

FROM SIMULATION TO INVESTMENT EVIDENCE: MULTISCALE VALIDATION AND TRANSPARENT TECHNO-ECONOMIC ASSESSMENT OF UTILITY-SCALE AND INSTITUTIONAL SOLAR PV SYSTEM

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Abstract

Photovoltaic project assessment requires an evidence framework in which simulated energy yield, measured generation, and economic performance remain explicitly traceable to their underlying data and assumptions. This study develops such a framework through a comparative assessment of two photovoltaic configurations in Pakistan: a 100 MWp utility-scale system (QASP/LSPP) and a 405 kWp institutional system (UOL/SSPP). The analysis integrates PVsyst energy predictions with reported generation records and project-level economic indicators, while distinguishing directly reported quantities from independently reconstructed financial metrics. For QASP/LSPP, twelve paired monthly observations covering September 2015–August 2016 are evaluated using correlation, goodness-of-fit, mean absolute error (MAE), root mean square error (RMSE), and paired statistical testing. The annual PVsyst estimate of 155,276 MWh is 2.48% lower than the reported generation of 159,216.63 MWh. Despite this close annual agreement, monthly correspondence is only moderate (Pearson $r = 0.690$; $R^2 = 0.476$), with MAE and RMSE of 1,312.24 and 1,508.84 MWh, respectively; paired tests do not indicate a statistically significant systematic difference at the 5% level. For UOL/SSPP, the reported annual generation is 700 MWh compared with 688 MWh from PVsyst, corresponding to a 1.71% model shortfall. However, only three dated paired observations are available, precluding a statistically comparable monthly validation. The reported project-level LCOE values are Rs 4.26/kWh for QASP/LSPP and Rs 5.53/kWh for UOL/SSPP. To examine the reproducibility of these economic indicators, an independent lifecycle reconstruction using a 25-year project horizon, an 8% discount rate, linear degradation to 80% of initial output by year 25, and the documented cost inputs yields LCOEs of Rs 12.32/kWh and Rs 9.96/kWh, respectively. The substantial divergence between reported and reconstructed LCOE values demonstrates that economic conclusions are highly sensitive to the treatment of degradation, discounting, operating expenditure, tariff assumptions, financing structure, and other omitted cost components. The findings therefore establish an important distinction between annual energy agreement and temporal model fidelity and demonstrate that photovoltaic techno-economic claims are reproducible only when measurement records, simulation outputs, and financial assumptions are maintained within a

1. Introduction

Solar photovoltaic (PV) deployment has expanded from large grid-connected power stations to institutional installations and distributed systems, yet the evidentiary requirements for evaluating their performance and investment implications vary substantially with system scale, operating conditions, and data availability. An investment-grade assessment therefore requires more than a comparison between simulated and reported annual generation. It requires an auditable chain linking the solar resource, system configuration, energy-yield model, operational measurements, uncertainty sources, and financial assumptions. The International Finance Corporation emphasizes this integrated perspective by treating site selection, resource assessment, plant design, energy-yield estimation, contractual arrangements, financing, and financial analysis as interconnected components of PV project development rather than independent calculations [1]. This perspective becomes particularly relevant when simulation outputs are evaluated retrospectively against operational records, because the two sources may differ in temporal resolution, system boundaries, loss treatment, and reporting conventions. PVsyst and comparable PV performance models convert solar irradiance and system-design information into expected energy production by representing module characteristics, temperature effects, inverter conversion, electrical losses, transformer losses, system availability, and other loss mechanisms. Their usefulness, however, depends not only on the sophistication of the underlying model but also on the quality and comparability of the observations against which its predictions are assessed. Field-based validation studies have emphasized the need to distinguish systematic model bias from random deviations and to evaluate performance over sufficiently resolved measurement periods [2,3]. Annual energy totals provide an important project-level indicator, but they can conceal month-specific discrepancies associated with seasonal irradiance, temperature, availability,

curtailment, data gaps, operational constraints, or differences in the boundary used to define reported generation. Consequently, close agreement between annual totals should not, by itself, be interpreted as evidence of equivalent temporal model performance. In this study, the twelve-month QASP/LSPP record is therefore used as the principal validation dataset, whereas the UOL/SSPP evidence is treated as a constrained cross-check because only three dated paired observations are available. The same principle of traceability applies to the economic assessment of PV projects. The levelized cost of electricity (LCOE) represents a discounted relationship between lifecycle expenditure and electricity production and is consequently dependent on the assumptions used to define the project cash flow. Capital expenditure, operation and maintenance costs, energy degradation, discount rate, project lifetime, financing structure, taxes, incentives, residual value, and other financial parameters can materially alter the resulting indicator. NREL guidance similarly distinguishes technical performance modeling from financial and cash-flow analysis and provides frameworks for examining the effects of uncertain or variable inputs through sensitivity and parametric analysis [4,5]. Accordingly, an LCOE reported in a project document cannot be assumed to be reproducible from a limited set of publicly available inputs. Rather than forcing agreement between reported and independently calculated values, this study preserves the distinction between the two: reported economic indicators are retained as documented project evidence, while an independent lifecycle reconstruction is presented explicitly as a scenario based only on the cost and performance inputs available in the evidence workbook. Against this background, the present study proposes an evidence-to-decision framework for the technically and economically consistent assessment of PV projects across substantially different scales. The framework combines four complementary elements: (i) month-by-month validation of PVsyst predictions against the

complete QASP/LSPP operational record; (ii) a bounded assessment of UOL/SSPP using its limited paired observations and annual generation totals; (iii) a transparent comparison between reported and independently reconstructed LCOE; and (iv) lifecycle sensitivity analysis examining the response of LCOE to discount rate and end-of-life generation assumptions. The framework is intentionally structured so that measured observations, reported project indicators, derived statistical quantities, and reconstructed financial results remain analytically separate. The principal methodological contribution is therefore not the generation of another single-point PV performance estimate, but the establishment of a traceable procedure for determining what the available evidence can and cannot support. The approach distinguishes annual energy agreement from monthly predictive fidelity, separates documented economic indicators from reconstructed scenarios, and makes the assumptions underlying lifecycle calculations explicit. For QASP/LSPP, the complete twelve-month paired dataset enables quantitative assessment of correlation, error magnitude, goodness of fit, and systematic differences. For

UOL/SSPP, the substantially smaller evidence base is treated within its statistical limits rather than being presented as equivalent validation. The resulting framework provides a reproducible basis for connecting PV simulation, operational evidence, and investment-oriented economics without obscuring differences in data quality or model assumptions. The analysis is consequently organized as an evidence-to-decision workflow rather than as a single blended model. Original project values are preserved at the input layer; statistical measures and reconstructed financial quantities are generated independently; and interpretation is explicitly conditioned on the temporal coverage, completeness, and provenance of the underlying records. Each major quantitative component is linked to its corresponding table or scientifically justified visualization, while data-availability limitations are stated alongside the results. This structure is intended to improve reproducibility and auditability in comparative PV assessment and to provide a practical basis for interpreting simulation accuracy and economic performance when project evidence is heterogeneous, incomplete, or reported under different assumptions.

Evidence-Oriented Solar Assessment Workflow: A Traceable, Layered Boundary

Organized as an evidence-to-decision workflow, prioritising traceability over forced agreement.

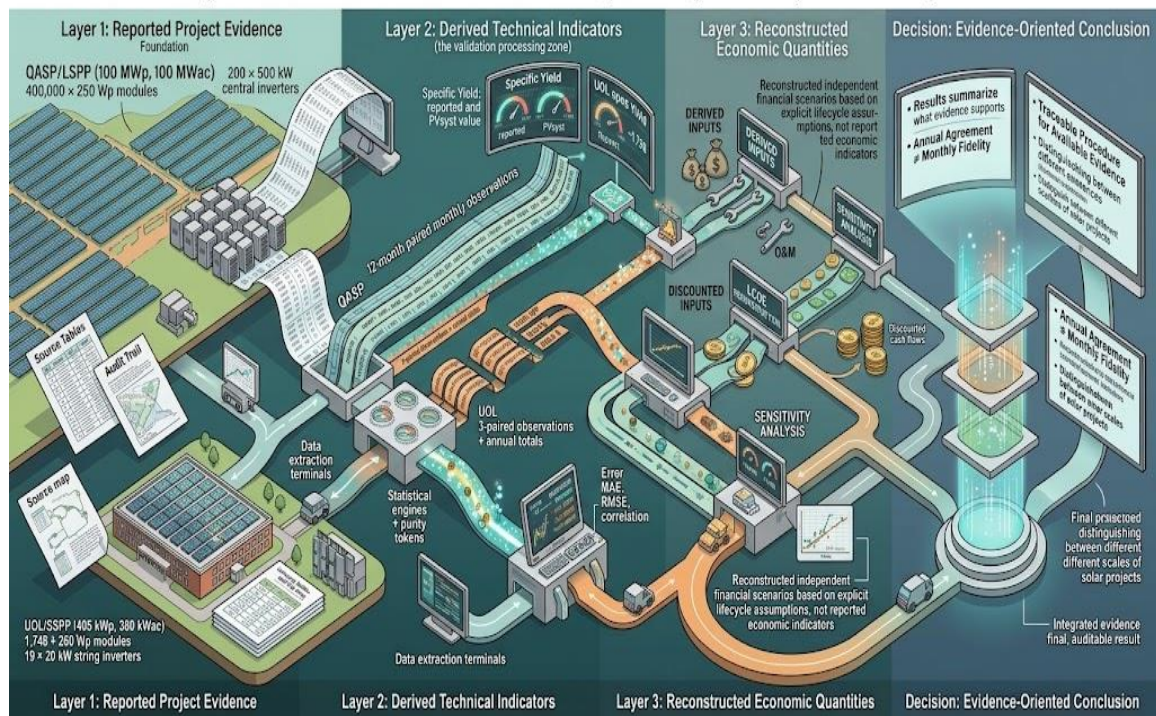


Figure: Isometric 3D rendering of the evidence-to-decision workflow framework for solar photovoltaic (PV) performance and economic assessment.

2. Materials and Methods

2.1. Evidence Boundary and System Definition

The methodological framework was established around a controlled evidence boundary defined by the numerical source tables preserved in the accompanying project workbook. Rather than supplementing incomplete records with inferred observations, the analysis retains the reported system characteristics and measured generation values as the primary evidence layer and explicitly distinguishes these from quantities calculated subsequently for validation and economic analysis. This approach is intended to preserve data provenance and prevent unsupported reconstruction of observations that are not available in the source record. Two photovoltaic systems with markedly different scales and configurations are examined. The Quaid-e-Azam Solar Power/Large Scale Power Plant (QASP/LSPP) is represented by a 100 MWp DC photovoltaic field comprising 400,000 modules, each rated at 250 Wp, coupled to 200 inverters with a nominal

capacity of 500 kW each. The University of Lahore/Small Scale Power Plant (UOL/SSPP) is represented by a 405 kWp DC system with a 380 kW AC conversion capacity, incorporating 1,748 modules rated at 260 Wp and 19 inverters rated at 20 kWp. These configurations provide a useful scale contrast between a utility-scale installation and a comparatively small institutional system while retaining a common analytical basis for energy-yield assessment. A critical feature of the evidence structure is the unequal temporal resolution of the two datasets. QASP/LSPP contains twelve paired observations of PVsyst-predicted and reported generation covering September 2015 to August 2016, thereby providing a complete annual cycle for month-level validation. UOL/SSPP contains only three dated paired observations together with annual generation totals. The latter dataset is therefore not treated as a complete monthly time series, and no missing monthly values are estimated, interpolated, or otherwise imputed. This distinction is maintained throughout the statistical analysis to ensure that the strength of the conclusions

remains proportional to the available evidence. Annual specific yield is calculated using the

$$Y_{spec} = \frac{E_{annual}}{P_{DC}}, Y_{spec} = \frac{E_{annual}}{P_{DC}}$$

where Y_{spec} is the annual specific yield in kWh/kWp/year, E_{annual} is annual electricity generation in kWh, and P_{DC} is the installed DC capacity in kWp. The same normalization is applied to both reported and PVsyst-derived annual generation, allowing the systems to be compared independently of their absolute installed capacities. Under this evidence definition, QASP/LSPP has a reported annual generation of 159,216.63 MWh and a

reported DC nameplate capacity as the normalization basis:

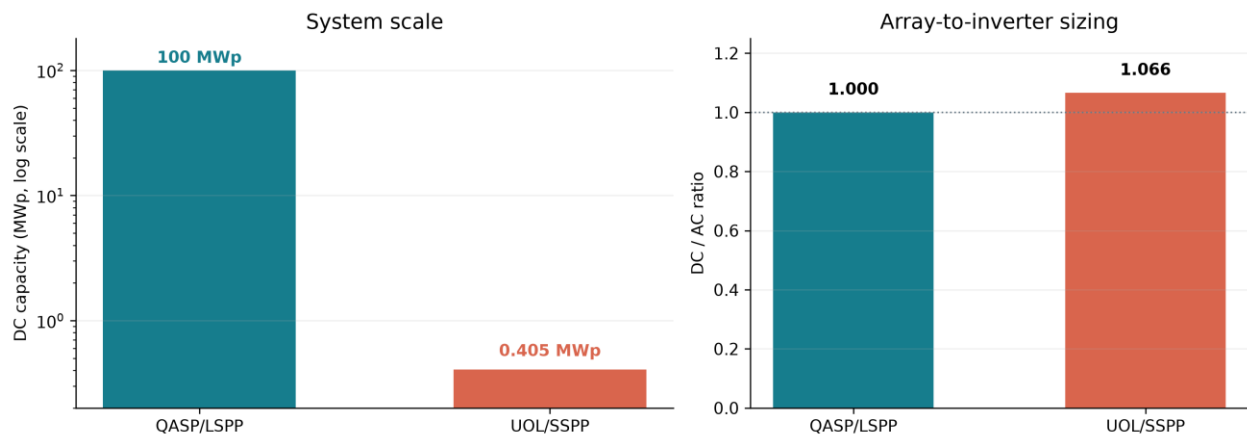
corresponding PVsyst estimate of 155,276 MWh. Based on the stated 100 MWp DC capacity, these values correspond to specific yields of 1,592.17 and 1,552.76 kWh/kWp/year, respectively. UOL/SSPP has a reported annual generation of 700 MWh and a PVsyst estimate of 688 MWh. Using the stated 405 kWp DC capacity, the corresponding specific yields are 1,728.40 and 1,698.77 kWh/kWp/year.

Table 1. System inventory, generation evidence, and normalization basis. Annual specific yield is calculated using the stated DC nameplate capacity. The validation-evidence column records the temporal extent of the source data and does not imply equivalent statistical strength between the two systems.

System	DC capacity	AC capacity	Module configuration	Inverter configuration	Reported generation (MWh/year)	PVsyst generation (MWh/year)	Reported specific yield (kWh/kWp/year)	PVsyst specific yield (kWh/kWp/year)	Validation evidence
QASP/LSPP	100 MWp	100 MWac	400,000 × 250 Wp	200 × 500 kW	159,216.63	155,276	1,592.17	1,552.76	12 paired monthly observations
UOL/SSPP	405 kWp	380 kWac	1,748 × 260 Wp	19 × 20 kW	700	688	1,728.40	1,698.77	3 paired observations + annual totals

The resulting evidence boundary establishes three analytical layers used throughout the study: (i) reported project evidence, consisting of source-table system specifications and generation records; (ii) derived technical indicators, including specific yield, prediction error, correlation, and goodness-of-fit statistics; and (iii) reconstructed economic quantities,

calculated independently under explicitly stated lifecycle assumptions. Maintaining these layers separately prevents derived values from being mistaken for reported project measurements and ensures that subsequent conclusions can be traced directly to either an original observation or a documented analytical assumption.

Figure 1. System architecture and scale contrast


To evaluate PV performance consistently across orders of magnitude, the physical system scale must be analytically decoupled from its core evidence logic. While QASP/LSP represents a 100 MWp utility-scale installation (200 inverters, 400,000 modules) and UOL/SSPP represents a 405 kWp institutional system (19 inverters, 1,748 modules), both adhere to an identical three-stage boundary sequence. This structural equivalence ensures that module

collection, inverter conversion, and grid export boundaries are processed symmetrically regardless of total plant capacity. Maintaining boundary symmetry prevents scale-dependent modeling biases when retrospectively comparing utility and distributed assets against PVsyst simulation outputs. The isometric system architecture, schematic topology, and scale contrast between both evaluated plants are illustrated in Figure 2.

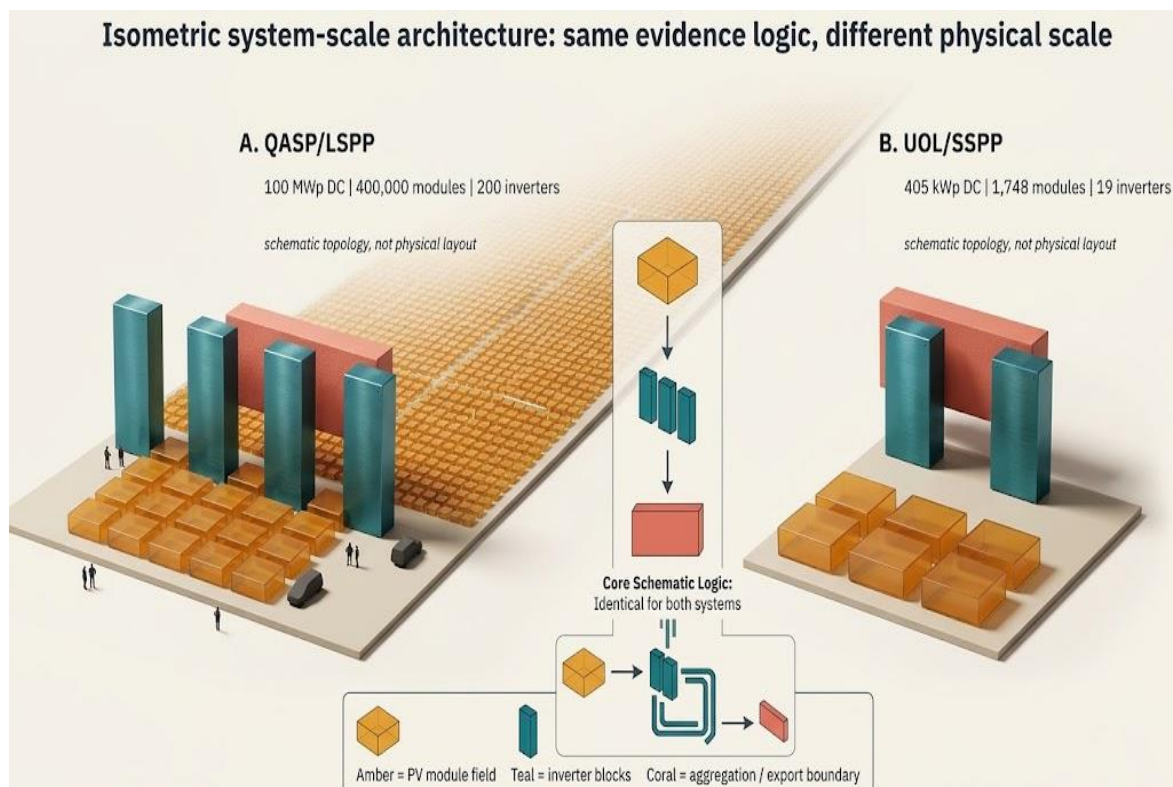


Figure 2. Isometric architecture comparison. Reported module and inverter counts are shown in a schematic topology; the geometry is illustrative and not a site layout.

2.1 Validation Statistics

The agreement between PVsyst predictions and reported electricity generation was evaluated using the paired observations

$$e_i = P_i - A_i, \quad (1)$$

where P_i denotes the PVsyst-predicted generation and A_i represents the corresponding reported actual generation. Thus, a negative value of e_i indicates underestimation by PVsyst,

available for each photovoltaic system. For the i -th observation, the prediction error was defined as

whereas a positive value indicates overestimation. The mean bias error (MBE) was used to quantify the direction and magnitude of systematic prediction bias:

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n e_i. \quad (2)$$

The mean absolute error (MAE) was calculated to measure the average magnitude of prediction error independently of its direction:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |e_i|. \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}. \quad (4)$$

$$\text{MAPE} = \frac{100}{n_0} \sum_{i \in I_0} \left| \frac{P_i - A_i}{A_i} \right|, \quad (5)$$

The root mean square error (RMSE) was calculated to characterize the overall dispersion of prediction errors while giving greater weight to larger deviations: The mean absolute percentage error (MAPE) was used as a scale-normalized measure of prediction error: where I_0 denotes the set of observations for which $A_i \neq$

0, and n_0 is the number of such observations. MAPE was therefore calculated only for observations with non-zero reported generation. The linear association between PVsyst predictions and reported generation was assessed using the Pearson correlation coefficient:

$$r = \frac{\sum_{i=1}^n (P_i - \bar{P})(A_i - \bar{A})}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2 \sum_{i=1}^n (A_i - \bar{A})^2}}, \quad (6)$$

where $\bar{P}$ and $\bar{A}$ denote the mean predicted and reported generation, respectively. The corresponding coefficient of determination was calculated as

$$R^2 = r^2. \quad (7)$$

Pearson correlation and R^2 were interpreted as measures of linear association and goodness of fit rather than as standalone measures of prediction accuracy. In particular, strong correlation can coexist with systematic bias, and close agreement between annual totals does not necessarily demonstrate accurate reproduction of monthly variation.

$$\alpha = 0.05. \quad (8)$$

Because the available datasets are small, particularly the three paired observations for UOL/SSPP, these tests were treated as supporting diagnostics rather than definitive

Systematic paired differences were examined using the paired-samples t -test and the Wilcoxon signed-rank test. The paired t -test evaluates whether the mean paired difference differs from zero, whereas the Wilcoxon signed-rank test provides a non-parametric complementary assessment. Statistical testing was conducted at

evidence of model equivalence. Agreement was additionally assessed using the Bland-Altman approach. The mean paired difference was calculated as

$$\bar{e} = \frac{1}{n} \sum_{i=1}^n e_i, \quad (9)$$

and the standard deviation of the paired differences was calculated as

$$s_e = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (e_i - \bar{e})^2}. \quad (10)$$

The corresponding 95% limits of agreement were defined as

$$\text{LoA}_{95\%} = \bar{e} \pm 1.96s_e. \quad (11)$$

The statistical framework was designed to distinguish prediction bias, error magnitude, linear association, and paired agreement. For QASP/LSPP, all twelve-monthly prediction-observation pairs were retained for the complete validation analysis. For UOL/SSPP, only the three available paired observations were used; no missing monthly observations were interpolated, extrapolated, or imputed. Consequently, the UOL/SSPP results are interpreted as a limited cross-check rather than a complete temporal validation.

Statistical non-significance was not interpreted as evidence of interchangeability between PVsyst predictions and reported generation. Similarly, a high R^2 , a small annual difference, or a non-significant paired test was not considered sufficient, in isolation, to establish model fidelity. The final assessment therefore considers the error metrics, temporal association, paired statistical tests, and agreement limits jointly, while explicitly relating the strength of the conclusions to the size and completeness of the available evidence.

2.3 Economic reconstruction

The source workbook reports LCOE, payback period, IRR, and selected cost inputs; however, it does not disclose all cash-flow components required to reproduce the underlying financial model. Accordingly, a transparent reconstructed cash-flow model was developed using only the documented inputs supplemented by explicitly stated assumptions. The reconstruction is intended to provide a reproducible basis for comparative techno-

economic analysis and does not purport to replicate the original project-finance model.

For the 100 MW_p QASP/LSPP system, the initial capital expenditure was reconstructed from the reported unit costs as

$$\begin{aligned} C_{0,LSPP} &= (131.15 \\ &\quad + 18.00) \times 10^6 \times 100 \\ &= 14.915 \times 10^9 \text{ Rs}, \end{aligned}$$

where the first term represents the PV-system cost and the second represents transmission cost. For the UOL/SSPP system, the corresponding initial investment was calculated as

$$C_{0,SSPP} = 150 \times 405 \times 10^3 = 60.75 \times 10^6 \text{ Rs}.$$

Both systems were evaluated over a 25-year operating horizon using a real discount rate of 8%. To represent progressive degradation, annual electricity generation was assumed to decline linearly from 100% of the first-year output to 80% in year 25. Thus, the generation in year t is represented by

$$E_t = E_1 [1 - 0.20(t - 1)/24], \quad t = 1, \dots, 25,$$

where E_1 denotes first-year electricity generation. For QASP/LSPP, variable operating expenditure was represented by a generation-dependent cost of Rs 2.898/kWh, obtained from the documented O&M component of Rs 1.739/kWh plus insurance of Rs 1.159/kWh. Hence,

$$O\&M_t = 2.898E_t.$$

For UOL/SSPP, annual O&M expenditure was fixed at Rs 800,000 per year. The reconstructed model deliberately excludes inflation, debt financing, taxation, replacement expenditure, subsidies, and terminal/residual value because these components are not sufficiently documented in the source material.

Consequently, the analysis is conducted on a real, unlevered, pre-tax basis. The reconstructed levelized cost of electricity (LCOE) is calculated using the present-value formulation

$$LCOE = [C_0 + \sum_{t=1}^{25} O\&M_t / (1 + r)^t] / [\sum_{t=1}^{25} E_t / (1 + r)^t],$$

where C_0 is the reconstructed initial capital expenditure (Rs), $O\&M_t$ is the operating expenditure in year t (Rs), E_t is electricity generation in year t (kWh), and $r = 0.08$ is the real discount rate. This formulation expresses the LCOE as the discounted lifetime cost per discounted unit of electricity generated and ensures that the effects of both capital intensity and generation degradation are incorporated consistently. Importantly, this reconstruction is not presented as the original project-finance calculation. Rather, it is a deliberately conservative and auditable financial framework designed to make the economic comparison reproducible when the source workbook does not disclose the complete underlying cash-flow structure. All reported inputs are retained as documented, while additional assumptions are explicitly identified so that alternative assumptions can be tested through sensitivity analysis.

3. Results

3.1 Annual performance and reported project indicators

The two systems exhibit relatively small annual model-to-actual differences in absolute percentage terms; however, the underlying

evidence differs substantially in completeness. For QASP/LSPP, the validation is supported by a complete set of twelve-monthly prediction-observation pairs, with PVsyst underestimating the reported annual generation by 3,940.63 MWh. In contrast, UOL/SSPP shows an annual model shortfall of only 12 MWh, but this comparison is based on a sparse record rather than a complete monthly series. The available dated observations for UOL/SSPP exhibit substantially larger positive model errors, ranging from 86.49% to 146.14% of the corresponding reported generation. This discrepancy between the apparently close annual totals and the substantially larger errors in the available observations highlights the limitations of relying on annual aggregation when temporal observations are incomplete. Accordingly, the UOL/SSPP results are treated as a limited validation cross-check rather than evidence of validated monthly predictive performance. Table 2 summarizes the reported annual generation and key technical and financial indicators for the two photovoltaic systems. The reported values provide the basis for comparing modelled generation with the corresponding annual observations while retaining the original project-level performance indicators. The annual generation figures are presented alongside the reported performance ratio, payback period, levelized cost of electricity (LCOE), internal rate of return (IRR), and cost-benefit ratio (CBR).

Table 2. Reported annual performance and project indicators. These values are reproduced as reported and are not replaced by the reconstructed scenario.

System	Actual MWh/y	PVsyst MWh/y	Annual error	PR	Reported payback	Reported LCOE	IRR	CBR
QASP/LSPP	159,216.63	155,276	-2.48%	79.10%	6.47 y	Rs 4.26/kWh	15%	3.54
UOL/SSPP	700	688	-1.71%	82.20%	5.63 y	Rs 5.53/kWh	17%	3.94

To provide a direct comparison between simulated and reported electricity generation, the annual generation values for both photovoltaic systems are presented in Figure 3. The comparison illustrates the magnitude of

the difference between the PVsyst estimates and the reported annual generation and provides an initial assessment of model observation agreement.

Figure 3. Annual energy comparison

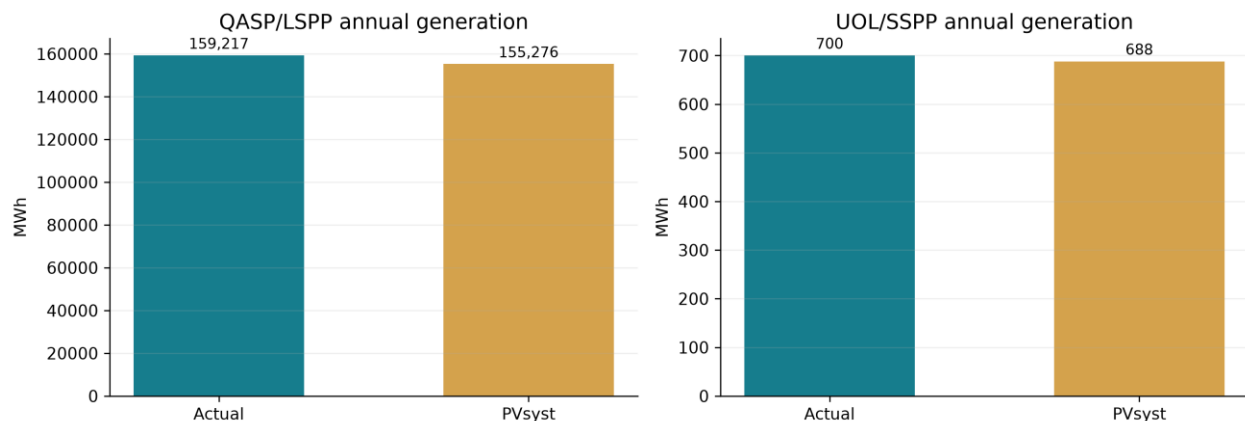


Figure 3. Annual generation comparison. Annual agreement is close for both systems, but annual totals alone do not establish monthly fidelity.

3.2 QASP/LSPP monthly validation

Across the twelve paired monthly observations, PVsyst underestimates the reported annual generation by 2.48%, corresponding to a mean bias of -328.39 MWh. The Pearson correlation coefficient of $r=0.690$ indicates a moderate positive linear association, whereas $R^2=0.476$ shows that the linear relationship accounts for 47.6% of the observed month-to-month variation. The largest positive prediction error occurs in January 2016, when PVsyst overestimates the reported generation by 3,323.19 MWh, equivalent to 36.44% of the actual value. The largest negative error occurs in June 2016, with an underestimation of 1,641.56 MWh (12.06% of the reported generation). The paired-samples t-test ($p=0.475$) and Wilcoxon signed-rank test ($p=0.380$) provide no statistically significant evidence of a systematic paired difference at the 5% significance level.

However, these results should not be interpreted as evidence of equivalence between the simulated and reported generation. The Bland-Altman analysis further indicates substantial dispersion in the paired differences, with 95% limits of agreement of approximately $-3,343$ to $2,686$ MWh. Thus, although the aggregate annual discrepancy is relatively small and the paired tests do not identify a statistically significant mean or median difference, the magnitude of the monthly limits of agreement indicates appreciable temporal variation in prediction error. Taken together, the results suggest reasonable agreement at the annual aggregate level but considerably less consistent correspondence at the monthly level. Table 3 summarizes the monthly validation statistics for QASP/LSPP, with the reported values interpreted descriptively because the dataset comprises a single annual cycle.

Table 3. QASP/LSPP validation statistics. Statistical tests are descriptive because the sample contains one annual cycle only.

Metric	Value	Interpretation
n	12	paired monthly observations
Annual model error	-2.48%	PVsyst total below actual
MBE	-328.39 MWh	small negative average bias
MAE	1,312.24 MWh	typical absolute monthly error
RMSE	1,508.84 MWh	penalizes larger deviations
MAPE	10.72%	scale-normalized absolute error
Pearson r / R^2	0.690 / 0.476	moderate association; limited explained variance

Paired t-test p	0.475	no 5% evidence of nonzero mean difference
Wilcoxon p	0.380	no 5% evidence of nonzero median difference
Bland-Altman LoA	-3,343 to +2,686 MWh	wide agreement band

Figure 4 presents the paired prediction-observation relationship, monthly signed errors, and Bland-Altman agreement for

QASP/LSPP. The diagnostics show substantial month-to-month variation, with January exhibiting the largest positive prediction error.

Figure 4. QASP/LSPP validation diagnostics

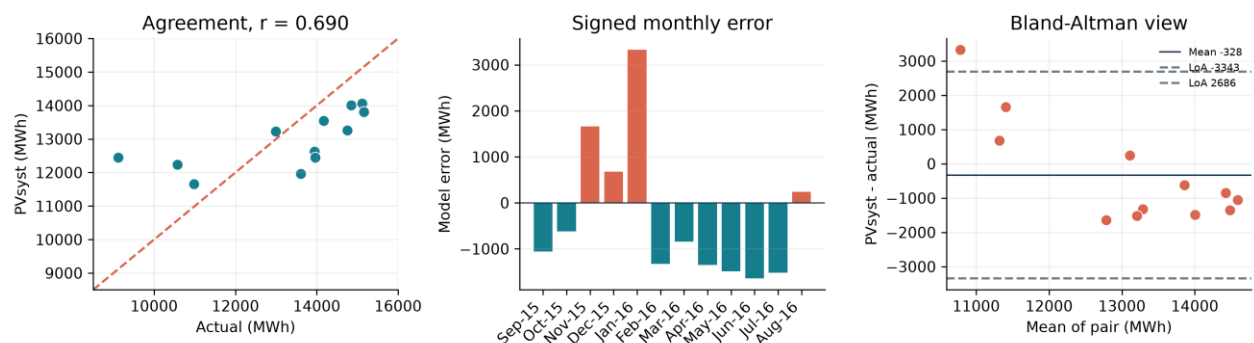


Figure 4. QASP/LSPP validation diagnostics: paired scatter, signed monthly error, and Bland-Altman agreement. January is the dominant positive-error outlier.

3.3 UOL/SSPP bounded validation

For UOL/SSPP, the reported annual generation is 700 MWh, compared with 688 MWh predicted by PVsyst, corresponding to an annual difference of -1.71% . This close aggregate correspondence contrasts with the three available dated paired observations, for which the PVsyst estimates exceed the corresponding reported values by 86.49% – 146.14% . Because these observations have not been established as a complete monthly series, they are treated as paired observations rather than as monthly validation data. The units, observation periods, and reporting boundaries of these paired records should therefore be

verified against the reported annual totals before any inference regarding monthly predictive performance is made. On the available evidence, the appropriate interpretation is limited annual agreement accompanied by unresolved inconsistency among the paired observations; the dataset does not support a claim of validated time-series accuracy. Figure 8 compares the reported annual generation with the available paired observations for UOL/SSPP. Although the annual totals are closely aligned, the three dated paired observations show substantially higher PVsyst values than the corresponding reported values.

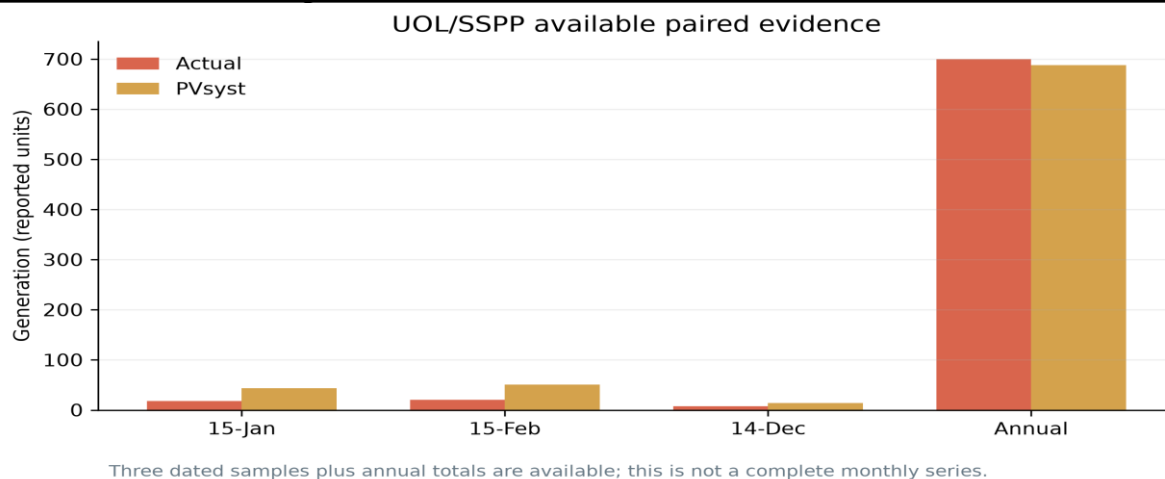


Figure 8. UOL/SSPP available paired evidence. The annual total looks close, while the three dated samples are materially higher in the model record.

3.4 Reported versus reconstructed economics

Under the transparent reconstruction, the estimated LCOE is Rs 12.32/kWh for QASP/LSP and Rs 9.96/kWh for UOL/SSPP, compared with the reported values of Rs 4.26/kWh and Rs 5.53/kWh, respectively. These differences are not attributable to arithmetic discrepancies; rather, they indicate that the reported project calculations incorporate inputs, assumptions, cost boundaries, or methodological definitions that cannot be fully recovered from the available source records. The discrepancy may also reflect differences between the reported LCOE definition and the formulation adopted for the present reconstruction. To maintain a clear distinction between reported project evidence and reconstructed analysis, the scenario uses implied electricity tariffs derived

from the reported payback periods solely to illustrate the resulting cash flows. The corresponding values of Rs 17.38/kWh for QASP/LSP and Rs 16.56/kWh for UOL/SSPP are therefore scenario-derived quantities, not observed or reported project tariffs, and should not be interpreted or cited as project-level facts. To separate documented project results from quantities derived through the present reconstruction, the economic analysis is reported using only inputs that can be traced to the available project records or explicitly defined assumptions. Table 4 summarizes the resulting reconstructed economic indicators, with all derived quantities retained as scenario-specific values rather than treated as replacements for the reported project metrics.

Table 4. Transparent reconstructed economics. Derived inputs and outputs are scenario values, not replacements for reported project metrics.

System	Derived capex	Derived tariff	Reconstructed LCOE	Reconstructed NPV	Approx. undiscounted payback	Reported LCOE
QASP/LSP	Rs 14.915B	Rs 17.38/kWh	Rs 12.32/kWh	Rs 8.01B	6.63 y	Rs 4.26/kWh
UOL/SSPP	Rs 60.75M	Rs 16.56/kWh	Rs 9.96/kWh	Rs 45.95M	5.75 y	Rs 5.53/kWh

Figure 5 compares the reported project-level economic indicators with the corresponding values obtained from the transparent reconstruction. The differences are presented

explicitly to reveal the effects of model boundaries and recoverable inputs rather than to treat reconstructed quantities as substitutes for the reported metrics.

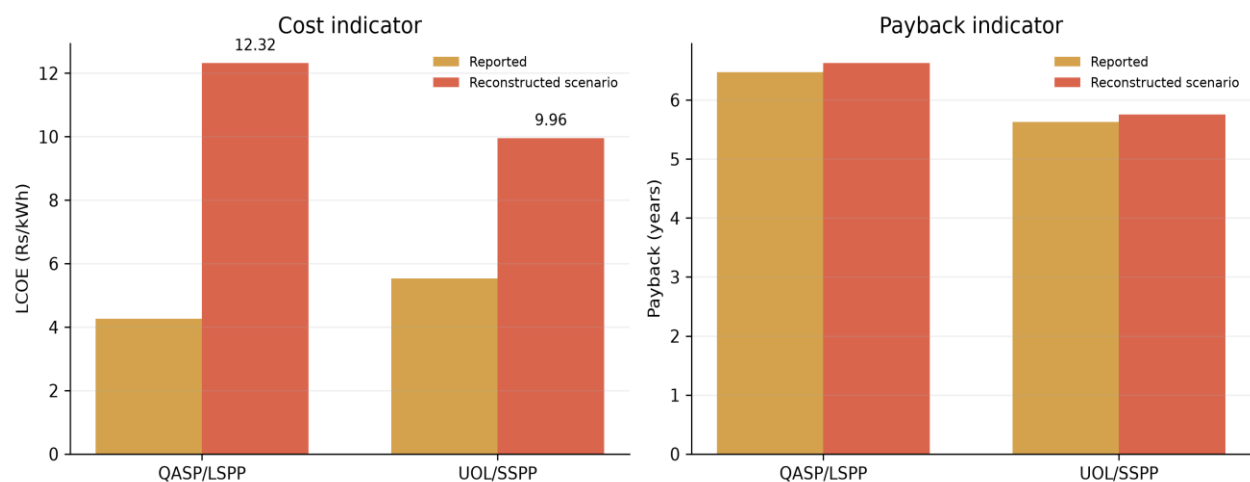
Figure 5. Reported project metrics vs transparent reconstruction

Figure 5. Reported project metrics versus transparent reconstruction. The separation is intentional: the chart exposes model-boundary differences rather than hiding them.

3.5 Sensitivity and 25-year cash

The sensitivity analysis shows that the reconstructed LCOE is more responsive to the discount rate than to the end-of-life factor. At the base case (80% end-of-life factor, 8% discount rate), LCOE is Rs 12.32/kWh for QASP/LSPP and Rs 9.96/kWh for UOL/SSPP. Increasing the discount rate from 6% to 14% raises these values to Rs 17.27/kWh and Rs 14.52/kWh, respectively, whereas varying the end-of-life factor from 70% to 90% at an 8% discount rate changes them

only from Rs 12.68 to Rs 11.99/kWh and from Rs 10.34 to Rs 9.60/kWh. Thus, financing assumptions exert the stronger influence within the tested ranges. To examine the robustness of the reconstructed LCOE under alternative financial and performance assumptions, Table 5 reports its sensitivity to the discount rate and end-of-life output factor. The results show how changes in these two parameters affect the estimated lifecycle cost while keeping the remaining reconstruction assumptions unchanged.

Table 5. Reconstructed LCOE sensitivity to end-of-life output factor and discount rate. Values are Rs/kWh.

Scenario	QASP 6%	QASP 8%	QASP 14%	UOL 6%	UOL 8%	UOL 14%
70% end factor	11.16	12.68	17.67	8.95	10.34	14.92
80% end factor	10.83	12.32	17.27	8.58	9.96	14.52
90% end factor	10.51	11.99	16.89	8.24	9.60	14.13

The sensitivity analysis was extended to visualize the joint effects of the discount rate and end-of-life output factor on the

reconstructed LCOE. Figure 6 illustrates how the estimated lifecycle cost changes across the tested parameter ranges for both systems.

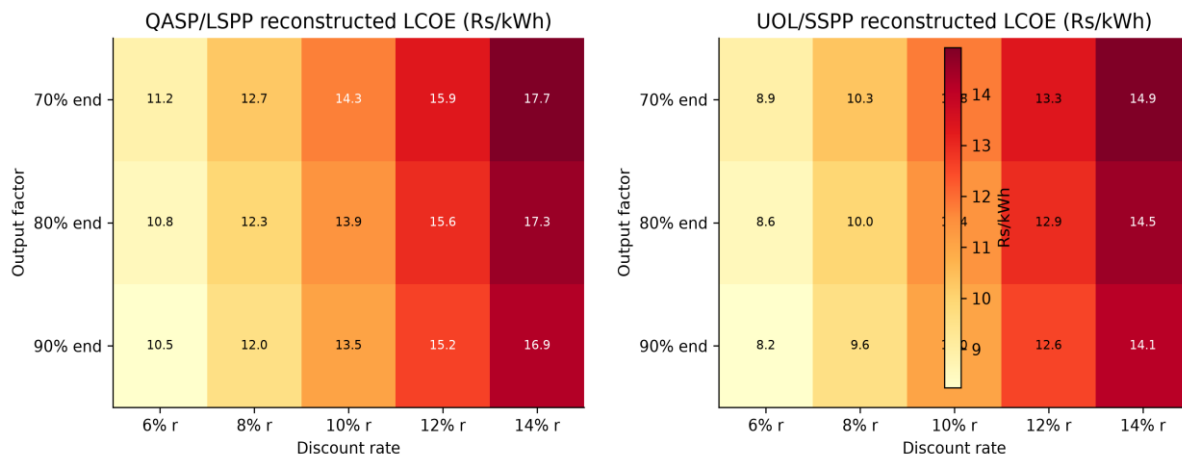
Figure 6. Sensitivity of reconstructed LCOE

Figure 7 Three-dimensional sensitivity surfaces for the reconstructed LCOE. The surfaces illustrate the joint effect of the discount rate and end-of-life output factor on the reconstructed lifecycle cost. The marker

identifies the base scenario at an 8% discount rate and 80% end-of-life output factor. All plotted values are derived from the transparent reconstruction and should not be interpreted as reported project-level LCOE values.

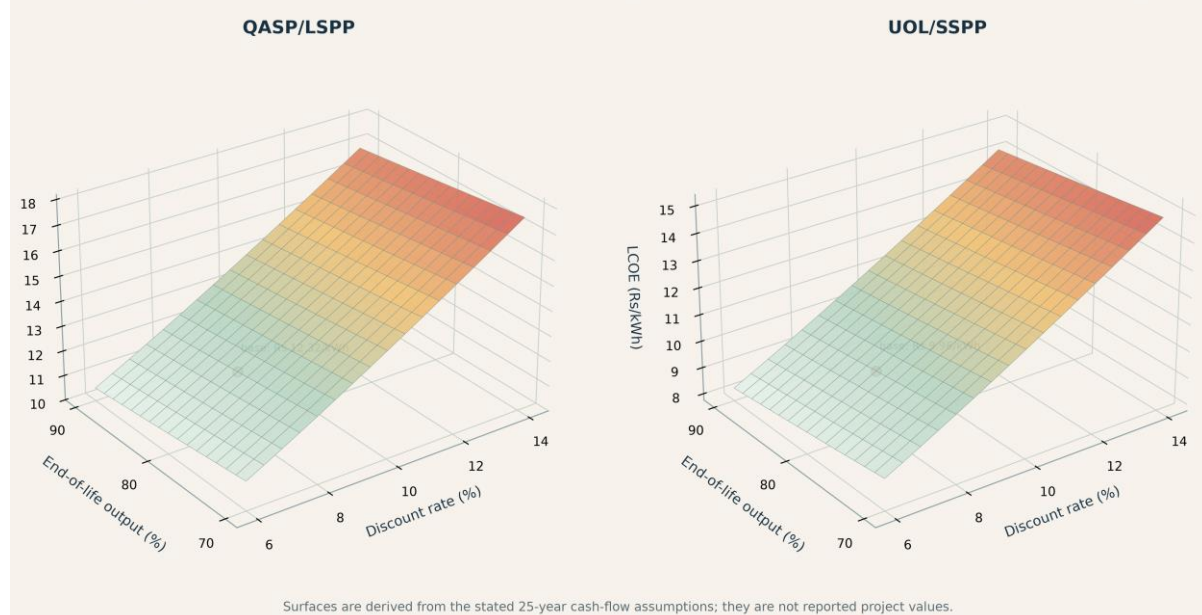
Transparent scenario economics: discounting is the dominant lever in the tested range

Figure 7. Three-dimensional reconstructed LCOE surfaces. The marker is the base scenario at 8% discount rate and 80% end-of-life output; all surfaces are derived, not reported project values.

Table 6 presents selected points from the 25-year reconstructed cash flow for both photovoltaic systems.

The reconstruction assumes a linear decline in annual electricity output to 80% of the initial level by year 25.

Annual operating and maintenance costs are incorporated according to the assumptions

defined in the financial model. For UOL/SSPP, the O&M cost is held constant at Rs 800,000 per year throughout the analysis period.

The reported values are not reproduced here; all cash-flow quantities shown in Table 6 are derived from the transparent reconstruction.

Table 6. Selected points from the 25-year reconstructed cash flow. Output declines linearly to 80% at year 25; UOL/SSPP O&M remains fixed at Rs 800,000/year.

System	Year 1 generation	Year 25 generation	Year 1 net cash flow	Year 25 net cash flow	NPV
QASP/LSPP	159,217 MWh	127,373 MWh	Rs 2.31B	Rs 1.84B	Rs 8.01B
UOL/SSPP	700 MWh	560 MWh	Rs 10.79M	Rs 8.47M	Rs 45.95M

Figure 7 illustrates the reconstructed 25-year trajectory of electricity output and cumulative undiscounted cash flow for the photovoltaic systems. The declining output reflects the assumed linear degradation of annual generation over the project life. The cumulative cash flow is presented to show the resulting long-term financial trajectory

under the defined reconstruction assumptions. These curves are derived from the scenario model and are intended to illustrate the implications of the adopted technical and economic assumptions. They should not be interpreted as a reconstruction of the original project financing or cash-flow structure.

Figure 7. 25-year scenario cash flow and output degradation

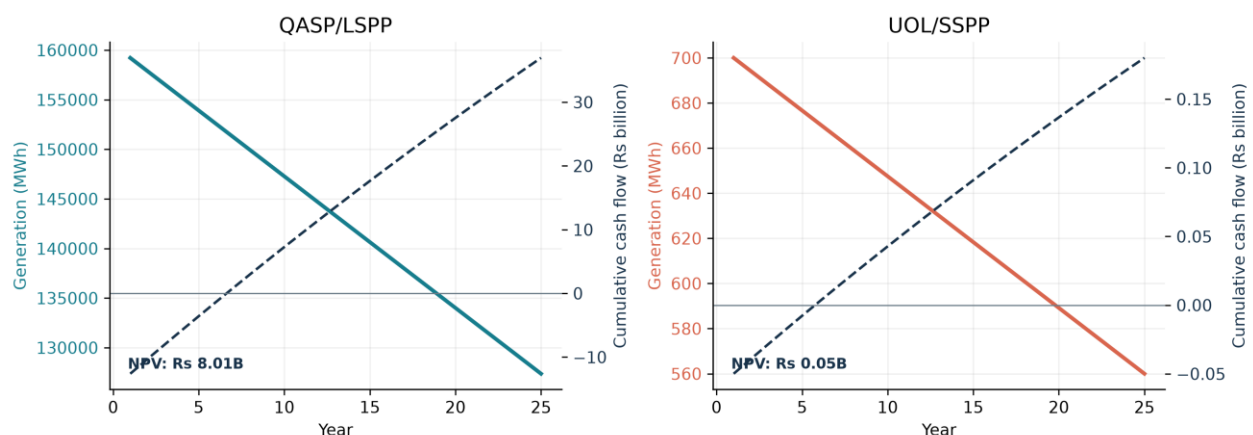


Figure 7. Reconstructed 25-year output and cumulative undiscounted cash flow. The plot is a scenario illustration, not a claim about the original financing structure.

4. Discussion

4.1 Validation Evidence and System-Specific Confidence The principal finding is not simply that the annual model errors are small, but that the available evidence supports different levels of confidence for the two photovoltaic systems. QASP/LSPP is supported by a complete set of paired monthly observations, allowing seasonal behavior, the pronounced January overprediction, and the dispersion of prediction errors to be examined explicitly. Although its annual bias is relatively small, the wide limits of agreement demonstrate that close annual correspondence does not imply uniformly accurate monthly prediction. In contrast, UOL/SSPP shows a close annual total but provides only three dated

paired observations, which are also substantially higher in the PVsyst record than the corresponding reported values. These records therefore do not provide a sufficient basis for claiming monthly validation. From a project due-diligence perspective, the two systems require different forms of evidence reconciliation: QASP/LSPP warrants investigation of seasonal inputs, plant availability, operational conditions, and the January reporting boundary, whereas UOL/SSPP requires verification of the sample units, metering boundary, observation period, aggregation procedure, and annualization method.

4.2 Economic Transparency and Reconstruction Uncertainty The difference between the reported and transparently reconstructed economic indicators is itself an important finding. In both systems, the reconstructed LCOE is higher than the reported value, with the discrepancy being particularly pronounced for QASP/LSPP. This divergence may arise from differences in capital-cost boundaries, tariff or revenue definitions, financing structure, taxation, O&M escalation, residual-value treatment, degradation assumptions, or discounting conventions. However, the available records do not contain sufficient information to identify the contribution of each factor uniquely. Rather than imposing an unsupported reverse-engineered explanation, the present analysis preserves this uncertainty explicitly. The reported metrics are therefore retained as documented project values, while the reconstructed results are treated as scenario-dependent estimates. The accompanying sensitivity analysis further demonstrates how changes in the recoverable assumptions affect the reconstructed LCOE and identifies the parameters to which the economic outcome is most responsive.

4.3 Evidence Requirements for Bankable Assessment The analysis also indicates a practical pathway for strengthening future project assessment. On the technical side, reproducibility would benefit from preserving the original PVsyst exports, software and model version, weather-data source, loss diagram, metered AC boundary, plant-availability records, curtailment information, and a consistent calendar definition. These records should be accompanied by a structured financial input sheet specifying the capital-cost boundary, PPA or tariff assumptions, debt and equity structure, tax treatment, insurance, O&M escalation, replacement schedule, degradation profile, and residual value. Such documentation would substantially reduce the uncertainty encountered when attempting to reconcile reported project economics with an independently reproducible model. This integrated evidence structure is consistent with the development logic described in the IFC

guide, in which resource assessment, energy-yield confidence, contractual arrangements, and financing considerations are evaluated as interconnected components of project development rather than as isolated analytical elements [1].

4.4 Visual and Numerical Cross-Checks

The additional visualizations are intended as supporting diagnostic tools rather than independent sources of evidence. Figure 10 represents the reported system scale through schematic blocks, whereas Figure 7 visualizes only the explicitly defined economic scenario and its sensitivity to the selected reconstruction parameters. Neither figure introduces an additional measurement, modifies the underlying project records, or substitutes for the numerical results reported in the corresponding tables. Their purpose is to improve interpretation of system scale and scenario dependence while maintaining a clear separation between documented project evidence and quantities derived through the present reconstruction.

5. Conclusions

This study assessed the agreement between PVsyst-simulated and reported electricity generation for two solar PV systems and examined their project economics through a transparent reconstruction. The results show that the difference between annual simulated and reported generation is small for both systems, but the available evidence does not provide the same level of confidence in their temporal validation. For QASP/LSPP, the reported annual generation is 159,216.63 MWh, whereas PVsyst predicts 155,276 MWh. The difference of 3,940.63 MWh corresponds to a 2.48% underestimation by PVsyst relative to the reported annual generation. Across the twelve paired monthly observations, the Pearson correlation coefficient is $r=0.690$, with $R^2=0.476$, indicating a moderate linear association between the simulated and reported monthly values. The largest positive error occurs in January 2016, when PVsyst exceeds the reported generation by 3,323.19 MWh, equivalent to 36.44% of the reported value for

that observation. The largest negative error occurs in June 2016, when PVsyst is 1,641.56 MWh below the reported value, corresponding to 12.06% of the reported generation. The paired *t*-test gives $p=0.475$, while the Wilcoxon signed-rank test gives $p=0.380$; neither test indicates a statistically significant systematic paired difference at the 5% level. Nevertheless, the 95% Bland-Altman limits of agreement, approximately $-3,343$ to $+2,686$ MWh, show that individual monthly differences can be substantial. Thus, the 2.48% annual difference should not be interpreted as evidence of equally close monthly agreement. For UOL/SSPP, the reported annual generation is 700 MWh, compared with 688 MWh predicted by PVsyst. The difference is therefore 12 MWh, corresponding to a 1.71% lower PVsyst estimate relative to the reported annual value. However, only three dated paired observations are available for comparison. In these records, the PVsyst values exceed the corresponding reported values by 86.49% to 146.14%. Because these three observations have not been established as a complete monthly series, they do not provide sufficient evidence for monthly or seasonal validation. The apparent 1.71% annual agreement must therefore be considered separately from the substantially larger differences observed in the available paired records. Verification of the measurement units, metering boundary, observation period, and annual aggregation method is required before these records can be used for stronger validation conclusions. The economic comparison also shows a clear difference between reported and reconstructed values. The reported LCOE is Rs 4.26/kWh for QASP/LSPP and Rs 5.53/kWh for UOL/SSPP, whereas the corresponding reconstructed LCOE values are Rs 12.32/kWh and Rs 9.96/kWh. Thus, the reconstructed LCOE is Rs 8.06/kWh higher than the reported value for QASP/LSPP and Rs 4.43/kWh higher for UOL/SSPP. In relative terms, the reconstructed value is approximately 189% higher than the reported LCOE for QASP/LSPP and approximately 80% higher for UOL/SSPP. These differences cannot be assigned to a single factor because the available

project records do not specify all inputs and assumptions used in the original financial calculations. The reported payback periods are 6.47 years for QASP/LSPP and 5.63 years for UOL/SSPP, while the reported IRRs are 15% and 17%, respectively. The reported CBRs are 3.54 for QASP/LSPP and 3.94 for UOL/SSPP. These values are retained as documented project metrics and are not replaced by the reconstructed financial model. The implied electricity tariffs of Rs 17.38/kWh for QASP/LSPP and Rs 16.56/kWh for UOL/SSPP are scenario-derived values used only within the reconstruction and should not be interpreted as reported project tariffs. The sensitivity analysis further shows that the reconstructed LCOE is more responsive to the discount rate than to the end-of-life output factor within the tested ranges. At an 8% discount rate and an 80% end-of-life output factor, the reconstructed LCOE is Rs 12.32/kWh for QASP/LSPP and Rs 9.96/kWh for UOL/SSPP. When the discount rate increases from 6% to 14%, the reconstructed LCOE increases from the corresponding lower-rate values to Rs 17.27/kWh for QASP/LSPP and Rs 14.52/kWh for UOL/SSPP at the 14% rate. By comparison, changing the end-of-life output factor from 70% to 90% at an 8% discount rate changes the reconstructed LCOE from Rs 12.68/kWh to Rs 11.99/kWh for QASP/LSPP and from Rs 10.34/kWh to Rs 9.60/kWh for UOL/SSPP. The larger change associated with the discount-rate range indicates greater sensitivity to the financing assumption within the tested scenarios. The numerical evidence supports close annual correspondence for both systems but does not support treating annual agreement as a substitute for detailed temporal validation. QASP/LSPP provides sufficient paired observations to quantify monthly variation, whereas UOL/SSPP remains limited by sparse and internally inconsistent dated records. Similarly, the difference between reported and reconstructed economic indicators demonstrates that the original financial model cannot be reproduced uniquely from the available inputs. Maintaining a clear distinction between reported project metrics and reconstructed scenario values therefore

provides the most transparent basis for interpreting the results. The accompanying workbook and machine-readable files preserve the calculations and assumptions used in the analysis and can be updated when complete PVsyst outputs, generation records, and original financial inputs become available.

Data availability statement

The accompanying workbook contains the source-table values reproduced for analysis, the QASP monthly pairs, the UOL available samples and annual totals, assumptions, validation metrics, sensitivity matrices, and 25-year cash flows. Raw PVsyst exports and a complete UOL/SSPP monthly series should be archived with any final journal submission.

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