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Economic Viability of Solar Systems in Uzbekistan: A Levelized Cost of Electricity-Based Approach

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ABSTRACT

Uzbekistan's growing solar potential and evolving energy needs call for informed assessments of photovoltaic (PV) system viability. This study evaluates the Levelized Cost of Electricity (LCOE) for three PV configurations: grid-connected without storage (PVS1), grid-connected with storage (PVS2), and off-grid with storage (PVS3). A MATLAB-based model simulates each system under varied technical and economic conditions, including orientation (tilt, azimuth), albedo, and loan rates. In optimal scenarios, PVS1 achieves an LCOE as low as $25/MWh, comparable to Uzbekistan's current electricity tariffs ($0.024–$0.048/kWh). Sensitivity analysis shows that loan rate and installation cost are the most influential factors, while the Yield Factor (YF) exhibits low sensitivity, supporting stable performance across irradiation levels. Adding storage increases LCOE above $100/MWh under worst-case conditions, though cost parity with non-storage systems is possible under favorable assumptions. PVS3 is especially sensitive to battery life, storage cost, and energy accumulation share. Optimizing tilt and azimuth, along with high-albedo surfaces, can reduce LCOE by up to 10%. Overall, grid-connected PV systems offer competitive electricity pricing in Uzbekistan, with clear optimization pathways. These results form a foundation for extending the model to hydrogen and water production systems in emerging markets.

1. Introduction

The global energy landscape is rapidly shifting toward solar photovoltaics, as the Levelized Cost of

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Energy (LCOE) for both grid-scale solar generation and battery storage continues to fall. BloombergNEF forecasts a 2 % global year-on-year drop in fixed-axis utility-scale solar LCOE—declining from approximately $36/MWh in 2024 to $35/MWh in 2025, and further to $25/MWh by 2035 [1]. In parallel, battery storage LCOE is expected to decrease by about 11 % from $104/MWh in 2024 to $93/MWh in 2025 [1].

According to Lazard's 2025 LCOE+ Report, the unsubsidized LCOE for U.S. utility-scale solar PV is estimated at US $38–78/MWh in 2025[2] , while including tax credits can lower it further to US $20–45/MWh [3]. IRENA's 2024 global data report an average utility-scale solar LCOE of $0.043/kWh, representing a modest 0.6 % year-on-year rise (i.e. nearly flat) [4]. Technology-specific comparisons show that small-scale PV systems (HJT, PERC, TOPCon, bifacial) achieve LCOEs of about 2.39–2.92 c€/kWh with subsidies and approximately 6.05–6.51 c€/kWh without them [5].

The current range of electricity prices in Uzbekistan, from $0.024 to $0.048 [6], ranks the country among those with relatively low conventional electricity costs globally [7]. This pricing raises questions regarding the viability of adopting renewable energy sources within the nation. While Uzbekistan's electricity prices are well-documented, a detailed comparison of the costs associated with different energy sources (such as natural gas, coal, or hydropower) is challenging due to the lack of official data on their actual expenses. Conversely, the cost of solar photovoltaic (PV) energy can be estimated using available public data, providing insights into the potential for solar PV adoption in various locations worldwide.

At the state-of-the-art forefront of photovoltaic (PV) technology, the focus is on innovations such as curved thin-film modules, Building-Integrated Photovoltaics (BIPV), advanced thermal management within BIPV systems, and the development of semitransparent solar cells, which are integral for enhancing efficiency, sustainability, and architectural integration. These advancements enable the creation of functional, yet aesthetically appealing solar installations, optimized for energy capture and efficiency. Central to this progress is the improvement of BIPV's thermal and electrical performance, the integration of efficient PV thermal systems, and the exploration of energy storage solutions like lithium-ion batteries. Bednar et al. [8] introduced a simulation for curved thin-film PV modules, designed for integration into buildings and products. The simulation, emphasizing flexibility in design for irregular shapes, demonstrated the potential for versatile applications, such as dome-shaped solar street lamps and active rooftop shading, although specific numerical outcomes were not detailed. Saifullah et al. [9] reported on the development of semitransparent (ST) CIGS solar cells with a notable efficiency of 5.94% and over 25% visible transparency. The study highlighted the achievement as the highest reported efficiency for ST CIGS solar cells with significant transparency, particularly aiming for BIPV applications. Multiple studies [10-13] collectively focused on enhancing BIPV systems' thermal and electrical performance. Notably, Komilov [12] compared photovoltaic thermal (PV/T) systems to standard PV panels, finding a 6-15% higher photovoltaic efficiency in PV/T systems. Tripathy et al. [11] observed that both electrical and thermal outputs increased with the mass flow rate, suggesting that semi-transparent BIPV systems as more efficient than opaque ones at all tilt angles. Zhou and Carbajales-Dale [14] emphasized the energetic performance of PV technologies, noting that advancements in thin-film technology have led to better energetic performance. Perkins [15] analyzed the LCOE for solar PV and battery storage, calculating an LCOE of 170 AUD/MWh under specific conditions, projecting a future range of 150-185 AUD/MWh depending on various factors. Few et al. [16] provided expert forecasts on the cost and cycle life of lithium-ion battery packs for off-grid stationary electricity storage for the years 2020 and 2030, suggesting significant improvements in cycle life are more achievable than in cost reduction. Tillmann et al. [17] explored bifacial solar module technology, demonstrating configurations that yield up to 23% lower LCOE compared to established guidelines by utilizing a Bayesian optimization algorithm.

The development and sustainability of photovoltaic (PV) technologies are continually assessed through their advancements and ecological benefits. This includes analyses of the economic efficiency and environmental advantages of solar power adoption. It highlights solar energy's potential as an economically beneficial alternative to traditional energy sources, emphasizing the importance of evaluating economic and environmental factors in deploying and integrating PV technology. This involves conducting Levelized Cost of Electricity (LCOE) studies and environmental impact assessments, crucial for effectively incorporating PV systems into the broader energy sector. Alim et al. [18] underscored BIPV's potential in Australia. Their findings indicate that buildings account for 20% of national energy consumption, emphasizing the significant but untapped solar energy potential due to high irradiance. Cucchiella et al. [19] conducted a comprehensive analysis in Italy, employing financial and performance indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (DPbP), Benefit-Cost ratio (BCr), and Emission Reduction cost (ERcd) to determine the optimal PV system capacity needed to meet renewable energy targets. Their analysis highlights the strategic importance of geographical factors in solar investment. Investigates hybrid PV systems with ground‑based heat exchangers and other thermal enhancements, demonstrating that such integration can reduce thermal losses, increase energy yields, and improve LCOE performance—particularly in high‑temperature climates [2]. Komilov [20] presented a method to analyze the dependency of LCOE on PV system orientation, showing a 2% fluctuation in LCOE minima with orientation adjustments, offering insights for optimizing PV installations in Uzbekistan. In their latest work the authors [21] demonstrated how updated capital cost assumptions, performance improvements, and operational parameters suggest significant declines in projected storage LCOE over the next decade. Hwang et al. [22] discussed the rLCOE (real Levelized Cost of Electricity) approach, incorporating indirect costs, with findings indicating that indirect cost savings decrease when the renewable energy share exceeds 20%, showcasing the nuanced economic impacts of renewable energy integration. Monte Carlo simulation approach for LCOE calculations for PV was proposed by Darling et al. [23], emphasizing the importance of underlying assumptions and confidence intervals in economic evaluations of solar energy. Nasim Hashemian and Alireza Noorpoor [24] proposed and performed a thermo-economic evaluation of a novel solar PV and wind-powered multi-generation system, assessing its ability to simultaneously produce electricity, heating, cooling, hydrogen, and ammonia, with detailed analysis of energy efficiency, exergy destruction, environmental impact, and overall cost-effectiveness.

The levelized cost of electricity (LCOE) for photovoltaic (PV) systems is projected to continue its decline, driven by a combination of factors. One key driver is the expected reduction in capital expenditures (CAPEX) for PV plants, with forecasts indicating that CAPEX will fall to between €250 and €430 per kW by 2030 and further decrease to €170 to €330 per kW by 2050, potentially resulting in LCOE reductions exceeding 70%. [25]. The global trend also points to a continuing decrease in LCOE, with the weighted-average cost for new utility-scale PV projects falling by 85% from 2010 to 2020, and similar reductions projected in regions like the UK, where the LCOE is expected to drop by 40%-50% by 2035 [26]. Policy support and market conditions are also expected to drive further declines in LCOE, with countries like China projecting cost-competitive solar PV by 2030 [27]. Manzolini et al. [28] presented global and regional LCOE benchmarking across PV technologies (including bifacial, tracking, HJT, TOPCon), and confirms that cost reductions in module efficiency, BoS, and system scaling have pushed utility‑scale solar LCOE in many high‑irradiance markets to below US $0.04/kWh - even reaching as low as US $0.033–0.036/kWh in China and India—while storage‑inclusive system costs continue to decline in tandem. Regional variations will influence LCOE, with locations like Nigeria forecasted to have some of the lowest LCOE values for PV/battery systems by 2029, ranging from $0.0748 to $0.113 per kWh [29]. Various factors, such as technological advancements, cost reductions, and integration costs, have played a key role in reducing the LCOE. Technological innovations have increased the efficiency of PV modules, reducing area-dependent costs by 8.7% and, in turn, lowering the LCOE [30]. Moreover, hardware and battery storage cost reductions have brought down the global LCOE for non-tracking solar PV systems, making them more cost-effective. For instance, in 2023, the LCOE for PV/battery systems in Nigeria ranged from $0.16/kWh to $0.169/kWh, highlighting its affordability [29, 31]. However, integration costs, such as grid reinforcement and balancing, are often overlooked in traditional LCOE calculations, resulting in a higher system LCOE (S-LCOE), which can be up to 50% higher. In Italy, for example, projected system LCOE for 2030 is 22 €/MWh. [32]. Regional variations further demonstrate diverse outcomes, with China achieving grid parity in some regions by 2023, while others may not reach it until 2042 [33]. In contrast, utility-scale PV systems in Poland have a national average LCOE of €0.045/kWh [34]. On a global scale, bifacial systems in desert regions can achieve an LCOE below 4 ¢/kWh, making them highly competitive [35]. Technological advancements have had a significant impact on reducing the levelized cost of electricity (LCOE). In terms of cost reductions, after a rise in hardware costs in 2022, the prices for solar PV systems and battery storage dropped in 2023, contributing to lower LCOE, especially for non-tracking systems [31]. Efficiency improvements in module performance, system durability, and degradation rates have significantly reduced the cost per kWh, as higher-efficiency modules generate more electricity per unit area [36]. Supportive policies, including tax reductions and subsidies, have also played a crucial role in reducing upfront costs and boosting investment in research and deployment of PV technologies [37].

Although the global trend in the decline of the Levelized Cost of Electricity (LCOE) for photovoltaic (PV) systems is well-documented, especially with the reduction in capital expenditures (CAPEX), technological advancements, and cost reductions in hardware and battery storage, there is a notable gap in region-specific analyses, particularly for countries like Uzbekistan. Most existing studies focus on global or high-income market trends, where LCOE reductions are primarily driven by technological advancements, economies of scale, and favorable policies. However, these studies often overlook the unique challenges faced by emerging economies, where local economic and environmental conditions—such as loan rates, installation costs, and regional factors like albedo—play a significant role in determining LCOE and the economic feasibility of solar energy systems. Moreover, while the impact of storage integration and system orientation is increasingly acknowledged, few studies have comprehensively analyzed how these factors interact in the context of Uzbekistan's energy market.

This paper fills these gaps by offering a detailed, region-specific analysis of LCOE for various solar energy system configurations (storageless, grid-connected with storage, and off-grid with storage) in Uzbekistan, considering both the local economic conditions and environmental factors. Unlike previous global or regional studies, this research accounts for local market dynamics, such as the affordability of electricity in Uzbekistan, and explores how these variables influence the cost-efficiency of solar systems, even under less favorable conditions. Furthermore, it uniquely addresses how optimizing system configurations, considering factors like storage and orientation, can make solar energy systems competitive with the local electricity prices. This study contributes new knowledge on solar energy economic optimization in Uzbekistan and offers actionable insights for stakeholders, such as policymakers, investors, and energy developers, who are aiming to advance sustainable energy solutions in emerging markets.

Novelty of the Study:

- Regionally Tailored LCOE Assessment: This study provides a comprehensive LCOE analysis for multiple PV system configurations in Uzbekistan, integrating local environmental conditions (e.g., albedo, irradiation) and economic variables (e.g., loan rates, installation costs). Unlike most global studies, this work offers a detailed, country-specific perspective on solar energy economics.
- Comprehensive System Configurations: Unlike many studies focusing on a single system type, this research compares storageless, grid-connected with storage, and off-grid systems with storage to evaluate the full spectrum of solar energy options.
- Innovative Assessment of Storage and System Orientation: By considering how storage integration and system orientation (azimuth and tilt angles) interact with economic factors, this research offers a more comprehensive view of cost optimization for solar energy systems.
- Competitive Feasibility in Uzbekistan: The study uniquely demonstrates that solar energy systems in Uzbekistan can achieve competitive LCOE values even under less favorable conditions, showing potential for solar to be cost-competitive with existing electricity prices in the region.

These innovations fill key gaps in the literature and offer actionable insights for stakeholders aiming to develop cost-effective and sustainable solar energy solutions in Uzbekistan and similar regions.

2. Materials and Methods

The Levelized Cost of Electricity (LCOE) for PV system is determined through various calculations that consider several influencing factors. These calculations are essential for the economic evaluation and comparison of different power generation technologies. Essentially, LCOE represents the cost per unit of electricity generated, factoring in the initial investment and operational costs over the lifespan of the power generation asset:

$$LCOE = \frac{\sum_{t=1}^{N} K_t}{\sum_{t=1}^{n} E_t} \quad (1)$$

where, N is the life of the photovoltaic system in years t, K_t represents annual costs:

$$K_t = C_{pv} + C_{om} N + \varepsilon_{om} (N-1) \quad (2)$$

$$C_{pv} = S_b + \sum_{t=1}^{N} S_b F_b (t-1) \quad (3)$$

$$S_b = S_{pv} + R_b C_b * roundup(\frac{N}{nb}, 0) \quad (4)$$

where, $S_{pv} = S_{b0} + C_i * roundup(\frac{N - ni}{ni}, 0)$

and C_{pv} total costs for installing the photovoltaic system, C_{om} total annual costs for operation and maintenance, ε_{om} annual rates of growth for operating and maintenance costs, S_b - initial capital costs, F_b - bank loan rate, S_{b0} - is the cost of installation without invertor, S_{pv} - is the cost of installation without storage system, R_b -is the share of accumulation of the generated energy, C_b - is the cost of installing the storage system, nb - is the battery lifetime, C_i and ni inverter price and lifetime, respectively;

E_t is the annual electricity yield:

$$E_t = E_{pv}(1 - f_{E_{pv}}(t-1)) \quad (5)$$

$$E_{pv} = \eta_i P_{pv}(1 - (1 - \eta_b) R_b) \quad (6)$$

with E_{pv} - the annual photovoltaic power output and $f_{E_{pv}}$ - the average annual degradation rate of the photovoltaic system, P_{pv} - the power output of the PVS, and η_i and η_b are the efficiencies of inverter and batteries respectively.

$$S_{LCOE} = \frac{dLCOE}{\frac{dV}{V_{\max} - V_{\min}} 100\%} \quad (7)$$

where, V is any variable in the formulas (1-6) within the range given in Table 1. Hence, S_{LCOE} is the change in LCOE due to the percentage change in the variable within its range.

Table 1. Values and ranges for variables used in calculation of LCOE

The total cost of installing the photovoltaic system, without batteries, S_{pv}	from 800 to 1600 kW/$
The average annual degradation coefficient of the photovoltaic system, $f_{E_{pv}}$	0.5%
Bank loan rate,	from 1 to 5%
The total annual cost of operation and maintenance, C_{om}	1% of C_{pv}
Annual growth rate of operating and maintenance costs, ε_{om}	8%
The life of the photovoltaic system, N	25 years
Inverter life time, ni	15 years
Inverter price, C_i	according to table 2
The share of accumulation of the generated energy	from 0 to 100%
Battery cycle efficiency, η_b	90%
*Battery lifetime, nb	from 5 to 15 years.
The price of the storage system, C_b	from 250 [15] to 550 kWh/$, considering all expenses;

*It is assumed that the battery power does not degrade until the end of its service life.

Variations in certain variables listed in Table 1 reflect the impact of additional factors. For example, the costs of installing Photovoltaic Systems (PVS) are influenced by the price of land, proximity to grid connection points, and other expenses incurred during setup. These costs might be reduced by investment return schemes similar to those in Uzbekistan or through other financial incentives. Likewise, subsidies can affect the pricing of storage systems, which also varies based on technology and may relate to battery life expectancy - typically, a lower cost is associated with a shorter lifespan. Loan rates are affected by financial aid such as subsidies, grants, and other advantages. The analysis involves calculating across the full spectrum of variables simultaneously using MATLAB, resulting in a comprehensive LCOE (Levelized Cost of Electricity) database for further analysis and visual illustrations.

The methodology implemented in the MATLAB code utilizes the logic outlined in reference [38].

Table 2 displays the breakdown of total installed capital costs for Solar PV, which reflect ratios comparable to those found in Uzbekistan.

Table 2. Breakdown of total installed capital cost for a 1 kWp solar PV system [10]

Expense	cost, USD	ratio to total cost
Modules	487.5	41%
Mounting system	157.5	13%
Electrical system DC	52.5	4%
Electrical system AC	15	1%
Inverters	105	9%
Substation infrastructure and connection	97.5	8%
Construction labour	142.5	12%
Spares	15	1%
Owner's engineering	30	3%
Contingency	90	8%
Total installed capital cost	1200	100%

Since all the variables used in LCOE calculation are annual, the total annual solar radiation data (kWh/m²) for the given area can be used to calculate the energy performance of the PVS for LCOE. Moreover, it is sufficient to use the yield values per kW of installed capacity per year from the Photovoltaic Electricity Potential map, shown in Figure 1. For the city of Tashkent, the value is 1500 kWh/kWp.

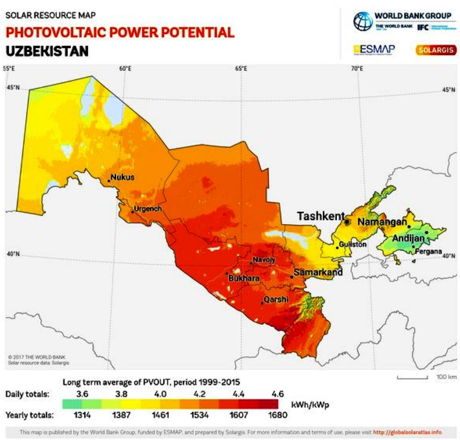


Figure 1. Photovoltaic Electricity Potential of Uzbekistan [39]

Another method for determining the PV power output for the location is using calculations with the average daily total solar radiation (kWh/m²) in a given territory. To ensure comparability of the two models, the calculation of power output in kWh/m² for a PVS with a given efficiency (η) is used to derive the unit kWh/kW, using the following formula:

$$P_{pv} = PA = \frac{I}{1m^2} \tag{8}$$

where $P = I$? and $A = \frac{I}{P * 1m^2} = \frac{I}{I\eta * 1m^2}$.

Hence, the calculation of the power output is optimized down to the calculation of total solar radiation per square meter that is quantitatively equal to the power output per kWp installed.

Table 3 displays the monthly average of daily direct normal radiation values. The formulas mentioned by Duffie and Beckman [40, 41] are used to calculate values on an hourly basis [40, 41]

$$r_\tau = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{9}$$

The coefficients a and b are given by [40, 41]:

$$a = 0.409 + 0.501\sin(\omega_s - 60) \tag{10}$$

$$b = 0.6609 + 0.4767\sin(\omega_s - 60) \tag{11}$$

The cosine of the angle between the direct radiation to the surface and the normal to the surface (θ) is used to determine the radiation on an inclined surface (I) [https://onlinelibrary.wiley.com/doi/book/10.1002/9781118671603].

$$I = \cos(\theta) I_{DNR} \tag{12}$$

$$\begin{aligned} \cos(\theta) = {} & \sin(\delta)\sin(\varphi)\cos(\beta) - \\ & \sin(\delta)\cos(\varphi)\sin(\beta)\cos(\gamma) + \\ & \cos(\sigma)\cos(\varphi)\cos(\beta)\cos(\omega) + \\ & \cos(\delta)\sin(\varphi)\cos(\beta)\sin(\gamma)\cos(\omega) + \\ & \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega) \end{aligned} \tag{13}$$

where, δ is the deviation angle, φ is latitude, β is the tilt angle, γ is the azimuth angle, ω is the time angle and ω_s is the sunset hour angle; deviation angle is calculated by the formula [40, 41]:

$$\delta = 23.45\sin(360\frac{284+n}{365}) \quad (14)$$

where, n is the day of the year (0-365); the time angle is calculated by the formula [40, 41]:

$$\omega = 15(\tau - 12) \quad (15)$$

where, τ is the time of day.

Table 3. The values of the monthly average daily direct normal solar radiation (kWh/m²) in the city of Tashkent [42].

Jan	3.33	July	8.50
Feb	3.97	Aug	8.23
March	4.87	Sep	7.38
Apr	6.02	Oct	5.98
May	7.33	Nov	4.33
June	8.66	Dec	3.08
Annual mean		5.98	

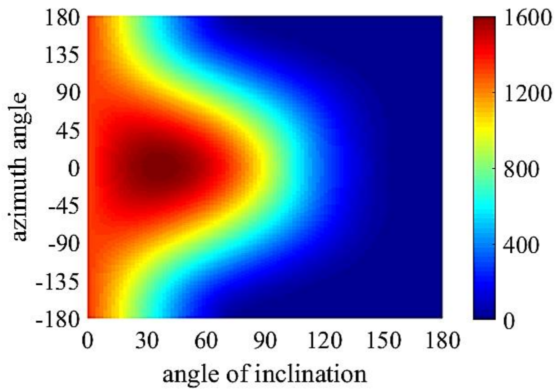


Figure 2. Estimated annual total productivity (kWh/kW) based on monthly average daily direct normal solar radiation

Figure 2 shows that the results of the model, based on the values of the monthly average daily solar radiation, are comparable with the map of the photovoltaic potential of Uzbekistan. However, the maximum annual total productivity of the model exceeds 1600 kWh/kWp, which is 7% higher than that in the Solargis map (Figure 1).

For the purpose of this study, the MATLAB model was developed using an algorithm that calculates the values of solar insolation at a particular location based on five variables: 1) time of day (τ), 2) day of the year (n), 3) tilt angle (β), 4) azimuth angle (γ) and 5) albedo (ρ) simultaneously. The calculation results form a multidimensional database of solar insolation for the given location based on any values of the above variables and their combinations. The model calculates the global solar radiation $I_G(\beta,\gamma,\tau,n,\rho)$, which consists of direct $I_B(\beta,\gamma,\tau,n,\rho)$, diffuse $I_D(\beta,\gamma,\tau,n,\rho)$, and reflected components $I_R(\beta,\gamma,\tau,n,\rho)$, where $I_G(\beta,\gamma,\tau,n,\rho) = I_B(\beta,\gamma,\tau,n,\rho) + I_D(\beta,\gamma,\tau,n,\rho) + I_R(\beta,\gamma,\tau,n,\rho)$

The variables are set to the following ranges: τ (sunrise:sunset), n (1:365), β (0:180), γ (- 180:180) and ρ (0:1).

The core of the model is based on the mathematical model for calculating hourly direct, diffuse, and reflected solar radiation for clear-sky conditions, as described by Duffie and Beckman [33]. The calculation of diffuse radiation uses the Liu-Jordan isotropic model, which was found to be the most accurate by [43].

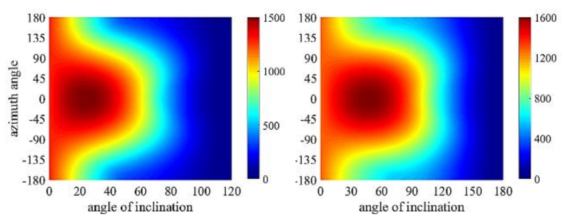
Values of the local clearness index (KT) are applied to the calculated data to reflect its influence on radiation data under clear-sky conditions (ICS).

$$I = K_T I_{CS} \quad (16)$$

The monthly values of the clearness index presented in Table 4 are applied to the monthly sums of the daily ICS values, which are then summed to obtain the annual power output as a function of the angle of inclination, azimuth angle, and albedo.

Table 4. Clearness index values for the city of Tashkent (latitude -41.2995N, longitude -69.2401E).

Jan	0.47	July	0.66
Feb	0.48	Aug	0.66
March	0.51	Sep	0.65
Apr	0.56	Oct	0.59
May	0.60	Nov	0.52
June	0.65	Dec	0.45
Annual mean		0.57	

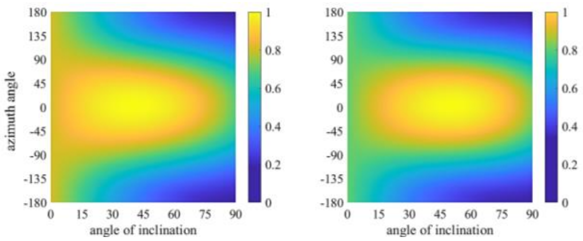


a) b)

Figure 3. The values of the annual power output (kWh/kW) from the developed database, for albedo value: 0.2 (a) and 0.6 (b)

It can be seen from Figure 3 that the database results based on the developed model are also comparable with the map of the photovoltaic potential of Uzbekistan. However, the value of the maximum annual power output varies depending on the albedo values, which are specific to each case.

The annual output of the photovoltaic power (E_{pv}) is directly related to the power output of the PVS (P_{pv}) which in our case is a function of location on the PEP map and the orientation in Figure 2-3. Values of the Photovoltaic Electricity Potential of Uzbekistan given in Figure 1 vary from 0.85 (1275) to 1.1 (1650), related to the value 1500 kWh/kW chosen for calculations for the territory of the city of Tashkent. A similar ratio applies to the available energy at different orientations of the PV, as shown in Figure 4, which uses data from Figure 3.



a) b)

Figure 4. The Yield Factor values corresponding to the calculated annual total productivity (kWh/kW) based on the developed database, for the albedo value: 0.2 (a) and 0.6 (b)

Considering the proportionality of the variables in the denominator, the Yield Factor $F_y(0.85:1.1)$ was introduced in Formula (1) to analyze the sensitivity of LCOE to the location and orientation of PVS, as follows [15]:

$$LCOE = \frac{K_t}{F_y E_t} \tag{17}$$

Figure 5 shows the overall methodological flow used in this study to evaluate the LCOE for three PV system configurations under varying technical and economic scenarios.

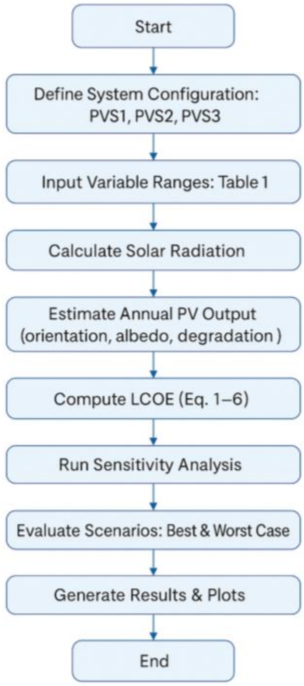


Figure 5. Methodology flowchart for the LCOE evaluation process.

3. Results and Discussion

3.1. LCOE analysis. Despite containing values for all ranges of variables, the database restricts the analysis to a maximum of two variables from Table 2, with the remaining parameters held constant. To facilitate analysis, extreme values from Table 2 are set as constants in two scenarios: 1) the Worst-Case, and 2) the Best-Case (Table 5).

Table 5. Constant values for calculations according to the scenarios

Variables	Worst-Case Scenario	Best-Case Scenario
Yield Factor (FY)	0.85	1.1
PVS installation costs (Pp), $/kW	1500	800
Loan rate (Fb), %	5	0
Storage system installation costs (Bp), $/kWh	550	250
Share of accumulation from the generated energy (Rb), %	99	1
Battery lifetime (BL), years	5	15

The storage system introduces extra capital costs and reduces energy yield due to battery efficiency. Hence, a large share of accumulation is used for the Worst-Case Scenario, which applies to a system with high internal consumption or a higher electricity price during non-generating periods. However, it cannot be equal to 100% when the grid connection would no longer make sense. A small share of accumulation in the Best-Case Scenario corresponds to a system with very low intrinsic consumption, but it cannot be equal to zero, as the purpose of the accumulation system would be lost. Nevertheless, the LCOE dependence on Rb is also demonstrated for both scenarios.

Three types of systems according to the grid connection were determined for LCOE analysis. The results are presented in the figures, varying only the parameters under consideration, while the rest remain unchanged and equal to the values specified in the scenario, as shown in Table 5. An LCOE over 100$/MWh was considered not feasible, and any amount above this value was set equal to 100$/MWh.

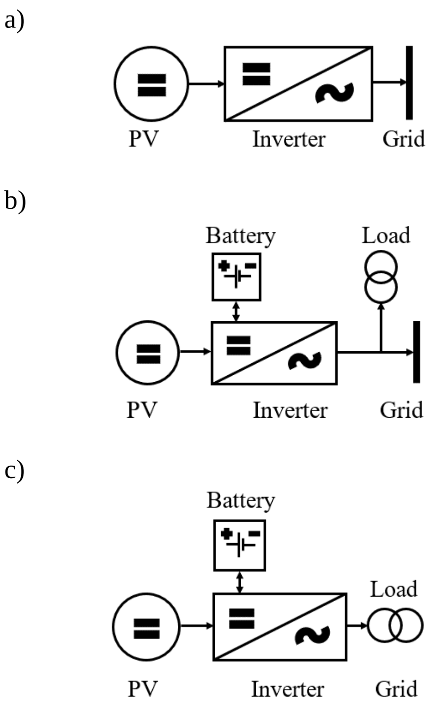


Figure 6. overview diagram of the systems: a) PVS1: Grid-connected without storage; b) PVS2: Grid-connected with storage; c) PVS3: Off-grid with storage

3.2. LCOE of the grid-connected system, without storage batteries (PVS1). The analysis also applies to scenarios where the Photovoltaic System (PVS) is not connected to the grid, with the generated electricity being fully utilized at the time of production. This situation arises when the capacity of the PV matches a segment of daily energy use, and the remainder of the energy needs is met from alternative sources. For this particular analysis, only three factors from Table 5 are pertinent: the Yield Factor, the costs associated with installing the PVS, and the interest rate on loans. Figures 7 and 8 display how the Levelized Cost of Electricity (LCOE) varies with these parameters under the worst-case and best-case scenarios, respectively.

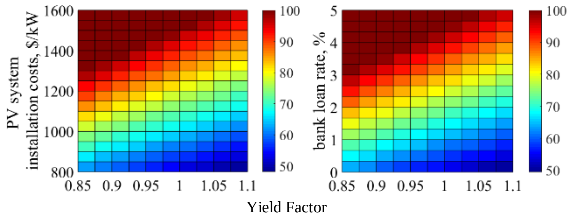


Figure 7. Dependence of the LCOE ($/MWh) of PVS1, on the combined influence of YF, Pp, and Fb in the Worst-Case Scenario

For grid-connected systems without battery storage, the Levelized Cost of Electricity (LCOE) reaches a low of approximately $49/MWh in the worst-case scenario (shown in Figure 7) and drops to about $25/MWh in the best-case scenario (Figure 8). The highest sensitivity of LCOE to factors such as Fb and Pp at Yield Factor (YF) in the worst-case scenario, as indicated in Table 7, surpasses the feasibility threshold, suggesting that LCOE increases and becomes feasible only at elevated YF levels (Figure 5). In both scenarios, the sensitivity of LCOE to YF remains the lowest for both Fb and Pp, never exceeding the feasibility threshold (Table 7). The interaction between Pp and Fb on LCOE, illustrated in Figure 9, reveals similar sensitivity levels to both factors in each scenario (Table 7).

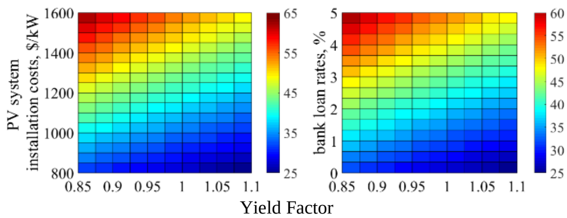
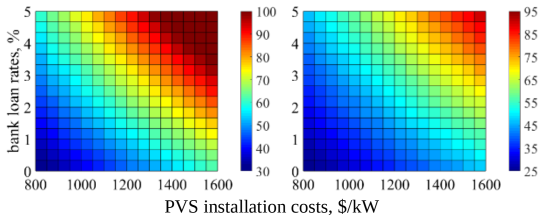


Figure 8. Dependence of the LCOE ($/MWh) of PVS1 on the combined influence of YF, Pp, and Fb in the Best-Case Scenario

Figures 7 and 8 show that the LCOE depends little on YF, with the minimum LCOE reached at the ratio of low Fb and Pp. The dependence of the LCOE of

PVS1 on the combined influence of Pp and Fb in both scenarios is shown in Figure 9. The steeper angle of the gradient contour in the figures indicates that the influence of YF on LCOE is smaller than that of Pp and Fb. At the same time, this angle in Figure 9 is close to 45 degrees, indicating that the influences of Pp and Fb are similar. It can be seen that the feasibility threshold is surpassed starting at 1300 $/kW for Pp and 3% for Fb in the Worst-Case Scenario, and is not reached in the Best-Case Scenario.

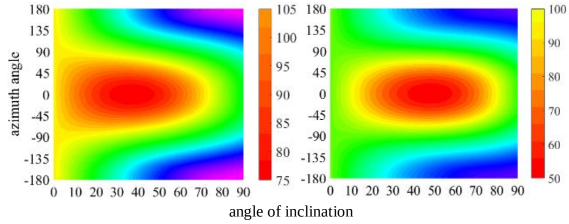
The orientation-based LCOE for PVS1, derived from the location-based calculations using YF related to Pp (Figure 10), shows that the lowest LCOE values (between 73 and 75, and 51 and 53) are achieved with azimuthal angles ranging from 10 to -10 degrees and tilt angles from 30 to 40 degrees for an albedo of 0.2, and from 15 to -15 degrees with tilt angles from 40 to 55 degrees, respectively, for an albedo of 0.6. The absolute minimum LCOE values (38 to 40 and 26 to 28) are found with azimuthal angles from 20 to -20 degrees and tilt angles from 25 to 50 degrees for an albedo of 0.2, and similarly for an albedo of 0.6 but with tilt angles from 40 to 55 degrees.



a) b)

Figure 9. Dependence of the LCOE ($/MWh) of PVS1 on the combined influence of Pp and Fb in the Worst-Case Scenario (a) and in the Best-Case Scenario (b).

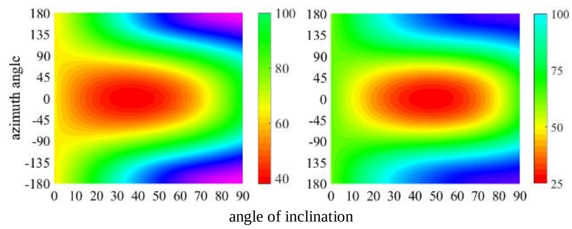
The PVS1 orientation-based LCOE, derived from location-based LCOE using YF in combination with Pp and Fb in the Worst-Case Scenario (Figure 7), differed by only around 3%. The corresponding data set in the Best-Case Scenario, generated from the data presented in Figure 8, was also very similar. For this reason, only one set of PVS1 orientation-based LCOE values in each scenario, for albedo values of 0.2 and 0.6, is presented in Figures 10 and 11.



a) b)

Figure 10. PVS1 orientation-based LCOE ($/MWh), considering the minimum from location-based LCOE for YF-Pp combination in the Worst-Case Scenario, for the albedo value: 0.2 (a) and 0.6 (b)

For grid-connected systems with storage batteries, negative feasibility limits for LCOE sensitivity (Table 8) indicate that the lowest LCOE values in the worst-case scenario exceed the $100/MWh feasibility threshold, even under the most favorable variable combinations. Consequently, the margin for feasible LCOE is narrow, observed only at the lowest Rb values, approaching the worst-case scenario for systems without storage batteries. No minimum S_LCOE values within the feasibility limit were identified in the worst-case scenario (Table 9). However, in the best-case scenario, all variables' S_LCOE values were below the feasibility limits outlined in Table 8, except for the maximum combinations of Rb and Fb, which led to higher LCOE values (Figure 13). The least impactful parameter on LCOE for systems with storage batteries is YF, while Rb and Fb are the primary drivers. The minimum LCOE for systems with storage batteries aligns with that of systems without storage batteries at $25/MWh (Figure 11), particularly when Rb is minimized, resulting in S_LCOE values for any YF, Fb, and Pp combination comparable to those of systems without batteries.



a) b)

Figure 11. PVS1 orientation-based LCOE ($/MWh), considering the minimum from location-based LCOE for YF-Pp combination in the Best-Case Scenario, for the albedo value: 0.2 (a) and 0.6 (b)

3.3. LCOE of the grid-connected system, with storage batteries (PVS2). The calculation is equally applicable to off-grid systems where the portion of energy not fed into a network is utilized at the time of its generation. This approach to using an off-grid Photovoltaic System (PVS) is common when the energy consumption matches only a fraction of the energy produced throughout the day. For this specific analysis, all six factors listed in Table 3 are considered to be relevant: the Yield Factor, the costs of PVS installation, the loan interest rate, the installation expense of the storage system, the proportion of energy stored from what is generated, and the lifespan of the batteries. Figures 12 and 13 illustrate how the Levelized Cost of Electricity (LCOE) varies with these key variables in the Worst-Case and Best-Case scenarios, respectively.

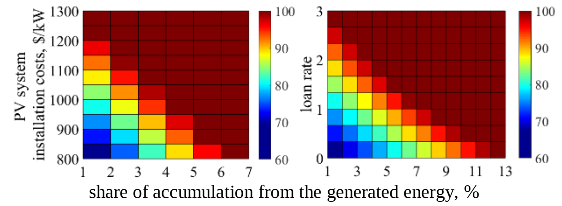


Figure 12. Dependence of the PVS2 LCOE ($/MWh) on the combined influence of Pp, Fb and Rb in the Worst-Case Scenario

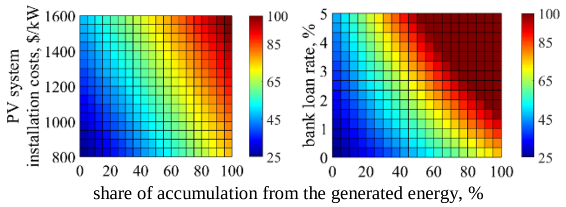


Figure 13. Dependence of the LCOE ($/MWh) of PVS2 on the combined influence of YF, Pp, Fb, Bp, Rb, and BL in the Best-Case Scenario

LCOE relation to the combined effects of YF with Rb and the Pp is presented in figure 14.

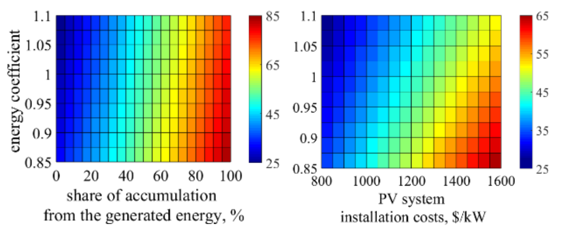
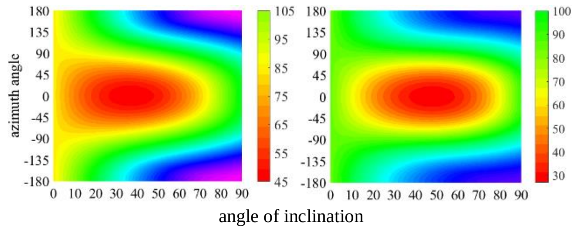


Figure 14. Dependence of the LCOE ($/MWh) of PVS2 on the combined influence of YF, Rb and the Pp in the Best-Case Scenario

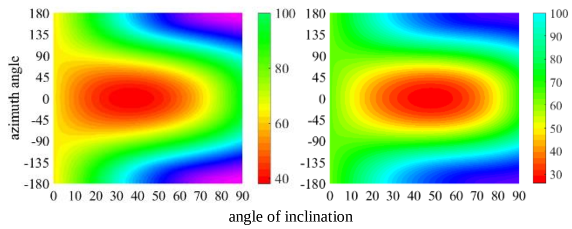
A steeper vertical angle of the gradient contour in the figures indicates a greater influence of Rb compared to YF, Pp, and Fb. This implies that in the Worst-Case Scenario, the feasibility threshold is surpassed at 7% and 13% of Rb for the lowest values of Pp and Fb, respectively. In the Best-Case Scenario, these values are 90% and 50% for the highest values of Pp and Fb, respectively.

PVS2 orientation-based LCOE, interpreted from location-based LCOE from figure 14 using YF in combination with Rb and Pp in Best-Case Scenario for the albedo value 0.2 and 0.6 is presented in figures 15-16.



a) b)

Figure 15. PVS2 orientation-based LCOE ($/MWh), considering the minimum from location-based LCOE for YF-Rb combination in the Best-Case Scenario, for the albedo value: 0.2 (a) and 0.6 (b)



a) b)

Figure 16. PVS2 orientation-based LCOE ($/MWh), considering the minimum from location-based LCOE for YF-Pp combination in the Best-Case Scenario, for the albedo value: 0.2 (a) and 0.6 (b)

The orientation-based LCOE for PVS2, using YF related to Rb (Figure 15), reaches its lowest values (45 to 48 and 27.5 to 29.5) with azimuthal angles between 15° to -15° and inclination angles from 30° to 45° for an albedo of 0.2. For an albedo of 0.6, similar results are found but with inclination angles from 45° to 55°. Orientation-based calculations for PVS2 using YF related to Pp (Figure 16) show that minimum LCOE values (38.5 to 40.5 and 26.5 to 28.5) are achieved with azimuthal angles ranging from -20° to 20° and inclination angles from 25° to 45° for an albedo of 0.2. For an albedo of 0.6, the minimum LCOE values occur with azimuthal angles from -15° to 15° and inclination angles from 40° to 55°.

3.4. LCOE of the off-grid system with storage batteries (PVS3). From the perspective of payback time, a grid-connected system appears to be more financially viable. However, incorporating batteries enhances the dependability of the electricity supply for consumers in areas distant from the central electric grid or those experiencing frequent power outages. The analysis applicable to grid-connected systems with batteries is also relevant for standalone systems. In such systems, batteries are used where the energy produced is partly utilized for generation while the remainder is stored; in these instances, only the stored energy is deemed beneficial, with any excess considered wasted. This scenario typically arises when PVS is employed solely for charging backup systems, vehicles, etc.

In the worst-case scenario, the outcomes of the LCOE calculations did not exceed the feasibility threshold of $100/MWh for any variable combination. The analysis identified fuel cost/biomass cost (Fb), baseline load (BL), and battery price (Bp) as the primary factors influencing this case. Figure 17 illustrates how the LCOE varies with these factors in the best-case scenario.

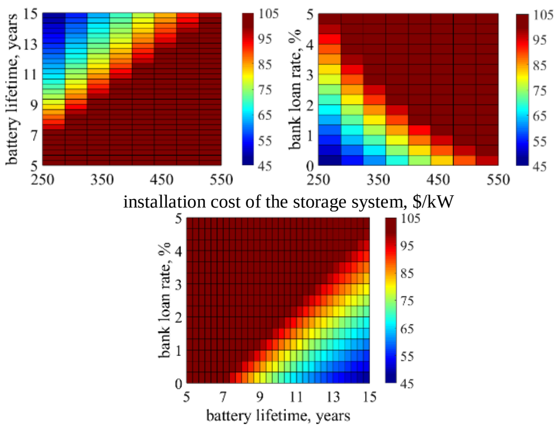


Figure 17. Dependence of the LCOE ($/MWh) of PVS3, on the combined influence of Fb, Bp and BL in the Best-Case Scenario

Since only the saved energy is considered useful, LCOE dependence on the main influencing parameters (Fb, Bp and BL) and Rb is presented in figure 18.

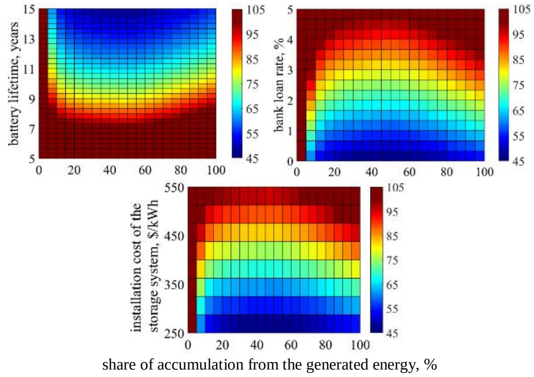


Figure 18. Dependence of the LCOE ($/MWh) of PVS3, on the combined influence of Fb, Bp and BL and Rb in the Best-Case Scenario

A more horizontal gradient contour in Figure 18 indicates a smaller influence of Rb compared to BL, Pp, and Fb. At the same time, the feasibility threshold is more likely to be exceeded at the extremes of Rb. At 0% Rb, the yield declines to zero because no energy is stored, while at nearly 100% Rb, the high battery system costs increase the LCOE.

Analysis of off-grid systems with storage batteries reveals that the sensitivity of LCOE to variables such as BL, Bp, Rb, and Fb often leads to minimum values (Table 11) that exceed the LCOE feasibility threshold. Thus, feasible LCOE values are attainable within specific ranges of these variables, as depicted in Figures 17 to 20. Without exceeding a 5% Rb, feasible LCOE cannot be achieved (Figure 18) due to the disproportion between generated and stored energy costs. Feasible LCOE is attainable across the entire range only for combinations of YF and Pp (Table 11), with these combinations showing the lowest values compared to other variables. The S_LCOE for Rb remains within the feasible range for most BL, Bp, and Fb values, exhibiting both negative and positive extremes with the smallest values centered around the LCOE minimums in Figure 18.

Two parameters happened to have the least influence on LCOE in the Best-Case Scenario: YF and Pp (figure 19).

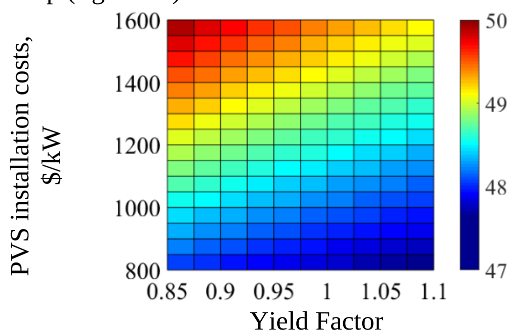
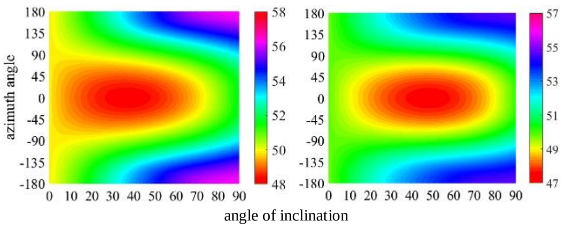


Figure 19. Dependence of the LCOE ($/MWh) of PVS3, on the combined influence of the YF and Pp in the Best-Case Scenario

PVS3 orientation-based LCOE, derived from location-based LCOE from figure 19 using YF in combination with Pp in Best-Case Scenario for the albedo value 0.2 and 0.6 are presented in figure 20.



a) b)

Figure 20. PVS3 orientation-based LCOE, considering the minimum from location-based LCOE for YF-Pp combination in the Best-Case Scenario, for the albedo value: 0.2 (a) and 0.6 (b)

For PVS3, orientation-based LCOE calculations using YF related to Pp (Figure 20) show that the lowest LCOE values (48 to 50 and 47.5 to 49.5) occur across all azimuthal angles (-180° to 180°) with inclination angles from 0° to 77° for an albedo of 0.2. For an albedo of 0.6, the lowest values are observed with azimuthal angles from -80° to 80° and inclination angles from 5° to 85°.

3.5. LCOE sensitivity analysis. Figures 7–20 illustrate how LCOE responds differently to variable changes across three systems: (1) grid-connected without storage batteries, (2) grid-connected with storage batteries, and (3) off-grid with storage batteries. Given that the sensitivity of LCOE is measured in $/MWh%, its feasibility limit is defined in alignment with the LCOE feasibility threshold of $100/MWh, as follows:

$$abs(S(dV)) \le \frac{100 - LCOE\min(V)}{100\%} \qquad (18)$$

here $LCOE\min(V)$ is the minimum value of LCOE calculated for *V*, *S(dV)* is the S_{LCOE} value for the variable V according to Formula (7). It is important to note that a sensitivity value exceeding the feasibility limit can still result in an LCOE below $100/MWh, but not across the entire range (100%) of the associated variables. The sensitivity values for each variable are presented in relation to the coupled variable, with 'W' representing the Worst-Case Scenario and 'O' representing the Best-Case Scenario.

The 'feasibility limits of LCOE sensitivity' define the range within which changes in input variables result in an economically viable Levelized Cost of Energy (LCOE). These limits are established to ensure that small variations in key factors (such as capital costs, operating expenses, fuel prices, etc.) do not lead to an LCOE that exceeds what is considered affordable or viable for energy production projects. This criterion sets the maximum permissible LCOE sensitivity to variable changes, ensuring economic feasibility despite fluctuations in critical inputs. This limit is vital for planning and risk management, helping identify variables with the greatest impact on energy costs that require careful oversight to maintain project feasibility. This approach helps in identifying and managing risks associated with variable changes, ensuring that the project remains economically viable across a range of potential scenarios.

The minimum and maximum values of LCOE sensitivity define the range within which it responds to changes in specific variables for an energy project. LCOE sensitivity reflects how factors like investment costs, operational expenses, fuel prices, interest rates, and technological efficiency affect it. High sensitivity indicates that small changes in these variables can significantly fluctuate the LCOE, raising financial risks and potential economic instability. The minimum sensitivity value reflects the least impact a variable change has on LCOE, highlighting when the project is most stable or resilient. Conversely, the maximum sensitivity value shows the highest variable impact, identifying vulnerabilities or risks to the project's economic feasibility. Understanding sensitivity ranges is crucial for assessing project risks, planning mitigation strategies, and making informed investment and design decisions. Positive values suggest that increasing variables (e.g., installation cost or loan rate) raises LCOE, reducing economic viability. Negative sensitivity values, especially for the yield factor (dYF), indicate that efficiency improvements can reduce LCOE and enhance viability.

Table 6 provides feasibility limits for PVS1 LCOE sensitivity (S), with corresponding minimums and maximums detailed in Table 7.

Table 5 outlines LCOE sensitivity feasibility limits for variable combinations in the PVS1 project under Worst-Case (W) and Best-Case (O) scenarios.

Table 6. Feasibility limits for LCOE sensitivity for variables in various combinations for PVS1

Fb_Pp_W	0.68	Fb_Pp_O	0.75
Fb_YF_W	0.51	Fb_YF_O	0.75

Pp_YF_W	0.52	Pp_YF_O	0.75

Worst-Case Scenario (W): Fb_Pp_W (0.68) shows moderate LCOE sensitivity to changes in both PV installation costs and bank loan rates. The project can accommodate some changes in these variables without losing economic feasibility. Fb_YF_W (0.51) and Pp_YF_W (0.52) are slightly lower, indicating that LCOE is more sensitive to changes in the yield factor when combined with either bank loan rates or PV installation costs. A smaller margin indicates stricter constraints on economic feasibility under adverse conditions.

Best-Case Scenario (O): Fb_Pp_O, Fb_YF_O, and Pp_YF_O (all 0.75) show higher feasibility limits, indicating greater tolerance for changes in these variables. The project is more resilient to shifts in PV installation costs, loan rates, and yield factors, preserving economic viability even with these variations.

Table 7. Minimums and maximums of the LCOE sensitivity of PVS1

dataset	min	max
S(dPp@YF)_W	0.49	0.63
S(dFb@YF)_W	0.47	0.61
S(dPp@Fb)_W	0.32	0.63
S(dFb@Pp)_W	0.31	0.61
S(dPp@Fb)_O	0.25	0.49
S(dPp@YF)_O	0.25	0.32
S(dFb@Pp)_O	0.24	0.47
S(dFb@YF)_O	0.24	0.31
S(dYF@Fb)_W	-0.12	-0.36
S(dYF@Pp)_W	-0.11	-0.36
S(dYF@Pp)_O	-0.06	-0.18
S(dYF@Fb)_O	-0.06	-0.18

S(dPp@Fb)_W and S(dFb@Pp)_W, at 0.31 and 0.30, respectively, show significant variability and risk in how PV installation costs and bank loan rates interact to affect LCOE. This suggests that effective financial and cost management strategies are crucial for mitigating LCOE sensitivity under adverse conditions. Sensitivities related to the yield factor (S(dPp@YF)_W and S(dFb@YF)_W) have identical ranges of 0.14, indicating moderate variability and the importance of optimizing efficiency and performance to manage LCOE in less favorable conditions.

Sensitivity variability is generally lower in Best-Case scenarios, reflecting greater stability and predictability in the impact of these variables on LCOE. The range for S(dPp@Fb)_O at 0.24 shows the highest potential for LCOE fluctuation in Best-Case scenarios, though still less than in Worst-Case scenarios. The smallest ranges, 0.07 for S(dPp@YF)_O and S(dFb@YF)_O, suggest that in optimal conditions, PV system efficiency (yield factor) and its interaction with installation costs or loan rates have a more predictable and lower impact on LCOE.

Negative ranges are observed in sensitivities involving the yield factor (S(dYF@Fb)_W, S(dYF@Pp)_W, S(dYF@Pp)_O, S(dYF@Fb)_O), with S(dYF@Pp)_W and S(dYF@Fb)_W showing the most significant negative impacts at -0.25 and -0.24, respectively. This indicates that improvements in the yield factor, when combined with PV installation costs or bank loan rates, can significantly reduce LCOE, particularly in Worst-Case scenarios. The reduced range in Best-Case scenarios (-0.12) suggests a more controlled, predictable impact of efficiency improvements on LCOE.

The data in Table 8 provides feasibility limits for the sensitivity of the Levelized Cost of Energy (LCOE) to changes in various variable combinations for PVS2, under both Worst-Case (W) and Best-Case (O) scenarios.

Negative Feasibility Limits: Several combinations show negative feasibility limits (Fb_Pp_W, Fb_YF_W, Pp_YF_W, YF_Rb_W), indicating that changes in these variables lead to a decrease in the economic viability or an increase in the LCOE beyond acceptable levels. The most notable is Pp_YF_W at -6.85, suggesting a significant sensitivity of LCOE to simultaneous changes in PV installation costs and the yield factor, making it the combination with the highest impact on economic feasibility under adverse conditions.

Combinations involving Rb (Fb_Rb_W and Pp_Rb_W) show positive feasibility limits, though relatively low (0.33 and 0.31 respectively), indicating a modest tolerance for changes in these factors. The positive values suggest that, in contrast to the other variables, changes in the Rb variable (and its combinations with Fb and Pp) have a less detrimental effect on the LCOE's economic feasibility under worst-case conditions.

All combinations in the Best-Case scenario have a uniform feasibility limit of 0.75, indicating a consistent and higher tolerance for changes in all variables. This uniformity suggests that, under optimal conditions, PVS2 has robust resilience to variations in installation costs, loan rates, yield factors, and the Rb variable, maintaining the project's economic viability across a broader range of changes.

The significant negative feasibility limits in the Worst-Case scenario, especially for combinations involving the yield factor and PV installation costs, highlight the critical impact of operational efficiency and initial investment costs on the economic viability of solar energy projects under challenging conditions.

The uniform positive feasibility limits in the Best-Case scenario indicate that, with favorable conditions, the project can withstand a wide range of changes in key variables without jeopardizing its economic feasibility.

The distinct behavior of combinations involving the Rb variable, showing positive feasibility limits even in the Worst-Case scenario, suggests that this factor might represent aspects of the project that are less sensitive to adverse conditions or that can be managed more effectively to maintain economic viability.

Table 8. Feasibility limits for LCOE sensitivity for variables in various combinations for PVS2

Fb_Pp_W	-2.68	Fb_Pp_O	0.75
Fb_YF_W	-2.88	Fb_YF_O	0.75
Fb_Rb_W	0.33	Fb_Rb_O	0.75
Pp_YF_W	-6.85	Pp_YF_O	0.75
Pp_Rb_W	0.31	Pp_Rb_O	0.75
YF_Rb_W	-0.03	YF_Rb_O	0.75

Table 9 presents the minimum and maximum sensitivity of the Levelized Cost of Energy (LCOE) for various variable combinations in PVS2, under both Worst-Case (W) and Best-Case (O) scenarios.

The combination Sb(dRb@Pp)_W shows the highest sensitivity range, with values from 6.71 to 8.23. This indicates that changes in the Rb variable in relation to PV installation costs have the most significant impact on LCOE under adverse conditions, reflecting a high risk or potential for cost variability. Sb(dRb@Fb)_W and Sb(dFb@Rb)_W also show significant ranges, especially the former, which matches the maximum of Sb(dRb@Pp)_W at 8.23. This suggests that the relationship between the Rb variable and both PV installation costs and bank loan rates critically affects the project's economic feasibility in less favorable conditions. Sb(dPp@Fb)_W has a relatively lower range from 0.36 to 0.70, indicating less variability and potentially lower risk in the interaction between PV installation costs and bank loan rates compared to those involving the Rb variable.

All combinations in the Best-Case scenario have significantly lower sensitivity ranges compared to the Worst-Case scenario. For example, Sb(dRb@YF)_O, Sb(dRb@Pp)_O, and Sb(dRb@Fb)_O show ranges of 0.11, 0.14, and 0.80 respectively, indicating more stability and predictability in how these variables affect LCOE under favorable conditions. Sb(dYF@Pp)_O and Sb(dYF@Rb)_O present negative sensitivity values, suggesting that improvements in the yield factor, whether in relation to PV installation costs or the Rb variable, could lead to reductions in LCOE, enhancing the project's economic viability in the Best-Case scenario.

Table 9. Minimums and maximums of the LCOE sensitivity of PVS2

dataset	min	max
Sb(dRb@Pp)_W	6.71	8.23
Sb(dRb@Fb)_W	3.08	8.23
Sb(dFb@Rb)_W	0.65	4.71
Sb(dRb@YF)_O	0.48	0.59
Sb(dRb@Pp)_O	0.48	0.62
Sb(dRb@Fb)_O	0.48	1.28
Sb(dPp@Fb)_W	0.36	0.70
Sb(dPp@YF)_O	0.25	0.32
Sb(dPp@Rb)_O	0.25	0.28
Sb(dFb@Rb)_O	0.24	0.87
Sb(dYF@Pp)_O	-0.06	-0.18
Sb(dYF@Rb)_O	-0.06	-0.10

The Rb variable plays a significant role in the sensitivity of LCOE, particularly in the Worst-Case scenario. Its interactions with PV installation costs and bank loan rates suggest areas of high variability and potential risk, highlighting the need for careful management and mitigation strategies. The negative sensitivity ranges in the Best-Case scenario underscore the importance of enhancing operational efficiency (yield factor) as a means to reduce LCOE and improve economic feasibility. The generally lower sensitivity ranges in the Best-Case scenario reflect a level of resilience and stability, indicating that under optimal conditions, the project is less vulnerable to fluctuations in these key variables.

Table 10 provides feasibility limits for the sensitivity of the Levelized Cost of Energy (LCOE) to changes in various variable combinations for PVS3, all within a Best-Case scenario (O).

All the feasibility limits provided are in a narrow range from 0.52 to 0.53, suggesting a uniform sensitivity across different combinations of variables affecting the LCOE. This uniformity in feasibility limits suggests that, under Best-Case scenarios, the LCOE of PVS3 exhibits a relatively consistent and moderate level of sensitivity to changes in these variables.

Table 10. Feasibility limits for LCOE sensitivity for variables in various combinations for PVS3

Fb_BL_O	0.52	BL_BP_O	0.52
Fb_Rb_O	0.53	Rb_BP_O	0.53
Fb_BP_O	0.52	Pp_YF_O	0.52
BL_Rb_O	0.53		

The data from Table 11 provides insights into the sensitivity of the Levelized Cost of Energy (LCOE) for various variable combinations within the PVS3 project, under a Best-Case scenario (O), focusing on an off-grid system (S_offG) where only accumulated energy (captured by the share of the accumulated energy, Rb) is considered useful.

Sensitivities involving Fb (bank loan rates) show a broad range of impacts on LCOE, particularly with BL (battery lifetime), with a dramatic negative sensitivity range in S_offG(dBL@Fb)_O going from -0.32 to -5.74. This suggests that improvements in battery lifetime can significantly reduce LCOE, especially in financing scenarios. The sensitivity of LCOE to changes in BP (battery cost) also shows variability, with a notable impact when considered with BL, where the range extends to 1.67. This indicates the critical role of battery cost and lifetime in determining the economic viability of off-grid systems. Sensitivities involving the share of accumulated energy (Rb) and battery cost (BP) exhibit a wide negative range in nS_offG(dRb@BP)_O, stretching to -14.04, highlighting the significant potential for reducing LCOE through efficient energy storage and management strategies.

The sensitivity of LCOE to changes between PV installation costs and yield factors is extremely low (S_offG(dPp@YF)_O), indicating a very stable or negligible impact on LCOE from these factors in this off-grid scenario. This stability is crucial for planning and investment decisions in off-grid systems. Positive sensitivities (pS_offG) show a potential increase in LCOE due to variable changes, albeit with relatively small ranges, suggesting controlled impacts. Negative sensitivities (nS_offG), particularly with the Rb variable, show much larger ranges, indicating that certain adjustments in the share of accumulated energy relative to bank loan rates and battery aspects can lead to substantial reductions in LCOE.

The data underscores the significant impact that battery-related variables (cost and lifetime) and the efficiency in energy storage (as indicated by Rb) have on the economic feasibility of off-grid solar projects. Efficient management and technological improvements in these areas are crucial for reducing LCOE. The sensitivity ranges related to bank loan rates highlight the importance of favorable financing conditions, especially in relation to battery lifetime, for maintaining or reducing LCOE in off-grid systems. The negligible sensitivity of LCOE to changes between PV installation costs and yield factors suggests that, in off-grid scenarios where energy accumulation is critical, the focus might be better placed on storage and financial management rather than solely on installation costs or operational efficiency.

Table 11. Minimums and maximums of the LCOE sensitivity of PVS3

dataset	min	max
S_offG(dFb_BL)O	0.57	1.68
S_offG(dFb_Rb)O	0.57	1.29
S_offG(dFb@BP)O	0.57	1.24
S_offG(dBP@Fb)O	0.56	1.22
S_offG(dBP@BL)O	0.56	1.67
S_offG(dBP@Rb)O	0.56	0.65
S_offG(dBL@Fb)O	-0.32	-5.74
S_offG(dBL@Rb)O	-0.32	-3.06
S_offG(dBL@BP)O	-0.32	-5.74
S_offG(dPp@YF)O	0.02	0.02
S_offG(dYF@Pp)O	0.00	-0.01
pS_offG(dRb@BP)O	0.01	0.53
nS_offG(dRb@BP)O	-0.01	-14.04
pS_offG(dRb@Fb)O	0.01	0.53
nS_offG(dRb@Fb)O	-0.02	-27.32
pS_offG(dRb@BL)O	0.01	0.73
nS_offG(dRb@BL)O	-0.01	-14.04

4. Future Trends and Challenges

The ongoing evolution of solar photovoltaic (PV) systems suggests several future trends that will shape their cost-effectiveness and adoption in regions like Uzbekistan:

1. Hybrid Systems Integration: The integration of PV systems with wind, biomass, or hydrogen-based storage will become increasingly viable. Hybrid energy systems offer more consistent output and better resilience in variable climates.
2. Advanced Energy Storage: The development of next-generation batteries—such as solid-state, sodium-ion, and flow batteries—will help reduce storage costs and improve cycle life, directly impacting LCOE for systems with high energy accumulation (PVS2 and PVS3).
3. AI-Based Optimization: Artificial intelligence and machine learning will play a growing role in optimizing system orientation, energy dispatch, and predictive maintenance, enabling more precise LCOE reduction strategies.
4. Policy and Financial Innovations: Future reductions in LCOE will depend heavily on innovative financing schemes, green bonds, and targeted subsidies. Regulatory frameworks will need to adapt to support off-grid and community-scale deployment models.

Challenges include ensuring grid stability with increasing renewable penetration, reducing capital costs without sacrificing quality, and managing the environmental impact of battery disposal. Additionally, climate variability and uncertain economic conditions in emerging markets will require adaptive and resilient planning tools.

5. Conclusions

This study evaluated the economic viability of three photovoltaic (PV) system configurations in Uzbekistan using LCOE analysis: grid-connected without storage (PVS1), with storage (PVS2), and off-grid with storage (PVS3). Results showed that PVS1 offers the lowest LCOE, ranging from \$49/MWh to \$25/MWh depending on economic conditions. Loan rate and installation cost were the most influential factors, while the Yield Factor remained stable across solar conditions.

Storage integration increased LCOE, often exceeding \$100/MWh under unfavorable scenarios. However, with optimal conditions, PVS2 and PVS3 could reach cost parity with storage-free systems. PVS3 was especially sensitive to battery life, storage cost, and energy accumulation share.

Optimal tilt, azimuth, and higher albedo surfaces reduced LCOE by up to 10%, particularly for off-grid systems. Under favorable financial assumptions, grid-connected PV systems achieved LCOE as low as \$0.025/kWh—competitive with Uzbekistan's electricity tariffs (\$0.024–\$0.048/kWh).

This study highlights the importance of system-level optimization and financial conditions in PV deployment. Future work will extend this framework to analyze the Levelized Cost of Hydrogen (LCOH) and Water (LCOW) for broader sustainable energy planning.

Nomenclature

BCr	Benefit-cost ratio
BESPVS	Battery electricity storage photovoltaic system
BESS	Battery electricity storage system
BIPV	Building integrated photovoltaic system
CAPEX	Capital expenditures
DPbP	Discounted payback period
ERcd	Energy return on cost of debt
IRR	Internal rate of return
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LCOW	Levelized cost of water
NPV	Net present value
PVS	PV system
PVS1	Storageless system
PVS2	On-grid system with storage
PVS3	Off-grid system with storage
YF	Yield Factor
(τ),	time of day
(n),	day of the year
(β),	tilt angle
(γ)	azimuth angle
(ρ)	albedo
a.u.	arbitrary unit
B_t	BESS cost (\$/kWh)
C_b	cost of installing the storage system (\$/kWh)
C_i	inverter price (\$)
C_{om}	annual costs for operation and maintenance (\$)
C_{pv}	PV installation costs including inverter costs (\$/kW)
E_{pv}	annual photovoltaic power output (kWh)
F_b	loan rate (%)
N	life of the photovoltaic system
nb	battery lifetime,
P_{pv}	power output of PV system (kWh)
R_b	share of accumulated energy (%)

S_{b0}	cost of PV system installation without inverter and storage system ($/kW)
F_{Epv}	average annual degradation rate of the photovoltaic system
t_i	inverter lifetime (years)
ε_{om}	annual rates of growth for operating and maintenance costs
η_b	Battery efficiency
η_i	Invertor efficiency
t_b	battery lifetime (years)

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