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An Integrated Maturity-Compliance Framework for Sustainable Public Photovoltaic Asset Management

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ABSTRACT

The expansion of photovoltaic generation in public organizations has become an important instrument of energy policy, public expenditure reduction, and institutional sustainability. However, the long-term effectiveness of these investments depends not only on installed capacity, but also on the ability of public organizations to preserve energy performance, availability, safety, and economic value throughout the asset life cycle. This paper proposes an integrated framework for the sustainable management of public photovoltaic assets, combining two independent and complementary tools: The Technical-Managerial Operation and Maintenance Maturity Index, which assesses the structuring of management practices, and the Contract Execution Compliance Index, which evaluates the fulfillment of contractual obligations during service delivery. The research is applied, exploratory-descriptive, documentary, and propositional, based on public procurement documents and photovoltaic operation and maintenance contracts. The model includes dimensions related to maintenance planning, cleaning, energy monitoring, technical records, contract oversight, safety, and economic management. The integrated analysis distinguishes four governance conditions: Vulnerable management, compliance without technical sufficiency, unrealized management capacity, and consolidated management. The study concludes that sustainable public energy governance requires maturity and compliance to be assessed separately to improve procurement design, contract oversight, accountability, and asset performance.

Keywords: Operation and Maintenance, Public Contracts, Photovoltaic Management
JEL Classifications: Q42, Q48, Q56, H54

1. INTRODUCTION

The expansion of solar photovoltaic generation in public organizations has become an important component of contemporary energy policy. Beyond increasing the share of renewable electricity in institutional consumption, photovoltaic systems installed in public facilities may reduce operating expenditures, improve the use of public resources, and support governmental commitments to climate mitigation and sustainable development. In this context, public photovoltaic assets should not be understood merely as isolated engineering projects, but as long-term public investments whose benefits depend on adequate planning, operation, maintenance, monitoring, and institutional governance throughout their life cycle.

The effectiveness of public policies aimed at expanding distributed photovoltaic generation therefore depends not only on installed capacity, but also on the ability of public organizations to preserve energy performance, availability, safety, and economic value over time. A photovoltaic plant may be formally installed and connected to the grid while operating below its expected potential due to failures, inverter unavailability, soiling, shading, communication losses, lack of monitoring, or insufficient maintenance routines. When such deficiencies are not detected and corrected, the public policy objective associated with renewable generation is only partially achieved, since the asset fails to deliver the expected energy, economic, environmental, and institutional outcomes.

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This issue is particularly relevant in the public sector because photovoltaic systems are often implemented through investment programs, energy-efficiency initiatives, sustainability plans, or decentralized procurement processes. However, after installation, the continuity of benefits depends on governance arrangements capable of translating technical requirements into operational routines, contractual obligations, performance indicators, and evidence-based oversight. In the absence of such arrangements, public organizations may face avoidable energy losses, longer payback periods, higher corrective maintenance costs, premature deterioration of components, and reduced transparency regarding the actual performance of the investment.

Operation and maintenance of photovoltaic systems thus constitute a strategic dimension of public energy management. Although photovoltaic systems are designed for long operating periods, their components remain exposed to degradation, corrosion, electrical faults, soiling, monitoring failures, and progressive performance losses (Jordan et al., 2017; Hérnandez-Callejo et al., 2019; Jahn et al., 2022). Inadequately structured O&M practices may reduce generation, increase unavailability, and compromise the economic and environmental returns expected from the asset. Soiling is especially relevant because the accumulation of particles on photovoltaic modules may reduce energy yield and require cleaning decisions that should consider not only fixed schedules, but also performance losses, local environmental conditions, cleaning costs, and expected energy recovery.

Effective public energy governance requires more than the execution of isolated maintenance activities. Corrective, preventive, predictive, and condition-based strategies should be organized according to equipment criticality, plant size, environmental exposure, operational data availability, and service contractual scope. Performance monitoring plays a central role in this process because it enables public managers to distinguish ordinary meteorological variability from losses associated with faults, unavailability, soiling, degradation, or inadequate maintenance (National Renewable Energy Laboratory et al., 2018; Solar Power Europe, 2020; Livera et al., 2022; Rediske et al., 2022). Indicators such as energy generation, specific yield, performance ratio, availability, failure records, response time, maintenance completion, and O&M costs provide a more consistent basis for evaluating whether the photovoltaic asset is effectively fulfilling its public purpose (International Electrotechnical Commission, 2021; Rediske et al., 2022).

This perspective connects photovoltaic O&M with the broader field of physical asset management (International Organization for Standardization, 2024). Public photovoltaic plants are assets intended to generate value throughout their life cycle, and their management should balance performance, risk, cost, accountability, and sustainability. From this viewpoint, maintenance, cleaning, monitoring, safety, documentation, component replacement, and outsourced services are not independent activities, but interrelated functions that determine whether renewable-energy investments remain productive and economically justified over time. Sustainable management of photovoltaic assets therefore requires institutional capacity to plan, monitor, evaluate, and continuously improve O&M practices (Branco et al., 2024).

In public organizations, this institutional capacity is inseparable from contractual governance. O&M services are frequently outsourced, and the responsibilities of contractors are established through preliminary studies, terms of reference, procurement notices, contracts, maintenance plans, service-level requirements, and reporting obligations. Consequently, public energy management depends on two complementary dimensions. The first concerns the technical-managerial quality of the management framework established for the photovoltaic asset. The second concerns the degree to which the contractor effectively fulfills the obligations defined in the contract and provides sufficient evidence of service execution.

While photovoltaic public investments are commonly justified by energy savings, emission reduction, and sustainability goals, their long-term effectiveness depends on post-installation governance mechanisms capable of preserving performance, accountability, and life-cycle value. This requires not only adequate technical operation and maintenance practices, but also procurement instruments, contractual obligations, performance indicators, and evidence-based oversight aligned with public energy management objectives (Hernández and Nieto Granados, 2025; Tarigan, 2025).

This distinction is central to the governance of public photovoltaic assets. A contract may be fully complied with while remaining technically limited, for example when it requires only periodic cleaning or generic maintenance reports without energy-performance indicators, availability analysis, failure management, or post-intervention verification. In this case, contractual compliance does not necessarily mean that the public asset is being managed sustainably. Conversely, a contract may contain advanced requirements, such as performance monitoring, preventive maintenance, service levels, technical reports, and traceability mechanisms, but these obligations may not be adequately executed by the contracted company. Therefore, maturity and compliance should be assessed as distinct but complementary dimensions of public energy governance.

The lack of this distinction may weaken the evaluation of photovoltaic policies in the public sector. When attention is restricted to installation or formal contract execution, public organizations may fail to identify whether underperformance results from poor procurement design, insufficient technical requirements, inadequate contractor performance, weak oversight, or a combination of these factors. As a result, decision-makers may renew technically insufficient contracts, accept services without adequate evidence, overlook persistent performance losses, or miss opportunities to improve future procurement instruments.

From a sustainability perspective, the governance of public photovoltaic assets is directly related to the continuity of the benefits expected from renewable-energy policies. Maintaining energy performance contributes to clean energy access and institutional decarbonization; preserving asset availability improves the effectiveness of public investment; extending equipment life reduces resource waste; and strengthening

documentation, traceability, and contract oversight improves transparency and accountability in public administration. In this sense, O&M governance is not a secondary administrative activity, but a mechanism through which the energy transition is sustained after the installation of generation capacity.

Despite its importance, the existing literature generally examines photovoltaic maintenance planning, performance monitoring, decision-support systems, asset management, maturity models, or contractual indicators as separate issues. Limited attention has been given to integrated assessment frameworks capable of simultaneously evaluating whether the management model established for a public photovoltaic asset is technically sufficient and whether the contractual obligations derived from that model are effectively fulfilled during service execution. This gap is particularly relevant for decentralized public photovoltaic systems, where different contracts, plant sizes, information availability levels, and institutional capacities may coexist within the same governmental context.

To address this gap, this study proposes an integrated framework for assessing the sustainable management of public photovoltaic assets. The model comprises two independent and complementary tools: The Technical-Managerial O&M Maturity Index, which evaluates the degree of structuring of the management practices established for the photovoltaic asset, and the Contract Execution Compliance Index, which assesses the fulfillment of contractual obligations during service delivery. The results are integrated through a Maturity–Compliance Gap measure and a two-dimensional matrix that distinguishes whether weaknesses originate mainly from procurement design, contract execution, or both.

The principal contribution of this study is to connect photovoltaic asset management, public energy policy, contractual governance, technical performance, and sustainability within a unified assessment framework. By distinguishing maturity from compliance and subsequently integrating their results, the proposed model may support the preparation of terms of reference, the definition of indicators and service levels, the standardization of technical reports, the planning of contract oversight, and the improvement of public policies aimed at sustaining the energy, economic, environmental, and institutional value generated by photovoltaic investments.

2. METHODOLOGY

This study is characterized as applied, exploratory-descriptive, documentary, and propositional research. It is applied because it seeks to develop an instrument to support the procurement and oversight of photovoltaic operation and maintenance services in public organizations. It is exploratory-descriptive because it organizes concepts and analytical dimensions that remain insufficiently systematized in this specific context. It is documentary because both the development and future application of the model rely on the analysis of contracts, terms of reference, technical reports, work orders, and contract execution records. Finally, it is propositional because its principal outcome is the formulation of two assessment tools and an integrated interpretive framework.

The first stage consisted of mapping Brazilian public contracts related to the operation, maintenance, and cleaning of photovoltaic systems available through Brazil's National Public Procurement Portal. The search was conducted in November 2025 using combinations of terms associated with photovoltaic solar energy, maintenance, operation, cleaning, solar power plants, and photovoltaic modules.

The inclusion criteria covered current or recent procurement documents issued by Brazilian public organizations that explicitly provided for services related to the operation, maintenance, or cleaning of photovoltaic systems. Contracts exclusively concerned with the supply and installation of new photovoltaic systems, without subsequent operation and maintenance activities, were excluded.

The search identified five contracts associated with decentralized photovoltaic plants. The limited number of retrieved documents should be interpreted in light of the constraints of the portal's search system and the lack of standardized descriptions for procurement objects. Photovoltaic operation and maintenance services may be embedded within broader contracts for building maintenance, energy efficiency, or engineering services, which reduces their retrievability through specific search descriptors.

The contracts were coded from C1 to C5 to preserve analytical focus on their technical and managerial characteristics rather than on the identity of the contracting organizations.

The conceptual development of the model followed five stages: Defining the object assessed by each tool; establishing the dimensions of technical-managerial maturity; defining the dimensions of contract execution compliance; formulating the calculation and interpretation procedures; and integrating the results into a two-dimensional matrix.

Multidimensional assessment instruments enable the integration of technical, managerial, economic, and sustainability-related factors, thereby providing a more comprehensive evaluation of project performance and condition (Adelakun et al., 2026). Accordingly, the proposed model was designed to distinguish between the structural quality of the management arrangements established for photovoltaic operation and maintenance and the extent to which the corresponding contractual obligations are effectively fulfilled (Kooduvalli et al., 2019).

In future applications, expected maturity should be assessed through preliminary technical studies, terms of reference, procurement notices, contracts, technical annexes, risk matrices, maintenance plans, operating procedures, service-level requirements, and reporting templates. Contract execution compliance should be assessed using monthly reports, work orders, service requests, monitoring-system records, photographic evidence, meeting minutes, formal notices, measurements, service certifications, acceptance records, professional responsibility documents,

failure records, and evidence that identified deficiencies have been corrected.

Sustainability frameworks must account for the institutional, economic, and operational characteristics of the contexts in which they are applied. General models may not adequately reflect the specific conditions of developing countries, which reinforces the importance of local factors, expert consultation, and subsequent validation procedures (Mohsin et al., 2023). The proposed model should therefore be understood as an adaptable framework rather than a rigid and universally standardized instrument. Its dimensions, criteria, weights, and interpretation thresholds may require adjustment according to the characteristics of public contracts, institutional capabilities, photovoltaic plant size, service scope, and the availability and quality of documentary and operational evidence.

3. RESULTS AND DISCUSSION

The mapping identified five public contracts related to the cleaning, maintenance, or operation of decentralized photovoltaic plants. Their respective scopes, procurement years, and contract values are presented below:

- Federal Institute of Education, Science and Technology of Rio Grande do Sul (IFRS) - Scope: Hiring a specialized company to clean the photovoltaic plants installed across IFRS campuses. Year: 2024. Contract value: BRL 119,188.26.
- Brazilian Army Command - Scope: Technical cleaning and preventive maintenance of 6,086 photovoltaic modules installed at the Army Headquarters Photovoltaic Power Plant. Year: 2024. Contract value: BRL 55,869.48.
- Municipality of Ouro Verde do Oeste - Scope: Cleaning of 175 photovoltaic modules rated at 560 W each, with the contracted company responsible for providing all instruments and materials required for service execution. Year: 2025. Contract value: BRL 25,640.00.
- Itajaí Municipal Council - Scope: Provision of cleaning and predictive, preventive, and corrective maintenance services for a photovoltaic plant with an installed capacity of 168.40 kWp and comprising 526 photovoltaic modules. Year: 2025. Contract value: BRL 23,950.00.
- Court of Justice of the State of Acre - Scope: Operation and preventive and corrective maintenance of photovoltaic plants installed in judicial facilities in the State of Acre, with installed capacities of 524 kWp, 264.6 kWp, 103 kWp, and 66 kWp. Year: 2025. Contract value: BRL 622,521.52.

The contracts differ substantially in terms of scope, plant size, range of services, and contract value. A direct price comparison is therefore insufficient to assess procurement quality, since the contracted scopes range from isolated cleaning services to the operation and preventive and corrective maintenance of multiple photovoltaic plants. Moreover, a lower contract value does not necessarily indicate greater life-cycle cost-effectiveness, particularly when the scope excludes performance monitoring, fault diagnosis, availability control, and verification of post-intervention performance recovery. Technically limited contracts may reduce short-term expenditure while increasing energy losses, periods of unavailability, and future corrective maintenance costs, thereby undermining part of the economic and environmental benefits associated with photovoltaic investment.

For this reason, the mapping exercise was extended through an analysis of the technical and managerial elements contained in the procurement documents. The findings indicate that the mapping does not merely provide a descriptive overview of the contracts; it also enables an assessment of the extent to which procurement arrangements contribute to preserving energy performance, operational reliability, and the value of public assets. The observed heterogeneity provides the empirical basis for developing the two proposed assessment tools. From a maturity perspective, it reveals different levels of management structuring across the asset life cycle. From a compliance perspective, it identifies categories of contractual obligations whose execution must be demonstrated through verifiable evidence to ensure that the expected benefits of public investment are effectively preserved.

3.1. Maturity Matrix

The first result of the study is the proposed Technical-Managerial O&M Maturity Matrix. Its purpose is to assess the degree to which the practices established in procurement instruments and photovoltaic plant management arrangements are structured. In this context, maturity also represents the institutional capacity to preserve performance, manage risks, and protect the value of public investment throughout the photovoltaic system life cycle. The more structured the management system, the greater its expected capacity to detect losses at an early stage, reduce periods of unavailability, plan interventions, and prevent minor failures from developing into more costly or prolonged damage.

The mapping exercise showed that the contracts range from scopes focused primarily on cleaning or isolated activities to more comprehensive arrangements that include preventive and corrective maintenance, performance monitoring, technical reporting, and professional responsibility. These differences are not limited to the number of services included. They reflect different institutional capacities to ensure the continuity of renewable electricity generation and to protect the expected economic and environmental outcomes of the installations. This finding supports the organization of management practices into progressive maturity levels.

Table 1 presents a qualitative synthesis of the elements identified in the contracts examined. The contracts were coded from C1 to C5, and the entries indicate the predominant presence of the documentary elements analyzed. The table does not constitute a ranking, a quality index, or a final assessment of the contracts. Its purpose is to demonstrate how documentary mapping supports the definition of the dimensions included in the maturity matrix.

As shown in Table 1, the contracts generally include corrective maintenance and module cleaning, but these activities are not consistently linked to energy-performance criteria. Cleaning is predominantly specified as a scheduled activity or described in generic terms, which limits its integration with energy-generation losses, accumulated soiling, weather conditions, and

Table 1: Qualitative synthesis of the elements identified in the contracts examined

Element assessed	C1	C2	C3	C4	C5
Preventive maintenance scope	Partial	Partial	Partial	Included	Included
Corrective maintenance	Not included	Not included	Not included	Included	Included
Module cleaning	Fixed schedule	Fixed schedule	Specified	Fixed schedule	Specified
Periodic technical reports	Basic	Included	Generic	Included	Included
Energy generation monitoring	Not explicitly specified	Not explicitly specified	Not explicitly specified	Specified	Specified
Performance indicators	Not included	Not included	Not included	Partial	Partial
Professional technical responsibility	Specified	Specified	Not explicitly specified	Specified	Specified
Service acceptance criteria	Service completion	Service completion and report	Service completion	Service completion and report	Service completion and report

the economic assessment of the intervention (Ilse et al., 2019; Micheli at al., 2021). This condition suggests an intermediate stage of management maturity, in which the activity is formally established but is not necessarily connected to a performance-optimization rationale.

The absence of such integration may produce two undesirable outcomes. The first is the performance of cleaning activities without a demonstrated technical or economic need, generating costs and consuming resources without a proportional recovery in energy generation. The second is the postponement of interventions during periods in which soiling or another anomaly is already causing substantial energy losses. In both cases, decisions based exclusively on fixed schedules may reduce management efficiency and limit the plant's effective contribution to renewable electricity generation.

From a life-cycle perspective, apparently minor losses, when accumulated over months or years, may represent a substantial amount of renewable energy not generated, a longer investment payback period, and a reduction in avoided emissions. Incorporating criteria related to performance, soiling, cost, and intervention effectiveness can therefore align maintenance decisions more closely with the economic and environmental sustainability of public assets.

Maturity models can be used to assess the degree of formalization, structuring, and development of processes associated with infrastructure management. A five-level progressive model was developed to identify the maturity stage of work and communication processes in organizations responsible for infrastructure management (Zeb et al., 2013; Bukowski and Werbinska-Wojciechowska, 2025). This approach supports the organization of technical-managerial photovoltaic O&M practices into progressive levels, ranging from predominantly reactive conditions to integrated management arrangements oriented toward continuous improvement.

Another relevant finding is the variation in technical reporting requirements and energy-generation monitoring across the contracts. When contracts require reports but do not establish minimum indicators, oversight may be restricted to documentary verification of service completion, without systematically assessing maintenance effectiveness. Conversely, when contracts require monitoring of energy generation, equipment availability, or the comparison between expected and measured output, management tends to approach more advanced maturity levels because operational data are used to support decision-making.

Based on these findings, six dimensions were defined for the maturity matrix: Maintenance, cleaning, energy monitoring, records and reporting, contract oversight, and economic management.

Table 2 summarizes the five proposed maturity levels and their respective managerial interpretations, while Table 3 presents the dimensions of the maturity matrix according to initial, intermediate, and advanced management conditions.

The proposed matrix enables the assessment of the degree to which O&M management is structured without requiring, at this stage, complete operational datasets or fully normalized indices. This is particularly relevant for public organizations that manage decentralized photovoltaic plants under different contracts and with varying levels of information availability. The qualitative classification facilitates the identification of fundamental gaps, including the absence of indicators, weaknesses in technical reporting, lack of service acceptance criteria, and insufficient linkage between cleaning activities and system performance.

The Technical-Managerial Maturity Index (TMMI) is quantified by assigning scores from zero to four to the criteria within each dimension. A score of zero indicates that the requirement is absent, whereas a score of four indicates that the requirement is fully structured and supported by indicators, historical records, and continuous improvement practices. The score for each dimension is converted to a scale ranging from zero to 100 by dividing the sum of the scores obtained by the maximum possible score. The overall TMMI corresponds to the mean of the dimensions assessed, preferably using equal weights in the initial application. The results are classified into five maturity levels: Reactive (0-20), basic preventive (>20-40), monitored (>40-60), managerial (>60-80), and optimized (>80-100).

The main practical application of the matrix lies in its capacity to support the planning of contract oversight. When a contract is classified, for example, between the basic preventive and monitored levels, the responsible public officer may prioritize requirements such as standardized reports, historical failure records, energy-generation monitoring, and the definition of minimum performance indicators. At more advanced stages, management may incorporate cost-effectiveness criteria, performance analysis, risk-based decision-making, and continuous improvement.

Table 2: Proposed maturity levels for photovoltaic O&M management

Level	Designation	Core characteristic	Managerial interpretation
1	Reactive	Action is taken only after failures, complaints, or evident performance losses.	Low predictability and strong dependence on isolated corrective actions.
2	Basic preventive	Scheduled routines are established, but they remain generic and weakly linked to performance.	A minimum level of organization is present, although management remains predominantly operational.
3	Monitored	Periodic monitoring of energy generation, failures, cleaning activities, and technical records.	Management begins to use evidence to oversee system operation.
4	Managerial	Indicators, technical criteria, and historical records are used to support decision-making.	Maintenance is integrated with contract oversight and asset performance.
5	Optimized	Performance, cost, risk, oversight, and continuous improvement are integrated.	Management is oriented toward public value, cost-effectiveness, and life-cycle performance.

Table 3: Dimensions of the maturity matrix

Dimension	Initial level	Intermediate level	Advanced level
Maintenance	Predominance of corrective actions after failures occur.	Preventive routines supported by basic records.	Maintenance guided by performance data and operational history.
Cleaning	Absence of clear criteria or only occasional execution.	Fixed cleaning schedule with records of service completion.	Cleaning criteria linked to performance, soiling, cost, and intervention effectiveness.
Energy monitoring	Occasional or nonexistent access to operational data.	Periodic monitoring of energy generation.	Analysis of expected generation, measured generation, availability, and performance deviations.
Records and reporting	Fragmented or merely descriptive documentation.	Periodic reports containing evidence of service execution.	Reports incorporating indicators, historical data, and technical recommendations.
Contract oversight	Formal acceptance of the service.	Documentary and technical verification of the activities performed.	Oversight based on objective criteria, performance indicators, and traceability.
Economic management	Costs treated in isolation.	Recording of costs and interventions.	Integrated decision-making based on cost, energy-generation losses, and asset value.

3.2. Contract Execution Compliance Index

The second result of the study is the proposed Contract Execution Compliance Index (CECI). The CECI uses the contract as the reference for defining the obligations to be fulfilled and contract-execution documents as the sources of evidence. The mapping exercise showed that contractual obligations can be organized into three recurrent groups: Technical, documentary, and operational. This structure was therefore adopted in the development of the index.

The index is intended to reduce subjectivity in contract oversight, systematize the evidence generated during service delivery, and enable comparisons of compliance levels over time. Its application does not replace the technical judgment of the responsible public officer, nor does it supersede the provisions established in the procurement notice, terms of reference, contract, or applicable legislation. Rather, the CECI functions as a decision-support tool by providing a measurable basis for service acceptance, the identification of outstanding issues, the issuance of formal notices, the recommendation of corrective measures, and, where applicable, the imposition of payment deductions or contractual penalties.

The index is structured into three dimensions: Technical compliance (TC), documentary compliance (DC), and operational compliance (OC). Technical compliance receives the highest weighting because of its direct relationship with safety, reliability, performance, and the preservation of photovoltaic assets. The other two dimensions address the quality and traceability of records and the contractor's capacity to comply with the procedures, deadlines, and service-response processes established in the contract.

Technical compliance encompasses the quality and effectiveness of activities directly related to maintenance and to the physical and functional condition of the photovoltaic plant. This dimension assesses whether the services were performed in accordance with the established scope and whether sufficient evidence was produced to demonstrate compliance with requirements related to safety, performance, and equipment preservation. The criteria and respective weights adopted for technical, documentary, and operational compliance are presented in Tables 4-6 respectively.

The technical criteria are intended to encompass the main activities capable of affecting photovoltaic system operation. Technical inspections, preventive maintenance, and fault correction receive the highest weights because they represent the core components of contract execution. Module cleaning and the inspection of electrical and mechanical components are also relevant, but they should be assessed in conjunction with the actual condition of the installation and the procedures established in the maintenance plan.

Documentary compliance assesses the contractor's capacity to demonstrate, in an organized and traceable manner, the services effectively performed. In the public administration context, consistent documentation is essential for control, transparency, auditing, and the accountability of the parties involved.

The mere submission of a report does not, in itself, demonstrate documentary compliance. The document must contain sufficient information to verify service execution, identify the responsible professionals, record the conditions encountered, and describe the measures adopted. Accordingly, generic reports that lack photographic records, dates, location details, equipment

Table 4: Criteria for the technical compliance dimension

Criterion	Weight within the dimension (%)
Completion of the required technical inspections	20
Completion of scheduled preventive maintenance	20
Appropriate correction of identified failures	20
Compliance with cleaning procedures	15
Inspection of modules, inverters, cables, connections, and support structures	15
Compliance with safety and professional technical responsibility requirements	10
Total	100

Table 5: Criteria for the documentary compliance dimension

Criterion	Weight within the dimension (%)
Submission of reports within the established deadline	20
Completeness and consistency of technical reports	20
Provision of photographic records and evidence of service execution	20
Recording of failures, interventions, and outstanding issues	15
Submission of work orders, checklists, and measurement records	15
Updating of the plant's operational history and documentary traceability	10
Total	100

identification, or descriptions of the interventions performed should receive lower scores, even when formally submitted within the established deadline.

Operational compliance, in turn, concerns adherence to maintenance schedules, service-response deadlines, and the communication and occurrence-management procedures established in the contract. This dimension seeks to determine whether the contractor possesses a response capacity consistent with contractual requirements and with the plant's operational continuity needs.

Operational assessment should not be limited to verifying that a service activity was initiated. It should also consider response time, the effective resolution of the occurrence, communication with the contract oversight authority, and the formal closure of the outstanding issue. Repeated failures without treatment of their underlying causes indicate low operational compliance, even when successive work orders have been issued.

Each criterion is assessed using an ordinal scale ranging from zero to four points. The scale represents progressive levels of compliance, from the complete absence of service execution or supporting evidence to full fulfillment and adequate verification of the requirement. Table 7 summarizes the ordinal scoring scale used to assess each CECI criterion.

Scores must be assigned on the basis of verifiable evidence. Relevant sources may include technical reports, photographic

Table 6: Criteria for the operational compliance dimension

Criterion	Weight within the dimension (%)
Compliance with the maintenance schedule	20
Response to service requests within the contractual deadline	20
Restoration of operation following failures	20
Monitoring of energy generation and inverter alarms	15
Communication of nonconformities to the contract oversight officer	15
Resolution of outstanding issues and recurring nonconformities	10
Total	100

Table 7: Scoring scale for the CECI criteria

Score	Level of compliance	Description
0	Not met	Service not performed or complete absence of evidence
1	Insufficient	Incomplete or inadequate execution, or absence of minimum supporting evidence
2	Partial	Requirement partially fulfilled, with significant outstanding issues
3	Satisfactory	Requirement fulfilled, with minor shortcomings that do not produce significant impacts
4	Full	Requirement fully fulfilled and adequately supported by evidence

CECI: Contract execution compliance index

records, data from monitoring platforms, work orders, checklists, electrical measurements, alarm logs, on-site inspections, and professional technical responsibility documents.

The absence of evidence prevents a criterion from being considered fully met. Therefore, even when the contractor declares that a particular service has been performed, the lack of minimum supporting documentation should limit the score assigned, because public-sector contract oversight requires traceability and objective verification.

The score for each dimension is calculated as the weighted average of the applicable criteria and converted to a scale ranging from 0 to 100 points.

The use of the sum of the applicable weights allows the index to be applied to contracts with different scopes. When a criterion is not included in the contract, it should be classified as "not applicable," and its weight should be redistributed proportionally among the remaining criteria within the same dimension. This procedure prevents contractors from being penalized for obligations that were not contractually established and preserves the internal comparability of the instrument.

After the three dimensions have been calculated, the CECI is obtained using the following expression:

$$CECI = 0{,}4 \cdot CT + 0{,}3 \cdot DC + 0{,}3 \cdot OC \quad (1)$$

Where CECI denotes the Contract Execution Compliance Index, TC represents technical compliance, DC represents documentary compliance, and OC represents operational compliance.

The final result is expressed on a scale from zero to 100 points, with higher values indicating greater adherence of contract execution to the established obligations and requirements.

To facilitate interpretation, five compliance ranges were defined. These classifications should be understood as references for contract oversight rather than as automatic mechanisms for service acceptance, payment deductions, or contractual sanctions.

Table 8 presents the proposed CECI classification ranges and the corresponding recommended contract-oversight actions.

The resulting classification should be interpreted in conjunction with the nature and severity of the identified nonconformities. A contract may achieve an apparently satisfactory overall score while still presenting a serious failure related to safety, professional technical responsibility, or evidence of service execution. For this reason, the CECI incorporates criticality rules designed to prevent high average scores from concealing materially relevant deficiencies.

Requirements are considered critical when their nonfulfillment may compromise human safety, equipment integrity, record reliability, or the operational continuity of the photovoltaic plant. Critical occurrences may include:

- Uncorrected electrical or mechanical hazards;
- Absence of professional technical responsibility when legally or contractually required;
- An intervention reported as completed but not supported by evidence;
- Manipulation, concealment, or unjustified unavailability of operational data;
- A significant failure not communicated to the contract oversight authority;
- Damage caused by an inappropriate procedure;
- Serious noncompliance with safety requirements; and
- Recurrence of a previously reported nonconformity.

Restriction rules should be applied when calculating and classifying the CECI to prevent favorable quantitative results from obscuring significant execution failures. Accordingly, the occurrence of one critical criterion with a score of zero limits the overall CECI to a maximum of 59 points. The identification of two or more critical criteria with a score of zero results in the automatic classification of contract execution as critical noncompliance. When the technical compliance score is below 50 points, the overall result cannot be classified as satisfactory or high compliance.

In the absence of documentary evidence, the score assigned to the corresponding criterion must be limited to a maximum of one point. Services performed after the contractual deadline, without a formally accepted justification, require a reduction in the corresponding operational compliance score. Finally, the recurrence of a serious nonconformity should lead to a more severe classification and the adoption of a specific corrective measure. These restrictions ensure that favorable documentary or operational scores cannot compensate for serious deficiencies in the technical execution of the services.

The CECI may be applied according to the measurement cycle established in the contract. For contracts involving monthly payments, monthly calculation of the index is recommended. The instrument may also be applied after preventive maintenance cycles, extraordinary interventions, critical operating periods, or before contract renewal or extension decisions.

The results should form a historical time series that enables the assessment of contractor performance, the recurrence of failures, and the effectiveness of the corrective measures adopted. Temporal analysis is particularly relevant because an isolated score represents only the condition observed during a specific period, whereas the trajectory of the index can reveal trends of improvement, stability, or deterioration in contract execution.

The application of the index may also support decisions related to service measurement, payment, formal notices, payment deductions, corrective action plans, and contract extensions. Such decisions must nevertheless comply with due administrative process, contractual provisions, and the technical judgment of the responsible oversight officer. The index should therefore not be used automatically or in isolation. Decision-making concerning photovoltaic infrastructure involves multiple technical, economic, territorial, environmental, and social criteria and consequently requires structured assessment instruments (Macedo et al., 2021).

A limitation of the proposed index is that its weights and classification ranges are preliminary and should be subjected to pilot application. Contracts with specific scopes may require the inclusion, exclusion, or reweighting of criteria. The CECI should therefore be understood as an adaptable framework whose standardization depends on empirical consolidation across different public-sector photovoltaic operation and maintenance contexts.

3.3. Maturity-Compliance Gap

The third result of the study is the proposed integrated analysis designed to reveal the difference between the expected level of technical-managerial maturity and the observed level of contract execution compliance. This difference is referred to as the

Table 8: CECI classification and recommended actions

CECI range	Classification	Recommended action
90-100	High compliance	Accept the services and maintain regular oversight
75-89.99	Satisfactory compliance	Accept the services, record minor deficiencies, and require their correction
60-74.99	Partial compliance	Condition acceptance upon the resolution of outstanding issues
40-59.99	Insufficient compliance	Issue a formal notice, require a corrective action plan, and assess the applicability of payment deductions
Below 40	Critical noncompliance	Reject the services and adopt the applicable contractual measures

CECI: Contract execution compliance index

Maturity-Execution Gap. The directional gap is calculated as the difference between the two proposed indices.

A positive result indicates that the expected maturity level is higher than the observed level of contract execution compliance. This condition suggests that the contract or management framework contains relatively advanced requirements, but that its intended capacity has not been fully realized in practice.

A negative result indicates that contract execution compliance is higher than technical-managerial maturity. This means that the existing obligations are being fulfilled satisfactorily, even though the underlying management framework remains technically limited.

The gap should not be interpreted in isolation. Two contracts may present similar TMMI and CECI scores and therefore a small gap, while still occupying substantially different managerial conditions. For example, a contract with a TMMI of 20 and a CECI of 18 shows relative alignment between the two indices, but it remains characterized by low maturity and low compliance. By contrast, a contract with a TMMI of 90 and a CECI of 88 also presents a small gap, but it reflects a substantially more advanced managerial condition.

For this reason, the two indices are positioned within a two-dimensional matrix. The TMMI represents the technical-managerial maturity axis, whereas the CECI represents the contract execution compliance axis. A preliminary threshold of 60 points is adopted to distinguish lower conditions from minimally adequate or higher levels. Figure 1 illustrates this comparison.

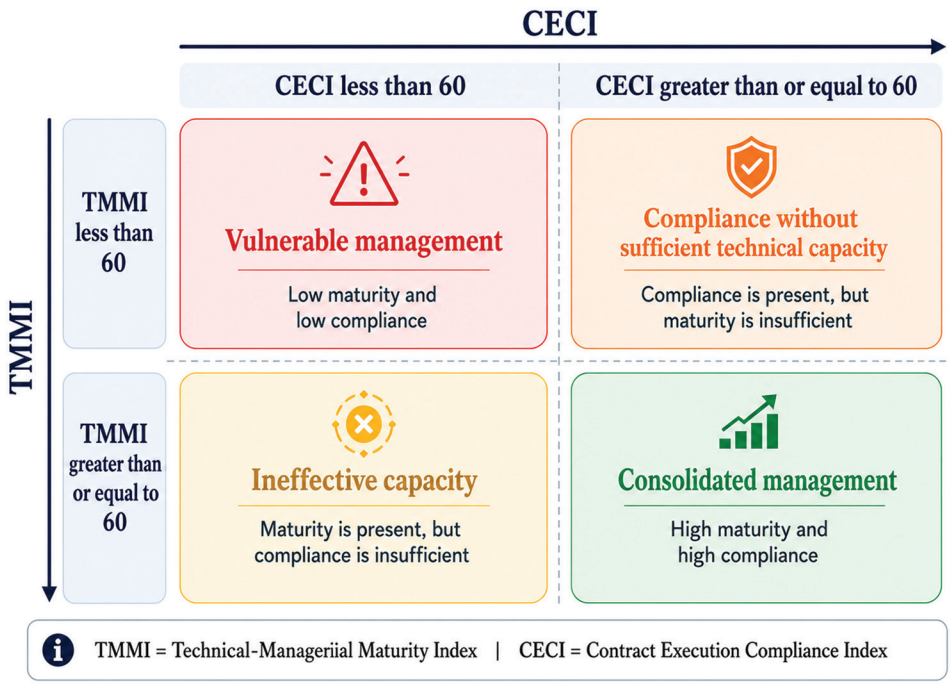
The first condition, termed vulnerable management, occurs when both maturity and compliance scores are below 60. Under this condition, the management framework is weakly structured, while the existing contractual obligations are also performed unsatisfactorily. Typical characteristics may include predominantly corrective maintenance, generic technical reports, delays, limited traceability, and the absence of performance indicators. Improvement therefore requires simultaneous intervention in both planning and execution.

The second condition, termed compliance without technical sufficiency, occurs when the TMMI is below 60 and the CECI is equal to or above 60. In this situation, the contractor adequately fulfills the established obligations, but the contractual scope reflects a low level of technical-managerial maturity. An example would be the complete execution of periodic cleaning activities without soiling monitoring, energy-generation analysis, or verification of post-cleaning performance recovery. The priority should therefore be the revision of future procurement instruments rather than attributing noncompliance to the contractor.

The third condition, termed unrealized management capacity, occurs when the TMMI is equal to or above 60 and the CECI is below 60. The contract contains structured requirements, including performance indicators, technical reports, preventive maintenance, monitoring procedures, and service levels, but these elements are not fully implemented. In this case, the priority is to strengthen contract oversight, require verifiable evidence, correct execution deficiencies, and apply the relevant contractual mechanisms.

The fourth condition, termed consolidated management, combines TMMI and CECI scores equal to or above 60. In this condition, the management framework is structured and the contractual obligations are executed with substantial or high compliance. This condition is generally associated with systematic planning, performance monitoring, indicators, failure management, service acceptance criteria, traceability, and continuous improvement.

Figure 1: Integrated maturity and compliance matrix



The principal contribution of the model lies precisely in this differentiation. Maturity assesses the technical sufficiency and development of the management system, whereas compliance assesses the fulfillment of contractual obligations. The gap between the two results indicates whether the main weakness lies in procurement design, contract execution, or both.

When maturity is low and compliance is high, the scope, indicators, reporting requirements, and service acceptance criteria should be revised. When maturity is high and compliance is low, oversight, evidence of service delivery, and the treatment of nonconformities should be strengthened. When both results are low, a comprehensive review of the management arrangement is required. When both are high, the priority shifts toward process maintenance and continuous improvement.

The proposed model can be incorporated into the Plan-Do-Check-Act cycle. The maturity matrix supports planning and the identification of the capabilities required for asset management. The CECI supports verification of service execution and the results produced. The gap analysis guides corrective actions, revision of terms of reference, improvement of contract oversight, and adjustment of maintenance processes.

The integration of maintenance planning, performance monitoring, operational records, and continuous improvement is consistent with contemporary photovoltaic O&M approaches that emphasize data-supported decision-making throughout the system life cycle (Jahn et al., 2022; Livera et al., 2022; Rediske et al., 2022).

This integration connects planning, execution, control, and continuous improvement with the life-cycle management of public photovoltaic plants. By facilitating the detection of contractual and operational weaknesses, the model may contribute to reducing avoidable energy losses, shortening periods of unavailability, preserving system components, and improving the effectiveness of resources allocated to O&M. Physical asset management can influence sustainability performance by integrating decisions related to asset performance, risk, cost, and equipment life cycle (Maletič et al., 2018).

From the perspective of the energy transition, the expansion of installed photovoltaic capacity produces sustainable outcomes only when systems remain operational and productive over time. O&M governance should therefore be regarded as an integral component of energy-transition governance because it helps ensure that publicly funded assets continue to deliver renewable electricity, economic savings, and environmental benefits throughout their useful lives.

4. CONCLUSION

This study addressed a gap in the literature on public photovoltaic asset management: The absence of an integrated framework capable of distinguishing the technical-managerial quality of post-installation governance from the effective fulfillment of contractual obligations during operation and maintenance. While previous approaches commonly emphasize photovoltaic deployment, economic viability, performance monitoring, or maintenance practices as separate issues, less attention has been given to how public organizations can jointly assess procurement design, contract execution, accountability, and life-cycle value preservation in decentralized photovoltaic assets.

To address this gap, the study proposed an integrated maturity-compliance framework composed of two independent and complementary tools: The Technical-Managerial Operation and Maintenance Maturity Index and the Contract Execution Compliance Index. The first assesses the degree of structuring of management practices established for the photovoltaic asset, while the second evaluates whether the obligations defined in the contract are effectively fulfilled and supported by verifiable evidence. Their integration through a Maturity-Compliance Gap and a two-dimensional matrix enables public organizations to identify whether weaknesses originate mainly from insufficient procurement design, poor service execution, or both.

The main scientific contribution of this study lies in demonstrating that maturity and compliance are analytically distinct dimensions of sustainable public energy governance. Full compliance with a technically limited contract does not necessarily indicate adequate asset management, just as a well-structured contract does not ensure effective implementation. This distinction advances the assessment of photovoltaic O&M by moving beyond formal contract fulfillment and incorporating the institutional capacity required to preserve performance, availability, safety, accountability, and economic value over the asset life cycle.

The proposed matrix also contributes to the interpretation of public photovoltaic management by identifying four governance conditions: Vulnerable management, compliance without technical sufficiency, unrealized management capacity, and consolidated management. These categories support differentiated decision-making. Low maturity indicates the need to revise scopes, indicators, service levels, and acceptance criteria in future procurement instruments. Low compliance indicates the need to strengthen contract oversight, evidence traceability, contractor accountability, and corrective action mechanisms. When both dimensions are insufficient, broader institutional and contractual restructuring is required.

From a policy perspective, the study reinforces that the effectiveness of public investments in photovoltaic generation depends not only on expanding installed capacity, but also on preserving the performance and value of these assets after installation. Operation and maintenance governance should therefore be treated as part of public energy policy, since inadequate post-installation management may reduce energy savings, increase corrective costs, extend payback periods, compromise transparency, and weaken the expected environmental and economic benefits of renewable-energy programs.

From a managerial perspective, the framework may support the preparation of terms of reference, the standardization of technical reports, the definition of performance indicators and service levels, the organization of evidence for contract oversight, and

the evaluation of contractor performance. It may also reduce subjectivity in service acceptance, improve accountability in public procurement, and guide decisions related to corrective measures, payment deductions, contract extensions, and the revision of future photovoltaic O&M contracts.

The study contributes to the sustainable management of public photovoltaic assets by connecting technical performance, contractual governance, public value creation, and life-cycle asset management within a single assessment structure. In this sense, the proposed framework helps public organizations evaluate not only whether contractual obligations have been fulfilled, but also whether the management system is sufficiently mature to sustain the energy, economic, environmental, and institutional outcomes expected from photovoltaic investments.

The main limitation of the study is that the proposed model is based on documentary analysis and a propositional framework. Although the structure was developed from public procurement and O&M contract evidence, future research should apply the indices to a larger sample of public photovoltaic contracts, test the weighting system with expert validation, compare results across different institutional contexts, and associate maturity and compliance levels with operational indicators such as energy generation, availability, failure recurrence, maintenance cost, and avoided emissions.

It is concluded that the integrated assessment of maturity and compliance can strengthen public energy governance by clarifying whether weaknesses are located in procurement design, contract execution, or both. By providing a structured basis for improving photovoltaic O&M contracts, oversight practices, and asset management decisions, the model may help public organizations preserve the long-term energy, economic, environmental, and institutional benefits associated with photovoltaic generation.

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