

Research Article

Integration of a Photovoltaic Power System and a Solar Water Heater at an Industrial Facility: Data Reconciliation, Hybrid Energy Balance, and Measurement and Verification Methodology

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Abstract

Industrial facilities increasingly combine photovoltaic electricity and solar thermal heat, but audit reports may compare incompatible energy records or aggregate electrical and thermal savings into a single figure. This creates a risk of overstating system performance and double counting displaced energy. This study develops a data-quality-aware measurement and verification methodology for an existing 40 kW rooftop photovoltaic system and a proposed 400 L/day solar water-heating system at an industrial confectionery facility. Audit records were classified by temporal coverage, measurement source, and alternating-current/direct-current boundary; partial-period specific yields were calculated; photovoltaic performance indicators were structured in accordance with IEC 61724-1; useful thermal demand was estimated from the water mass, specific heat capacity, and temperature rise; and a 50-85% solar-fraction sensitivity analysis was integrated with separate electricity and heat ledgers. The audit reports 52.5 MWh for July-December 2025 and 36.2 MWh for January-April 2026, corresponding to partial-period specific yields of 1,312.5 and 905 kWh/kWp. These values cannot be compared directly with a separate 26.928 MWh annual forecast until meter identity, capacity boundary, period completeness, and self-consumption/export allocation are reconciled. For the 400 L load, 18.6 kWh of useful heat is required per cycle, and annual useful solar heat varies from 3.39 to 5.77 MWh over the investigated solar-fraction range. The proposed architecture prevents double counting by maintaining separate physical ledgers and integrating them only at the cost, emissions, or primary-energy layer. Data reconciliation and uncertainty disclosure are therefore prerequisites for credible technical and economic decisions.

Keywords

Photovoltaic Performance Monitoring, Solar Water Heating, Data Reconciliation, Performance Ratio, Solar Fraction, Measurement and Verification, Hybrid Energy Balance

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1. Introduction

Industrial decarbonization increasingly relies on portfolios that combine photovoltaic (PV) electricity with solar thermal heat. Although both outputs can be expressed in kilowatt-hours, they represent different physical products, measurement boundaries, losses, and displaced energy carriers. Credible energy management therefore requires the electrical and thermal streams to be quantified separately before they are integrated at a common cost, primary-energy, or emissions layer [1, 3, 8, 9].

For PV systems, energy production alone is insufficient to diagnose performance. International monitoring practice distinguishes final yield, reference yield, performance ratio, availability, and data completeness [4, 11]. These indicators are sensitive to irradiance, module temperature, downtime, soiling, shading, measurement location, and degradation [12, 16]. Consequently, a register total cannot be interpreted without an explicit time period, rated-capacity boundary, meter identity, and statement of whether the value represents alternating-current generation, direct-current production, export, or facility self-consumption.

Solar water-heating performance is likewise governed by the useful hot-water demand, collector and storage losses, load timing, backup energy source, and solar fraction [17, 24]. A theoretical heat requirement is not equivalent to delivered solar heat, and a fixed annual saving cannot be defended unless the demand profile and solar contribution are measured or transparently modelled.

The case-study audit contains an existing 40 kW rooftop PV system, partial-period generation records for 2025-2026, a separate annual forecast, and a proposed 400 L solar water-heating concept. The reported PV values differ substantially, yet they do not share the same temporal coverage or epistemic

status. The research gap is therefore not a lack of another annual-energy estimate; it is the absence of a unified procedure that separates forecast, measured, and verified evidence while preventing double counting between electrical and thermal savings [6, 7].

Accordingly, the objective of this study is to develop and demonstrate a data-reconciliation and measurement-and-verification framework that: (i) classifies PV records by period, source, and boundary; (ii) calculates only defensible partial-period indicators; (iii) quantifies solar-water-heating sensitivity to solar fraction; (iv) integrates electricity and heat through separate physical ledgers; and (v) identifies the evidence required before technical, economic, or contractual claims are made.

2. Methodology

2.1. Case-Study Data and Analytical Boundary

The analysis uses the numerical records contained in the source manuscript. The PV asset is described as a 40 kW rooftop installation using LONGi modules and a Huawei inverter. Monthly generation values are available for July-December 2025 and January-April 2026. A separate screening calculation estimates 81.6 kWh/day and 26.928 MWh/year for 330 operating days. The solar-thermal concept assumes 400 L of water heated by 40 °C per cycle. No raw inverter time series, irradiance data, bidirectional-meter records, commissioning documents, hot-water load profile, or sensor-calibration certificates were supplied.

Table 1. Case-study assets, records, and evidence status.

Item	Available information	Evidence limitation
PV system	40 kW rooftop installation; LONGi modules; Huawei inverter	DC/AC rating and commissioning capacity not confirmed
PV records	52.5 MWh for Jul-Dec 2025; 36.2 MWh for Jan-Apr 2026	Meter ID, completeness, and export/self-use allocation not provided
PV forecast	26.928 MWh/year from a screening formula	Scenario assumptions are not equivalent to measured performance
Solar thermal	400 L/day; 40 °C temperature rise; 75% factor	Collector area, demand profile, and delivered-heat meter not provided

2.2. Data Reconciliation Procedure

Each reported value was first assigned four attributes: (1) temporal coverage, (2) evidence class (forecast, operational

record, or verification record), (3) measurement source, and (4) physical boundary. Values were compared only when these attributes were compatible. The resulting workflow is shown in Figure 1.

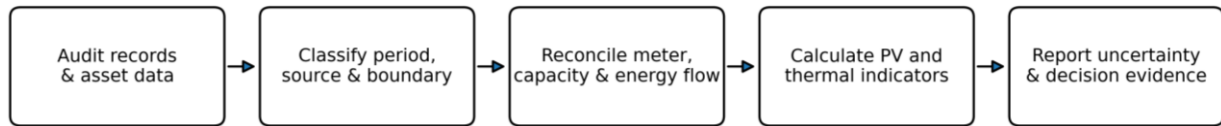


Figure 1. Data-reconciliation and hybrid M&V workflow.

For a period with measured alternating-current energy E_{AC} and rated PV capacity P_0 , the final or specific yield is calculated from Eq (1) [4, 11]. Because irradiance data were not available, the reference yield and performance ratio are defined methodologically but are not numerically reported.

$$Y_f = E_{AC} / P_0 \quad (1)$$

$$Y_r = H_{POA} / GSTC \quad (2)$$

$$PR = Y_f / Y_r \quad (3)$$

PV energy was represented by the balance in Eq (4). The storage term is zero when no storage system is installed, but the boundary-loss term remains conceptually important because inverter and revenue-meter readings may be taken at different points.

$$EPV = E_{self} + E_{export} + \Delta E_{storage} + E_{loss} \quad (4)$$

2.3. Solar-Thermal and Hybrid-Balance Method

The useful heat required to raise the water temperature was calculated from Eq (5). The annual useful solar heat was then evaluated as a function of the solar fraction using Eq (6). The source manuscript reports a 75% factor; this study treats that value explicitly as a scenario rather than a verified annual result.

$$Q_{load} = m c_p \Delta T \quad (5)$$

$$Q_{solar, annual} = f_s Q_{load} N \quad (6)$$

where m is the water mass, c_p is the specific heat capacity of water, ΔT is the temperature rise, f_s is the solar fraction, and

N is the number of operating cycles per year. Gas equivalence was calculated using a nominal heating value of 9.4 kWh/m^3 ; boiler efficiency was not applied because it was not reported.

The hybrid portfolio preserves electricity and heat as separate physical ledgers. Conversion to a common portfolio indicator is permitted only after the displaced energy carrier, tariff, emissions factor, and reporting period are defined. This rule prevents solar thermal from being counted both as avoided grid electricity and as avoided gas when only one backup energy source is displaced.

2.4. Uncertainty and Acceptance Criteria

The study applies a structured uncertainty screen rather than a numerical uncertainty budget because instrument classes and raw interval data were unavailable. A performance claim is considered acceptable only when the rated capacity, meter identity, timestamp completeness, AC/DC boundary, energy-flow allocation, and change history are documented. For a future full M&V study, combined standard uncertainty may be propagated according to Eq (7), with sensitivity coefficient c_i and standard uncertainty u_i .

$$uc = \sqrt{\sum (c_i u_i)^2} \quad (7)$$

3. Results and Discussion

3.1. PV Data Reconciliation

The source manuscript reports 52.5 MWh for July-December 2025 and 36.2 MWh for January-April 2026. Dividing these totals by 40 kW gives partial-period specific yields of 1,312.5 and 905 kWh/kWp, respectively. These values are valid only for the stated periods and must not be presented as annual yields.

Table 2. PV records and their correct interpretation.

Record	Coverage	Energy	Specific yield	Classification
2025 register total	Jul-Dec 2025	52.5 MWh	1,312.5 kWh/kWp	Measured partial period
2026 register total	Jan-Apr 2026	36.2 MWh	905 kWh/kWp	Measured partial period
Project estimate	Full-year scenario	26.928 MWh	673.2 kWh/kWp	Forecast

Figure 2 visualizes the three reported values. Their numerical proximity or difference is not evidence of underperformance or overperformance because the measured bars cover incomplete and unequal periods, while the forecast covers a full year and derives from a simplified screening expression.

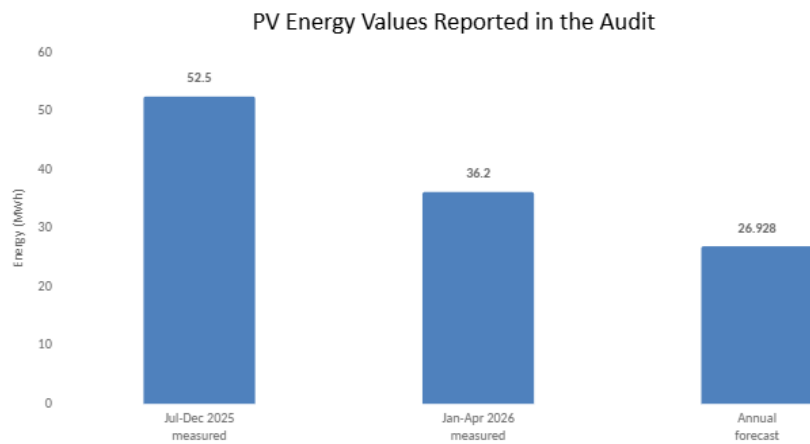


Figure 2. Measured partial-period PV records and the separate annual forecast.

A conclusion such as “the PV system generated twice the planned value” would therefore be scientifically unsupported. At minimum, the checks in Table 3 must be completed before a normalized comparison or payback calculation is performed.

Table 3. Acceptance controls for PV data reconciliation.

Control	Question	Required evidence
Capacity boundary	Is 40 kW the installed DC or AC rating?	Commissioning record and as-built single-line diagram
Meter source	Where was generation measured?	Inverter portal and revenue/verification meter ID
Temporal coverage	Are all intervals and months complete?	Timestamped interval data and completeness ratio
Energy flow	Are self-consumption and export separated?	Bidirectional import/export balance
Change history	Was the array or inverter capacity modified?	Asset register and change log
Reviewer-critical result: the inconsistency is retained as a data-quality finding. No performance-ratio, degradation, or financial claim is made until the evidence boundary is reconciled.		

3.2. PV Performance-Monitoring Indicators

The recommended monitoring set separates generation performance from facility net savings. Generation performance

evaluates the PV technology; facility net savings evaluate the normalized reduction in grid imports after accounting for production volume and operational changes. This distinction is consistent with energy-baseline and M&V practice [2, 3, 8, 9].

Table 4. Key PV monitoring indicators.

Indicator	Definition	Decision use
Final yield, Y_f	AC energy divided by rated PV capacity	Comparison across capacity and time
Reference yield, Y_r	Plane-of-array irradiation divided by reference irradiance	Solar-resource normalization
Performance ratio, PR	Y_f / Y_r	Aggregate system-loss indicator

Indicator	Definition	Decision use
Availability	Time ready for operation / reporting time	Downtime control
Self-consumption ratio	$E_{\text{self}} / E_{\text{PV}}$	Internal economic value
Export share	$E_{\text{export}} / E_{\text{PV}}$	Grid-delivery value
Data completeness	Valid intervals / expected intervals	Confidence in annualization

If annual energy declines, the investigation sequence should begin with data completeness and irradiation, followed by downtime, soiling, shading, string mismatch, inverter alarms, and component degradation [5, 10, 12-16]. This sequence reduces the risk of attributing a data or weather effect to equipment failure.

3.3. Solar Water-Heating Sensitivity

For 400 kg of water, a 40 °C temperature rise requires 67.0

MJ, equivalent to approximately 18.6 kWh of useful heat per cycle. This is the demand delivered to the water, not the solar energy incident on the collector. Collector, piping, and storage losses mean that the required incident energy is greater.

Assuming one cycle per day and 365 cycles per year, annual useful heat varies linearly with solar fraction. The 75% scenario gives 5.09 MWh/year, close to the 5.022 MWh/year value in the source manuscript; the minor difference reflects rounding and the stated daily-cycle assumption.

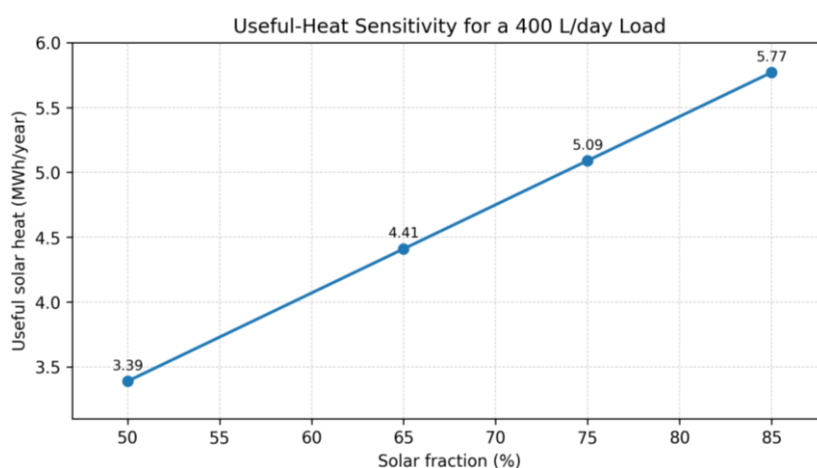


Figure 3. Useful-heat sensitivity to solar fraction for a 400 L/day load.

Table 5. Solar-fraction sensitivity for the 400 L/day load.

Solar fraction	Useful solar heat	Nominal gas equivalent	Interpretation
50%	3.39 MWh/year	≈361 m ³ /year	Conservative solar contribution
65%	4.41 MWh/year	≈469 m ³ /year	Moderate solar contribution
75%	5.09 MWh/year	≈542 m ³ /year	Source-manuscript scenario
85%	5.77 MWh/year	≈614 m ³ /year	High solar contribution

The sensitivity range demonstrates that a single annual saving is not an inherent property of a 400 L tank. It depends on useful demand, collector sizing and orientation, weather, con-

trols, and backup energy. A heat meter based on flow and supply/return temperatures is therefore required for post-investment verification [18-24].

3.4. Hybrid Electricity-Heat Balance and M&V Architecture

The hybrid balance must identify the displaced carrier. When hot water is produced by electricity, solar thermal reduces electrical load and can change the PV self-consumption

profile. When the backup source is gas, solar thermal reduces gas consumption and does not physically overlap with PV generation. The common portfolio result should therefore be constructed only after the two ledgers are verified.

Table 6. Measurement architecture for the hybrid solar portfolio.

Flow	Measurement point	Unit	M&V role
PV AC generation	Inverter and verification meter	kWh	Technology output
Grid import/export	Bidirectional revenue meter	kWh	Facility net electricity balance
Delivered solar heat	Heat meter: volume flow $\times$ temperature difference	kWh _{th}	Useful thermal output
Backup heat	Gas or electricity meter	m ³ or kWh	Displaced conventional energy
Hot-water demand	Flow and inlet/outlet temperature sensors	L and °C	Demand normalization

Sensor class, calibration date, timestamp synchronization, data-gap rules, and reporting-period consistency should be included in the M&V package. Forecast models, inverter portals, and revenue meters form different levels of evidence and are not interchangeable. Financial ledgers must also separate avoided-purchase tariffs, export tariffs, and gas tariffs.

3.5. Implementation Strategy, TRL, and Decision Use

The existing PV hardware has a high technology-readiness level; the immediate development need is data quality and performance analytics. The solar-thermal technology is mature in general, but the site-specific concept remains at a lower readiness level because demand logging, collector sizing, hydraulic integration, and commissioning evidence are absent.

Table 7. Phased implementation plan.

Stage	PV task	Solar-thermal task	Outcome
1	Reconcile inverter and revenue-meter records	Log hot-water flow and temperature for 2-4 weeks	Reliable baseline
2	Add irradiation, PR, availability, and completeness monitoring	Complete collector sizing and hydraulic design	Design evidence
3	Implement O&M analytics and alarm tracking	Pilot, commission, and install heat metering	Measured performance
4	Conduct annual normalized M&V	Conduct annual normalized M&V	Portfolio optimization

Economic ranking should use verified annual energy, tariff structure, maintenance cost, useful life, and uncertainty range. The largest nominal kilowatt-hour value is not automatically the best investment because electrical and thermal energy can have different marginal values and verification risks.

4. Conclusions

This study reformulates the available audit evidence into a data-quality-aware framework for combined PV and solar wa-

ter-heating assessment. The principal finding is that inconsistency in energy accounting must be separated from conclusions about technology performance. The 52.5 MWh and 36.2 MWh PV records are partial-period totals, while 26.928 MWh is a full-year forecast; they cannot be compared directly.

For the solar water-heating concept, the useful demand is approximately 18.6 kWh per 400 L cycle. Annual useful solar heat ranges from 3.39 to 5.77 MWh/year for solar fractions of 50-85%, demonstrating that the source value is a scenario rather than a verified outcome.

A defensible hybrid M&V system must maintain separate electricity and heat ledgers, define meter and capacity boundaries, distinguish forecast from measured and verified data, report completeness and uncertainty, and integrate results only at the cost, emissions, or primary-energy layer. The immediate priority is therefore not additional extrapolation, but collection of the missing meter, irradiance, commissioning, and hot-water-demand evidence.

Abbreviations

$m_{initial}$	Weight of the Component Before Testing (g)
m_{next}	Weight of the Component After Testing (g)
Δm	Mass Loss (g)

Author Contributions

Kenjaboev Shukurjon: Methodology, Project administration, Supervision, Writing – review & editing

Muydinova Nilufar: Methodology, Resources, Validation, Writing – review & editing

Akbarov Alisher: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

Nishonov Farkhod: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Badalov A. A is a researcher specializing in history, with a particular focus on the history of Central Asia and the Fergana Valley. His research interests include the history of medicine and healthcare, social history, and the development of public health and pharmacy in the region. His academic work focuses on the study and analysis of historical sources related to the social and medical development of Central Asia.



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Research Field

Badalov A. A: History, History of Medicine, Central Asian Studies, Social History

Suyunova X. A: History, Central Asian Studies, Social History, Cultural History, and Historical Research Methods

Abdushaxarov J. A: History, Central Asian Studies, Social History, Cultural History, and Historical Research Methods