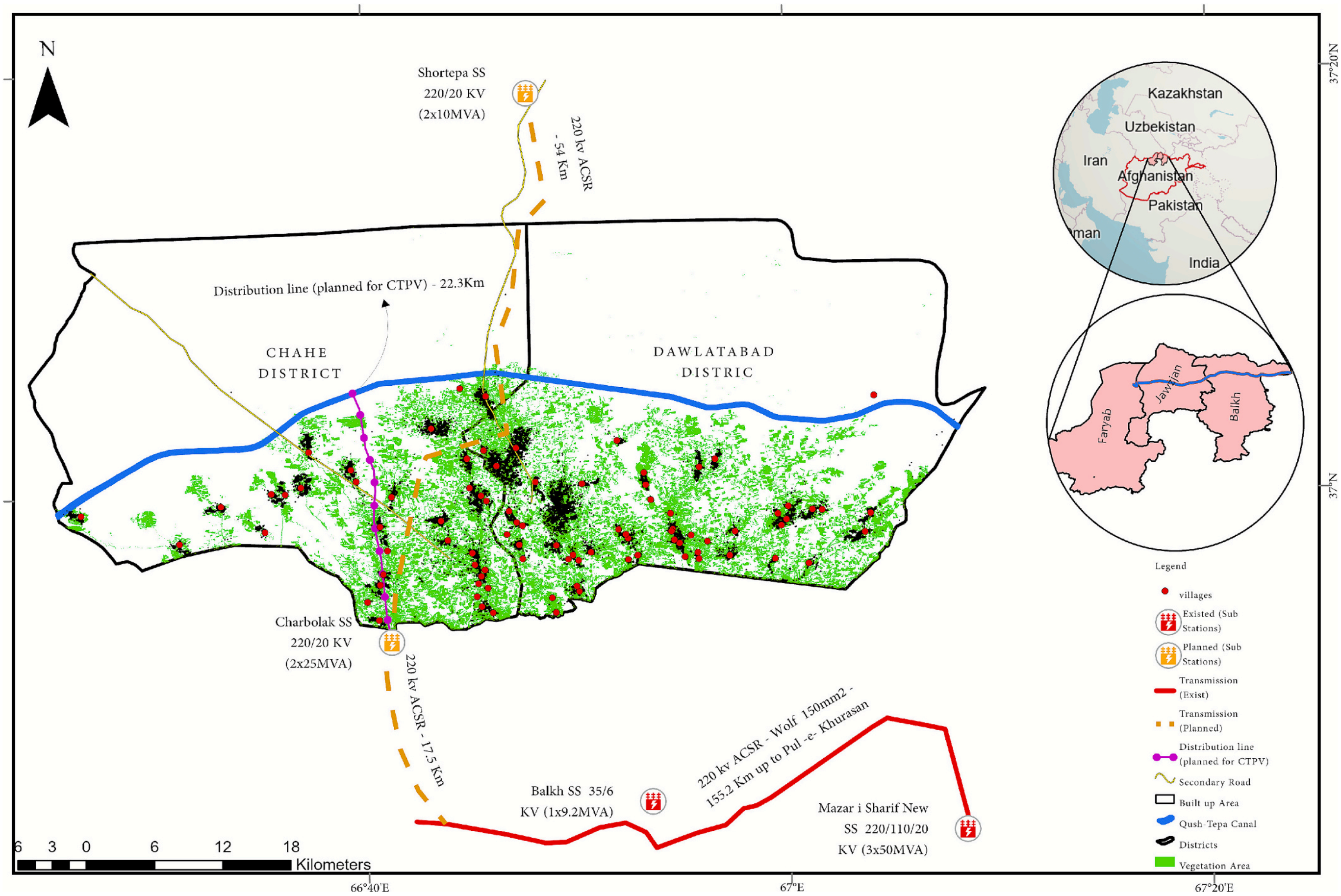

Fig. 12. Geospatial layout of the Qush-Tepa Canal segment in Balkh province, Afghanistan, showing the proposed CTPV installation corridor, existing and planned substations, transmission lines, agricultural zones, village settlements, and road infrastructure.

Table 4
Sensitivity of net project profitability to discount rate and capacity factor.

Interest	CF	Net profit at year 25 with substation	Land saving benefits	Water saving benefits	Total	Payback period
8 %	18 %	$ 295,317,432.17	$ 118,238,400.00	$ 200,250,000.00	$ 613,805,832.17	20
	20 %	$ 3,703,980,091.22	$ 118,238,400.00	$ 200,250,000.00	$ 4,022,468,491.22	12
	23 %	$ 8,914,427,662.85	$ 118,238,400.00	$ 200,250,000.00	$ 9,232,916,062.85	9
10 %	18 %	$ –	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	20 %	$ 1,515,558,675.23	$ 118,238,400.00	$ 200,250,000.00	$ 1,834,047,075.23	15
	23 %	$ 5,685,534,453.97	$ 118,238,400.00	$ 200,250,000.00	$ 6,004,022,853.97	10
12 %	18 %	–	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	20 %	$ 170,204,174.94	$ 118,238,400.00	$ 200,250,000.00	$ 488,692,574.94	20
	23 %	$ 3,165,466,805.78	$ 118,238,400.00	$ 200,250,000.00	$ 3,483,955,205.78	11
14 %	18 %	–	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	20 %	–	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	23 %	$ 1,282,158,158.34	$ 118,238,400.00	$ 200,250,000.00	$ 1,600,646,558.34	14
16 %	18 %	$ –	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	20 %	$ –	$ 118,238,400.00	$ 200,250,000.00	$ 318,488,400.00	#N/A
	23 %	$ 98,599,251.83	$ 118,238,400.00	$ 200,250,000.00	$ 417,087,651.83	20

year 25 to variations in discount rate (8–16 %) and capacity factor (18 %, 20 %, and 23 %), including the effects of grid connection via the Charbolak substation. In addition to electricity revenue, the analysis incorporates land-saving benefits and water-saving benefits, which are held constant across scenarios. Results indicate that project profitability is highly sensitive to both financing conditions and system performance. Lower discount rates and higher capacity factors substantially increase net profit, while higher discount rates (≥14 %) significantly reduce economic viability, particularly at lower capacity factors. Scenarios marked as “N/A” indicate cases where the project does not achieve a positive payback within the analysis period. Overall, the results highlight the dominant influence of financing cost and operational performance on long-term economic outcomes for canal-top photovoltaic systems in high-risk investment environments.

The yearly and overall water savings during the CTPV system's lifespan were used to estimate potential revenues under different water pricing scenarios in Afghanistan. Depending on the prevailing water tariff, the annual revenue from avoided water losses is projected to range between $2.67 million and $8.01 million, while over the 25-year lifetime of the system the total revenue reaches between $66.75 million and $200.25 million. These findings highlight the considerable economic benefits of reducing water evaporation, which not only generate direct revenue but also alleviate Afghanistan's severe water scarcity. By conserving around 445 million cubic meters of water over its operational life, the system can enhance irrigation capacity and support more sustainable agricultural practices, underscoring the dual economic and environmental advantages of CTPV deployment.

Moreover, land acquisition is a major component of solar farm investments due to the large area required for optimal panel spacing and tilt angles. By utilizing the CTPV system, this system eliminates the need for land acquisition, saving an estimated $20.7 per square meter, a total of $118,238,400, which is a significant reduction in capital costs. This not only improves the system's payback period but also preserves land for agricultural and other uses, highlighting the dual economic and environmental benefits of CTPV systems in Afghanistan's renewable energy strategy.

The financial analysis reveals that this system achieves a break-even point within the 9th–20th years of operation, driven by a combination of energy sales, water savings, and avoided land costs over different financing scenarios. Over its 25-year lifetime, the CTPV system is projected to generate a total revenue of $318 million to $9.2 billion as lower and upper boundaries depending on capacity factor and interest rate.

In addition to the conventional LCOE, the analysis incorporates monetized environmental co-benefits to evaluate environmental viability. Water conservation benefits resulting from reduced canal evaporation and land-use benefits from avoided land occupation were quantified and treated as annual monetary credits. The conventional LCOE is estimated at approximately 104 USD/MWh under the base-case assumptions. When water- and land-saving benefits are included, the environmentally adjusted LCOE decreases to approximately 95 USD/MWh, representing a reduction of about 9 %.

PBTM was computed as the year in which the cumulative discounted net monetary benefits, comprising electricity sales revenue and environmental co-benefits minus capital and operating costs, become non-negative. Under the base-case scenario, the discounted PBTM is estimated at approximately 16 years, highlighting the importance of environmental co-benefits in improving long-term project viability.

This impressive statistic underscores the economic viability of the system, offering substantial long-term returns that significantly exceed initial investment costs. Compared to similar CTPV initiatives globally, such as India's Gujarat project, the Qush-Tepa canal system demonstrates a strong financial advantage, largely due to its scale and dual benefits of energy and water savings but highly sensitive to *i* and *Cp*. By explicitly linking SAM-based performance metrics (capacity factor, system losses, and energy yield) with capital cost structure and financing assumptions, the analysis moves beyond standalone cash-flow evaluation and presents an integrated techno-economic assessment of canal-top photovoltaic deployment. These findings highlight the potential of CTPV systems to not only address Afghanistan's energy and water challenges but also attract investment for sustainable infrastructure projects in the region.

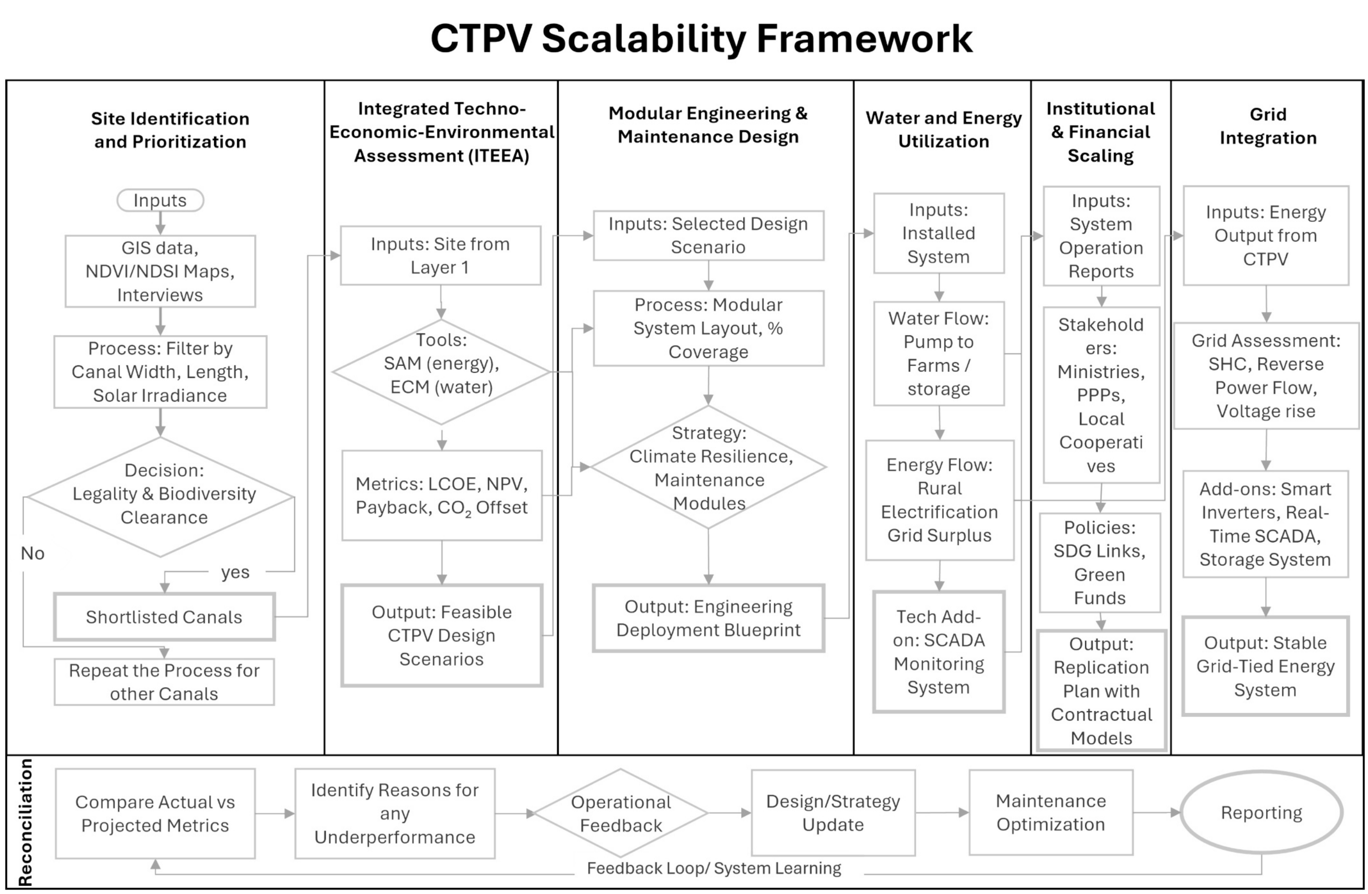

Fig. 13. CTPV framework for replicability and scalability.

3.5. Framework for systematic design and deployment of CTPV systems

In response to the growing imperative for integrated energy–water–climate solutions, this study introduces a comprehensive and replicable CTPV Planning and Deployment Framework. The framework, depicted in Fig. 13, encapsulates a structured methodology that spans from geospatial site identification through to system operation, monitoring, feedback, and replication. It is conceived to serve as a scalable planning tool for governments, utility planners, and development institutions pursuing synergistic interventions in renewable energy, water conservation, and rural development.

3.5.1. Process architecture and operational flow

The framework is composed of six interlinked layers, each representing a distinct but integrative component of the CTPV project lifecycle:

- Layer 1: Geospatial Screening and Pre-Feasibility Assessment.

Initial screening employs remote sensing datasets such as GIS layers, Normalized Difference Vegetation and Snow Indexes (NDVI/NDSI), and stakeholder interviews to identify canal segments suitable for PV installation. Selection criteria include canal width, segment length, and annual solar irradiance. A decision node evaluates legal admissibility and biodiversity sensitivity. Canals failing this filter are excluded, while qualifying segments advance for detailed assessment.

- Layer 2: Techno-Economic and Environmental Modeling.

Shortlisted sites undergo multi-dimensional modeling using the SAM for energy simulation and an ECM for hydrological assessment. Key performance indicators such as LCOE, NPV, payback period, and CO_2 emissions offset are computed. This layer generates a portfolio of feasible design scenarios evaluated against cost-effectiveness, environmental benefit, and water–energy efficiency.

- Layer 3: Engineering Design and System Optimization.

This stage focuses on modular system configuration, including spatial layout over canals and percentage surface coverage. It integrates strategies for climate resilience, maintenance accessibility, and modular scalability. The output is an engineering deployment blueprint that aligns physical system design with resource optimization and long-term operability.

- Layer 4: Installation, Operation, and Real-Time Monitoring.

Following deployment, the framework accounts for bifurcated system outputs: (i) water flow via pumps to agricultural storage or farms, and (ii) electrical output for rural electrification or grid surplus. Real-time Supervisory Control and Data Acquisition (SCADA) systems are recommended for operational monitoring and diagnostics, ensuring robust feedback mechanisms.

- Layer 5: Policy Integration, Grid Compliance, and Stakeholder Engagement.

To ensure institutional sustainability and scalability, this layer addresses regulatory compliance and stakeholder alignment. It includes integration with SDGs, access to green finance, and partnerships with public–private stakeholders and local cooperatives. Technical assessments such as Substation Hosting Capacity (SHC), reverse power flow, and voltage rise are conducted, enabling mitigation through grid-tied add-ons like smart inverters and storage systems.

- Layer 6: Performance Analysis and System Learning.

A closed-loop system learning approach is embedded to compare real-time performance data against baseline projections. Sources of underperformance like technical, environmental, or operational are analyzed. The feedback mechanism enables iterative updates to design assumptions, maintenance protocols, and replication models. Final outputs include knowledge products, impact reports, and revised strategic guidelines.

3.5.2. Novel Contributions

- The proposed framework advances the state of the art in renewable energy infrastructure planning in several critical ways:
- Cross-Sector Integration: Unlike conventional PV siting tools, this framework explicitly incorporates biodiversity screening, hydrological impacts, energy–water co-benefits, and modular design strategies within a single decision-support architecture.
- Embedded Circular Learning: System feedback and performance analytics are not ancillary but integral, enabling real-time adaptation, policy learning, and dynamic replication planning.
- Climate Resilience and Maintenance Readiness: Design scenarios are evaluated not only for economic return but also for resilience to climate variability and logistical feasibility of system upkeep.
- Operational Scalability: The modular structure supports phased implementation and can be easily adapted across geographic contexts with similar canal infrastructure.

3.5.3. Scalability and transferability

Designed with regional generalizability in mind, the framework is inherently scalable to other developing regions with aligned characteristics such as India, Pakistan, North and East Africa, and parts of Southeast Asia. Its reliance on globally available data (e.g., GIS, NDVI), open-access simulation tools (SAM, ECM), and adaptable stakeholder models ensure replicability. Furthermore, policy modules within the framework can be customized to reflect national priorities such as electrification targets, irrigation modernization plans, or climate financing mechanisms, thereby enhancing institutional adaptability.

3.5.4. Implications for policy and research

The framework not only facilitates robust planning but also offers a blueprint for policy-driven scaling of decentralized renewable energy systems. It bridges infrastructure design with environmental safeguards and participatory governance. Future research should focus on empirical validation across diverse geographic sites, integration with AI-based optimization engines, and modeling of cumulative socio-economic impacts of widespread CTPV deployment.

4. Discussion

The results of this study demonstrate both the technical feasibility and the dual economic–environmental benefits of deploying CTPV systems on large-scale artificial water bodies in Afghanistan. When compared with international reference projects, the findings are broadly consistent but also reveal important contextual differences.

The Gujarat floating solar project in India has been widely cited for its ability to reduce evaporation losses while supplying low-cost renewable electricity. Similar to that project, this study shows significant water conservation potential, with an estimated 445 million m^3 saved over 25 years, translating into substantial financial value when monetized under national water pricing scenarios. However, while Gujarat's project benefited from strong grid integration and a relatively lower cost of capital, Afghanistan faces higher financing constraints and infrastructural limitations, which may raise the effective cost of deployment despite comparable technical performance.

The Nexus project in California, analyzed through the NREL benchmark model, provides another relevant comparison. That project reported an LCOE of approximately 0.3–0.35 $/kWh, which closely aligns with this study's finding of 0.34 $/kWh. Both results confirm the competitiveness of CTPV systems against conventional generation sources. Importantly, while Nexus focused primarily on energy generation and grid economics, the Afghan case underlines the added dimension of water scarcity mitigation, making the dual benefits more critical in local sustainability planning.

Taken together, these comparisons suggest that the Afghan CTPV system not only aligns with international benchmarks in terms of cost and energy output but also provides proportionally greater societal benefits due to its impact on water conservation in a drought-prone context. This strengthens the argument for positioning CTPV as a strategic technology in Afghanistan's renewable energy transition.

At the same time, this study addresses key gaps in existing literature. Previous research on FPV and CTPV systems has rarely accounted for the climate-specific dynamics of arid and drought-prone regions, nor has it engaged with the unique challenges of post-conflict and fragile states where infrastructure, governance, and financing capacities are constrained. Moreover, earlier studies often presented site-specific case outcomes without developing a robust framework for scalability and replicability across diverse geographies. By explicitly integrating these dimensions, the present study contributes not only to Afghanistan's renewable energy discourse but also to the global debate on how CTPV technology can be adapted for contexts that differ markedly from stable, well-capitalized energy markets.

5. Conclusion

This study examined the potential of CTPV systems as an integrated response to Afghanistan's energy insecurity and water scarcity, with a specific focus on the Qush-Tepa Canal. The analysis was conducted using the ITEEA framework, which combines SAM-based performance modeling, evaporation reduction analysis, and economic evaluation to jointly assess energy output, environmental co-benefits, and financial viability of dual-purpose infrastructure in arid and conflict-affected contexts.

Key findings indicate that the proposed 836 MW fixed-tilt CTPV system is technically feasible and capable of generating approximately 1.46 TWh annually under a base-case capacity factor of 20 %, with outcomes strongly dependent on performance and financing assumptions. The framework further demonstrates that canal coverage can reduce water evaporation by approximately 20 %, and that monetizing this water conservation, together with avoided land use, substantially improves overall project viability. While the conventional LCOE remains higher than that of ground-mounted PV due to elevated structural and grid-connection costs, the environmentally adjusted LCOE and PBTM reveal that integrated resource benefits play a critical role in enhancing economic performance.

Key limitations should be acknowledged. The ITEEA framework relies on benchmarked cost assumptions and modeled performance under typical meteorological conditions rather than site-specific construction and operational data. Long-term uncertainties related to sediment accumulation, soiling dynamics, maintenance requirements, and grid integration may affect realized performance. In addition, financial and institutional constraints, including access to capital and policy support, introduce risks that cannot be fully resolved through modeling alone.

Key implications emerge for both policy and practice. The results reinforce the value of dual-purpose infrastructure and demonstrate that CTPV systems derive a significant share of their value from integrated energy–water–land synergies rather than electricity generation alone. For Afghanistan, embedding CTPV deployment within national energy and water strategies could support electricity supply expansion while enhancing water security and minimizing land-use conflict. More broadly, the ITEEA framework developed in this study offers a transferable and scalable approach for evaluating canal-top PV systems and other multi-functional infrastructure in arid and semi-arid regions facing similar environmental and economic constraints.

CRediT authorship contribution statement

Hameedullah Zaheb: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mohammad Shahab Sharifi:** Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Shafi Sharifi:** Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdul Ghayoor Shokory:** Software, Formal analysis. **Atsushi Yona:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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