

Governance and operational management of public photovoltaic systems: A decision support framework for decentralized installations

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Abstract

This study proposes PMOC Solar, a decision-oriented management framework for decentralized public photovoltaic systems, designed to strengthen operation and maintenance (O&M), contractual governance, operational sustainability, and public-sector decision-making. An applied mixed-methods approach combined technical and normative review, documentary analysis of procurement records from the Brazilian National Public Procurement Portal, assessment of O&M and cleaning contracts, and calculation of normalized cost–energy indicators. The findings reveal a limited number of active contracts and substantial heterogeneity in scope, pricing, and technical requirements. The absence of standardized performance indicators emerged as a major weakness for the long-term operational sustainability of photovoltaic assets. Normalized costs ranged from BRL 25.87 to BRL 650.09/kWp-year and from BRL 15.85 to BRL 491.74/MWh. PMOC Solar was structured around five dimensions: technical registry, monitoring and performance indicators, preventive and predictive maintenance, operational and document management, and continuous performance assessment. The study contributes to infrastructure and utility governance by translating dispersed technical, operational, and contractual evidence into a structured lifecycle management framework for decentralized public photovoltaic assets. Its originality lies in linking asset performance, procurement practices, and contractual oversight to support more consistent lifecycle management of public photovoltaic infrastructure.

Keywords: distributed generation; life-cycle management; cost-energy assessment.

Highlights

- Brazilian public PV O&M contracts show wide cost and technical heterogeneity.
- No assessed contract included standardized performance indicators.
- PMOC Solar integrates technical, contractual and economic management.
- Normalized O&M costs varied from BRL 25.87 to 650.09 per kWp-year.
- The framework supports auditable lifecycle management of public PV assets.

1. Introduction

The expansion of photovoltaic generation in public institutions has increased the need to ensure not only the economic feasibility of these investments but also their long-term operational sustainability, particularly in public buildings and universities (Silva et al., 2024). However, selected studies indicate that the operational stability of these systems depends not only on initial installation conditions but also on the ability to monitor losses, perform timely interventions, and continuously assess the effectiveness of contracted services. In operational systems, relatively simple O&M actions, such as periodic cleaning, visual inspections, and inverter checks, have already demonstrated the potential to increase energy production and reduce losses that, in some cases, exceed 10% of expected annual generation (Iftikhar et al., 2021). Additionally, a Brazilian field study identified losses between 22% and 56% associated with soiling, hotspots, and previously undetected failures in public buildings with photovoltaic systems (Costa

et al., 2021). These findings show that the problem is not restricted to photovoltaic technology itself but also concerns how the assets are monitored, maintained, and governed over time.

Within the current state of knowledge, the selected studies converge around three groups of evidence is observed. The first shows that performance loss results from multiple and progressive operational failures, requiring structured monitoring strategies (Jordan and Kurtz, 2013). The second demonstrates that O&M assessment must be supported by objective indicators, for example, KPIs distributed between energy performance and O&M services (Rediske et al., 2024a). Also, the absence of systematic financial control compromises the economic viability of projects (Rediske et al., 2024b). The third group, focused on soiling, shows that cleaning should not be treated as a fixed, undifferentiated routine. Synthesized findings for this group indicate that losses due to dirt are relevant, variable, and site-dependent; monitoring through soiling ratio is appropriate to support the timing of cleaning; dry periods favor loss accumulation and rainfall events may partially restore performance; and the optimal decision should consider both monitoring and techno-economic rationality (Bessa et al., 2021; Ilse et al., 2019; Mejia and Kleissl, 2013; Muller et al., 2017; Schill et al., 2022)

Barriers to the adoption of renewable energy technologies remain a critical issue, particularly in institutional environments where regulatory complexity, financial constraints, and governance challenges affect implementation. Recent studies highlight that beyond technical feasibility, organizational, contractual, and policy-related factors play a decisive role in the effective deployment of solar systems, reinforcing the need for structured management and decision-support frameworks to enhance performance and scalability (Kharoubi et al., 2026; Molepo et al., 2026; Prasad et al., 2025).

These studies indicate a lack of standardized technical parameters for scope, oversight, performance targets, and economic proportionality in procurement. The central gap lies at the intersection of these two levels of evidence. On one hand, the selected studies demonstrate that energy losses, operating costs, and intervention decisions can be better managed using technical, energy, operational, and financial indicators, with particular emphasis on the specificity of soiling monitoring and the techno-economic assessment of cleaning. On the other hand, the analysis of public contracts shows that these elements still do not consistently involve management and oversight practices for decentralized public photovoltaic plants (Bosman et al., 2026). Additionally, in the Brazilian context, there is no normative instrument equivalent to the Brazilian PMOC (*Plano de Manutenção, Operação e Controle*), which is a maintenance, operation and control plan for air-conditioning systems. In Brazil, a federal law makes the PMOC mandatory for public and collective use buildings with air conditioning systems. This regulatory gap for photovoltaic systems further widens the disconnect between available technical knowledge and its integration into public sector routines for operation, maintenance, and control.

Against this background, this study aims to present and discuss a structured instrument for the management of the operation, maintenance, and control of decentralized public photovoltaic plants, called PMOC Solar. It integrates normative requirements, performance indicators, preventive and predictive maintenance routines, and technical and economic criteria to support decision-making, particularly for initiating cleaning services and improving contract management. Under these conditions, PMOC Solar emerges not merely as a terminological adaptation, but as a technical and managerial response to the need to convert dispersed evidence into an integrated, traceable, and applicable framework suited to the institutional reality of public administration.

2. Theoretical Background

The theoretical foundation of PMOC Solar is based on the understanding that the operation and maintenance of photovoltaic plants is central for preserving energy performance, operational reliability, and the economic sustainability of systems throughout their life cycle. The literature reviewed shows that performance losses in photovoltaic plants are linked to technical failures, premature module degra-

dation, soiling accumulation, inverter failures, string disconnections, and insufficient monitoring, indicating that the actual efficiency of these systems depends on systematic O&M strategies, not just on the quality of design and initial installation (Jordan and Kurtz, 2013; Orosz et al., 2024). Additionally, relatively simple operation and maintenance practices, such as periodic cleaning, visual inspections, and verification of inverter operation, can generate significant production gains, while the absence of these routines can cause substantial losses, including values between 22% and 56% in the Brazilian context analyzed through thermographic inspection and corrective cleaning (Costa et al., 2021; Iftikhar et al., 2021).

This understanding becomes even more relevant when considering the Brazilian regulatory framework for photovoltaic systems. The Brazilian standards ABNT NBR 16690 (IEC 62548) and ABNT NBR 16274 (IEC 62446) represent significant advances by establishing requirements for the design, installation, commissioning, initial inspection, and technical documentation of grid-connected systems. However, both standards focus mainly on the initial phases of the project and have limitations regarding guidelines for long-term performance monitoring, preventive maintenance, predictive maintenance, and systematic monitoring of failures and degradation. Thus, although they help ensure initial performance, these standards do not provide an adequate framework for the continuous operational management of plants, especially in the public sector, where the lack of objective criteria undermines contract inspection, results assessment, and the sustainability of investments (Bansal et al., 2021; Jordan and Kurtz, 2013).

A second essential theoretical axis of PMOC Solar involves management by performance indicators. The analyzed literature highlights that the lack of standardized indicators undermines the ability to identify performance losses, recurrent failures, and progressive degradation, and that many projects still rely solely on monthly energy generation, which is insufficient for consistent technical diagnosis. To address this gap, (Rediske et al., 2024a) propose a structured set of 25 indicators organized into energy performance and O&M services, including specific yield, performance ratio, operational availability, losses due to unavailability, failure frequency, mean time to repair, and compliance with executed services. Additionally, the financial dimension must also be integrated into this assessment, as the lack of systematic control over operating costs compromises the long-term economic viability of projects (Ayora et al., 2023; Rediske et al., 2024b).

Within this set of indicators, special emphasis is placed on the Performance Ratio due to its high practical utility. PR is considered a high-impact, low-effort implementation indicator, is included in Brazilian standards, and is required for operation and maintenance contracts. This gives it strategic importance as a summary metric of overall plant performance. However, although indispensable, PR alone is not sufficient to explain all observed losses, which justifies adopting a broader monitoring and evaluation system, as proposed in PMOC Solar (Agbogla et al., 2025; Sa'ad et al., 2021).

Another key theoretical foundation of PMOC Solar concerns the treatment of photovoltaic module cleaning as a technical, economic, and contractual issue, since dirt directly affects electricity production and the indiscriminate use of fixed cleaning schedules tends to be inefficient. Soiling losses are variable and highly dependent on location, rainfall regime, emission sources, module tilt, and operating conditions. The syntheses presented in the study indicate that dirt mitigation must consider the local context and that cleaning decisions should be guided by monitoring and techno-economic criteria rather than by fixed schedules alone (Ilse et al., 2019; Mani and Pillai, 2010; Mejia and Kleissl, 2013; Schill et al., 2022).

In this context, PMOC Solar is based on the proposal of a specific indicator to trigger cleaning, rather than relying solely on overall efficiency decline. Using PR alone as a trigger for cleaning is limited because decreases in this indicator can result from thermal effects, shading, unavailability, string and inverter failures, degradation, sensor drift, and inconsistencies in the reference model. Therefore, the literature recommends using dedicated soiling measurements to isolate the effect of dirt and reduce the risk of incorrect contractual decisions. At this stage, the Soiling Ratio (SR), obtained through a soiling station, is identified as the most objective and auditable metric for supporting cleaning decisions, as it

enables comparison between a clean reference device and one exposed to natural dirt accumulation (Bessa et al., 2021; Muller et al., 2017; Schill et al., 2022).

The justification for using SR is also based on the need to combine technical precision with contractual governance, as cleaning in decentralized public plants should be triggered by two complementary criteria: a technical trigger, based on persistent evidence of significant soiling, and an economic trigger, based on the balance between recoverable energy benefit and intervention cost. This approach aligns with evidence that dry periods promote daily dirt accumulation, rainfall can partially restore performance, and soiling mitigation should be optimized by balancing recoverable energy and cleaning costs. Thus, PMOC Solar should incorporate a theoretical foundation that integrates monitoring, cost-effectiveness, and contractual auditing within the same decision-making framework (Ilse et al., 2019; Mejia and Kleissl, 2013).

Another theoretical pillar of PMOC Solar lies in the incorporation of predictive maintenance and continuous monitoring as management guidelines. International literature has advanced techniques based on continuous monitoring, the Internet of Things, SCADA systems, electrical signal analysis, thermography, and machine learning algorithms to predict failures and optimize photovoltaic asset management. Although implementation barriers remain, especially in institutional environments with technical and organizational limitations, these approaches reinforce the understanding that efficient O&M management should be guided not only by correcting failures that have already occurred but also by the ability to anticipate anomalies and reduce losses before they materialize (Casalta et al., 2024; Kull et al., 2025; Ledmaoui et al., 2025). This perspective is incorporated into PMOC Solar by including specific areas for monitoring, preventive maintenance, and predictive maintenance, coordinated with performance history and adopted indicators (Abdulla et al., 2024; Rojas et al., n.d.).

At the organizational level, PMOC Solar is also supported by Lean philosophy and PDCA cycle logic, originally associated with waste elimination, process standardization, continuous improvement, and value maximization for the end user. This perspective was adopted as the conceptual basis for structuring PMOC Solar. In public photovoltaic plants, it allows prolonged equipment downtime, lack of feedback from performance data, recurrence of failures, and absence of systematic review of O&M procedures to be interpreted as waste. Thus, PMOC Solar is not conceived as a static instrument but as a dynamic system of planning, execution, verification, and corrective action, consistent with the continuous improvement (Pingulkar et al., 2024) and explicitly incorporated into the model validation stage.

3. Methodology

For methodological purposes, the term decentralized photovoltaic plants refers here to public-sector PV systems installed on rooftops, parking structures, institutional land, or adjacent ground areas, whose operation is directly linked to local public consumption or administrative energy compensation arrangements. Thus, decentralization is defined not only by installed capacity, but also by the asset's institutional embedding and operational linkage to specific public facilities, excluding utility-scale plants primarily intended for commercial power generation.

The research was organized into sequential stages. In the first stage, a technical, bibliographic, and normative review was conducted, examining Brazilian and international standards applicable to photovoltaic systems, scientific literature on operation and maintenance, performance indicators, predictive maintenance, institutional documents and public audit reports. This stage provided the conceptual basis for defining PMOC Solar axes, selected indicators, and analytical criteria used in later stages.

In the second stage, a documentary mapping of decentralized public photovoltaic plants and their operation, maintenance, and cleaning contracts was conducted. The Brazilian National Public Procurement Portal (PNCP) served as the primary data source, with searches targeting current contracts related to the maintenance, cleaning, and operation of photovoltaic plants. The survey focused on public agen-

cies of various sizes and institutional contexts to identify how services have been contracted and executed. The PNCP search used keywords related to photovoltaic plants, cleaning, and panels, followed by screening to select contracts specifically linked to small and medium-scale decentralized plants.

Given that the documentary material revealed limitations in standardizing contractual object descriptions, the possibility of underreporting contracts related to operation and maintenance was acknowledged, especially when these services were included in broader building maintenance or energy-efficiency contracts. Even so, the contracts found were organized by contracting agency, object, modality, value, and scope of services to enable comparisons among different public procurement arrangements.

In the third stage, a technical, operational and economic assessment of the identified contracts was conducted. Technical and financial data of the plants were extracted from the contractual documents, focusing on nominal installed capacity and costs associated with the contracted services. The expected annual energy for each system was estimated using regional PV yield data from the Brazilian Solar Energy Atlas, with annual yield determined by the geographic location of the public agency. Based on these values, expected annual energy was calculated, and for analytical consistency, average monthly energy was derived.

Decision-support frameworks for maintenance should consider not only failure occurrence but also asset criticality, downtime consequences, data availability, diagnostic capability and organizational resources (Goli et al., 2025). These principles were incorporated into PMOC Solar through proportional requirements and differentiated monitoring strategies according to plant size and operational relevance.

Data collection considered contracts in force in January 2026, including records that allowed identification of: (i) contractual amount and duration; (ii) scope of service; and (iii) characteristics of the photovoltaic asset (installed capacity and/or information enabling inference of energy potential). When necessary, additional information was obtained from documents attached to the record itself (such as terms of reference, bidding documents, contracts, and technical annexes). Contracts were included if they met all of the following criteria: explicit association with a photovoltaic plant or system; presence of contract value and duration, or elements sufficient to annualize cost; and availability of installed capacity (kWp or MWp) and/or minimum parameters for estimating expected annual energy. The following were excluded: contracts without clear identification of the photovoltaic asset; records with incomplete values, missing duration, or unavailable documentation; and procurements not related to O&M or operational services (for example, equipment supply only, without services).

Generation estimates were obtained by region from the Brazilian Solar Energy Atlas (INPE, 2017), using the annual energy yield map expressed in kWh/kWp·year. For each plant, the annual productivity value was assigned based on the agency's geographic location, resulting in a representative annual yield Y_{annual} (kWh/kWp·year). Expected annual energy was then calculated using Equation (1). For compatibility, average monthly energy was calculated as annual energy divided by 12. These indicators make it possible to compare contracts of different sizes on the same technical basis, assessing whether the procurement shows economic coherence relative to the system's expected generation potential.

$$E_{Annual} = \frac{P_{inst} * Y_{annual}}{1000} \quad (1)$$

Where E_{annual} is the expected annual energy generation (MWh/year), P_{inst} is the installed nominal power of the photovoltaic plant (kWp), and Y_{annual} is the annual energy yield assigned according to the plant location (kWh/kWp·year).

Consequently, the core diagnostic analysis uses indicators relating contractual expenditure to the asset's energy potential:

Normalized cost per installed capacity (BRL/kWp·year)

$$I_{kWp} = \frac{C_{annual}}{P_{inst}} \quad (2)$$

Normalized cost per expected annual energy (BRL/MWh).

$$I_{MWh} = \frac{C_{annual}}{E_{annual}} \quad (3)$$

Where I_{kWp} is the normalized annual cost per installed capacity (BRL/kWp·year), I_{MWh} is the normalized annual cost per expected annual energy (BRL/MWh), and C_{annual} is the annual contractual cost (BRL/year).

Alongside the quantitative analysis, bidding documents, terms of reference, and other contracted related documents were qualitatively reviewed for the presence of minimum technical elements of O&M management, such as scope of services, measurement and verification criteria, objective indicators of operational performance, oversight requirements, and documentary traceability mechanisms. This review was used to identify governance weaknesses, information asymmetries, and a lack of uniform technical parameters among contracts, which supported the development of the instrument PMOC Solar.

In the fourth stage, PMOC Solar was developed as a technical-managerial artifact using a design science research approach. The instrument was structured by integrating normative requirements, scientific literature, and empirical evidence from the documentary diagnosis. Its formulation was organized into management axes, indicators, and operational procedures, covering plant characterization and technical registration, monitoring and performance indicators, preventive and predictive maintenance planning, operational and document management, and continuous performance assessment. Energy, operational, financial, and maintenance indicators consistent with the reviewed standards and literature were also incorporated. As an outcome of this stage, an assessment matrix was proposed for diagnosing public photovoltaic plants, featuring technical criteria, an ordinal scoring scale, verifiable evidence, and links to standards and indicators. This matrix was designed as a practical tool to assess the degree of technical, operational, and managerial compliance of plants with PMOC Solar principles, enabling the identification of gaps, risks, and opportunities for improvement.

The research also adopted the principles of Lean philosophy and the PDCA cycle, using them as a conceptual basis to organize the instrument and interpret the continuous improvement of public photovoltaic plant management. This methodological choice supported the logic of planning, execution, verification, and corrective action incorporated into PMOC Solar, ensuring that the proposed model would not be limited to diagnosis but would also provide an evolutionary framework for performance management and contractual improvement.

In summary, before presenting the integrated proposal (PMOC Solar), a preliminary diagnostic assessment of Brazilian public contracts for the operation, maintenance, and cleaning of decentralized photovoltaic power plants was conducted in order to examine how current contractual practices support the hypothesis and central rationale of this study. Therefore, the diagnostic assessment serves as the analytical foundation for the PMOC Solar proposal, as it reveals, within the real context of public administration, technical, operational, and governance gaps that justify the need for a structured management instrument for public photovoltaic assets.

4. Results and Discussion

Initially, keywords such as photovoltaic plant, cleaning, and panels were used to identify maintenance and cleaning contracts for medium- and small-scale decentralized plants. Many results referred to contracts for very small systems, such as public libraries or small schools, which are not the focus of this study. As a result, only five current maintenance or cleaning contracts for decentralized plants were found in Brazil. The results of this search are presented in Table 1.

Table 1. Contracts made available in the PNCP in 11/2025

Agency		Object	Year	Value
IFRS		Hiring of a specialized company to clean the photovoltaic plants on IFRS campuses.	2024	BRL 119,188.26
Army	Command	Technical cleaning and preventive maintenance of 6,086 photovoltaic modules installed at the Army General Headquarters Solar Photovoltaic Plant.	2024	BRL 55,869.48
Ouro Verde do Oeste	City	Cleaning of 175 modules of 560 W. Note: all instruments and materials required for the service shall be the contractor's responsibility.	2025	BRL 25,640.00
Itajaí	City Council	Cleaning and predictive, preventive, and corrective maintenance services for a 168.40 kWp photovoltaic solar plant, with 526 photovoltaic modules.	2025	BRL 23,950.00
Acre	Court of Justice	Preventive and corrective operation and maintenance of photovoltaic plants installed in units belonging to the Judiciary of the State of Acre (524 kWp + 264.6 kWp + 103 kWp + 66 kWp).	2025	BRL 622,521.52

These results raise both scientific and management-related questions. The contracts show very different values; even when proportionality is considered in relation to capacity or number of panels, a substantial value gap persists. Therefore, it was necessary to examine the specifications of each contract in greater depth to enable comparisons and relationships. The titles in the second column correspond exactly to the contractual objects described in the PNCP documents. It is also clear that there are no long-term contracts currently in force, a situation that requires explanation and may indicate problems during contract execution or poorly planned procurements.

Two of the five contracts are exclusively for cleaning services, excluding maintenance and operation: IFRS and the Municipality of Ouro Verde do Oeste. Both contracts establish a fixed cleaning routine, with no triggers based on efficiency, financial, or maintenance indicators. Preventive maintenance is therefore limited to cleaning, as these agencies do not have maintenance contracts. This raises the question of whether these agencies perform preventive and corrective maintenance themselves; if not, the lack of maintenance tends to reduce equipment life, decrease efficiency, and allow the degradation of public assets.

The remaining contracts, which include maintenance and cleaning, also show inconsistent values. This suggests that the contracts are not based on uniform technical principles but rather on the discretion of public administration. This initial assessment aims to characterize the current situation in order to develop recommendations for public agencies and provide a scientific basis for such procurements.

Since the purpose of photovoltaic plants is electricity generation, and one of the goals is to achieve cost savings on electricity bills, a calculation was performed below based on the capacity of each plant. This estimates the electricity generated by each plant assuming ideal operational conditions. Using the cost of electricity, it is possible to interpret the cost-loss relationship and analyze economic benefits. Table 2 presents several data for the plants and the normalized cost by nominal plant power and expected annual energy.

Table 2. Cost-energy proportionality of contracts

Agency	P_{inst} (kWp)	Y_{annual} (kWh/kWp ·year)	E_{annual} (MWh/ year)	C_{annual} (BRL/ year)	Contract/ economy ratio (%)	I_{kWp} (BRL/k Wp·year)	I_{MWh} (BRL/ MWh)
IFRS (RS)	1,593.0	1,274	2,029.48	119,188.26	8.39	74.82	58.73
Army Com- mand (DF)	2,160.0	1,632	3,525.12	55,869.48	2.14	25.87	15.85
Municipality of Ouro Verde do Oeste (PR)	98.0	1,501	147.10	25,640.00	26.82	261.63	174.31
Itajaí City Council (SC)	168.4	1,359	228.86	23,950.00	14.95	142.22	104.65
Acre Court of Justice (AC)	957.6	1,322	1,265.95	622,521.52	62.25	650.09	491.74

Based on Table 2, there is a clear percentage discrepancy between the value of the maintenance and/or cleaning contract and the savings generated by the photovoltaic plant. Only the Army Command contract has a ratio below 5%, which is a favorable level for maintaining and justifying the continued operation of the plant. However, the city of Ouro Verde do Oeste plant shows a ratio of approximately 27%, and the Acre Court of Justice plant has a ratio of 62%. These values were calculated assuming perfect operation, a hypothetical and overestimated scenario that does not account for unavailability or degradation. Thus, this ratio could exceed 70%, which is alarming for plant managers.

Table 2 also presents the cost–energy proportionality indicators defined in the methodology, calculated for each agency. Comparing contracts using normalized indicators reveals significant variation in the proportionality between contractual expenditure and the nominal electrical capacity of the analyzed photovoltaic systems. The normalized cost by nominal power (I_{kWp}) varies from BRL 25.87/kWp·year (Army Command) to BRL 650.09/kWp·year (Acre Court of Justice), while the normalized cost by annual energy (I_{MWh}) ranges from BRL 15.85/MWh to BRL 491.74/MWh, representing a difference of more than one order of magnitude. This heterogeneity persists even after normalization by system size and estimated annual energy, indicating that the differences are not explained solely by installed capacity, but possibly by different contracting structures and technical specifications.

In particular, the Acre Court of Justice contract stands out as an extreme case, with a cost ratio about 30 times higher than the lowest value observed, suggesting a misalignment between service cost and expected energy benefit. Although some variation may be justified by expanded scope, logistics, operational criticality, service levels, and local conditions, the magnitude of these discrepancies reinforces the hypothesis that uniform technical parameters are lacking, such as standardized scope, performance and availability targets, measurement and verification criteria, and objective oversight mechanisms. Thus, the quantitative results support the interpretation that contracts lacking robust technical requirements tend to produce pricing that is not proportional to actual electricity generation, increasing recurring O&M costs and compromising system cost-effectiveness.

As discussed elsewhere, among the financial indicators of operation analyzed, the Maintenance Expense Index is statistically the most significant for a plant's financial impacts (Rediske et al., 2024b). Analysis of the bidding documents and terms of reference for these procurements shows that none of the contracts reviewed include objective operational performance indicators, such as availability rate, Performance Ratio (PR), or maximum annual degradation limits, which weakens control over the effectiveness of contracted maintenance.

The analysis of contracts available in the PNCP also allows identification of potential governance weaknesses resulting from information asymmetry between the Public Administration and specialized suppliers. In operation and maintenance contracts for photovoltaic plants, the technical knowledge needed to properly specify services, inspection routines, performance criteria, and quality parameters is highly specialized, which may put public managers at a disadvantage compared to contractors.

The literature on public contracts and governance indicates that information asymmetry is a major cause of inefficiency in contracts for specialized technical services, especially when contractual objects are complex and subject to operational uncertainty. In the electricity sector, particularly in photovoltaic systems, this asymmetry is worsened by rapid technological change and the lack of specific technical training in many public agencies.

This condition tends to worsen when there are no objective performance indicators or independent contractual verification mechanisms, creating an environment where services may be contracted that are oversized, undersized, or technically inadequate. The lack of metrics such as operational availability, performance, and annual degradation limits hinders contractual oversight and compromises the Administration's ability to assess the effectiveness of maintenance performed (IEC 61724-1, 2017).

Therefore, the lack of instruments to mitigate information asymmetry undermines contract management efficiency and may lead to economic losses, reduced asset lifespan, and progressive degradation of public photovoltaic plants, a situation contrary to the principles of efficiency and cost-effectiveness established in Brazilian public administration (Matas et al., 2025).

Although there is no consolidated national guideline establishing ideal cost parameters for the operation and maintenance of photovoltaic plants in the public sector, technical studies and international experience indicate that annual O&M costs represent a relatively small share of the economic benefits from electricity generation. According to the International Energy Agency (Singh et al., 2024) and the National Renewable Energy Laboratory (NREL, 2021), typical O&M costs for medium- and large-scale photovoltaic systems are generally 1% to 3% of the annualized initial investment, or only a few percentage points of the annual savings generated.

Given this understanding, the results in Table 2 show significant discrepancies among the contracts analyzed. Some contracts demonstrate a relationship between maintenance cost and generated savings consistent with economically rational operation, while others exceed thresholds that could compromise the plant's economic viability over its life cycle. This is especially relevant because the calculations adopted optimistic generation assumptions, ignoring losses from dirt, module degradation, and periods of unavailability, factors well documented in the technical literature (Chalgynbayeva et al., 2022; Jordan and Kurtz, 2013).

In this context, maintenance contracts whose cost represent a high fraction of a plant's potential savings tend to conflict with the principle of cost-effectiveness, highlighting the need for clearer and more standardized technical criteria to define the scope and value of these services. The diagnosis shows that the models currently used to contract cleaning, operation, and maintenance services for photovoltaic plants in the Brazilian public sector are heterogeneous and lack technical, economic, and institutional standardization. The analysis demonstrates the absence of uniform criteria for defining scope, contract duration, performance indicators, and cost limits, resulting in contracts with significantly different values and service levels for assets of a similar nature.

Given this scenario, the need to move toward the development of technical and governance guidelines to guide the procurement of operation and maintenance services for photovoltaic plants in the public sector becomes evident. Therefore, there is a gap for proposing technical, economic, and institutional parameters capable of supporting public agencies in structuring more efficient contracts aligned with the principles of efficiency, cost-effectiveness, and long-term sustainability.

4.1 Maintenance, Operation, and Control Plan (PMOC SOLAR)

The primary outcome of this study is the PMOC Solar proposal (Maintenance, Operation, and Control Plan for Decentralized Solar Plants in Public Agencies), designed as a technical and managerial

tool to organize the operation, maintenance, monitoring, and continuous performance assessment of public photovoltaic plants. Its development addresses the gap in the Brazilian context of a framework equivalent to the PMOC already established for air-conditioning systems, even though photovoltaic plants also require minimum maintenance routines, performance criteria, technical responsibilities, and oversight mechanisms. Thus, PMOC Solar represents an innovation in the management of public photovoltaic assets, integrating normative requirements, empirical evidence, and operational control tools.

The relevance of this proposition is supported by the analysis of the public contracts reviewed. The documentary survey identified only five current maintenance and/or cleaning contracts for decentralized photovoltaic plants, showing significant variation in scope, value, and technical criteria. In two cases, the contracts covered only cleaning services at fixed intervals, without triggers based on performance, financial, or maintenance indicators. Additionally, none of the contracts included objective operational performance indicators, such as availability, performance ratio, or maximum annual degradation limits, which undermines control over the effectiveness of contracted maintenance. These findings highlight the lack of uniform technical parameters for contracting and oversight, underscoring the need for a structured plan such as PMOC Solar.

4.2 General structure of PMOC Solar

PMOC Solar was designed as a dynamic, adaptable, and cyclical management system suitable for plants of various sizes and different institutional contexts in the public sector. Its structure organizes plant management into five main, interdependent axes. This setup enables the integration of normative requirements, O&M practices, documentary evidence, and continuous improvement within a single management framework. The five axes are:

- I. characterization and technical registration of the plant;
- II. monitoring and performance indicators;
- III. preventive and predictive maintenance planning;
- IV. operational and document management; and
- V. continuous evaluation and performance improvement.

The first axis, characterization and technical registration of the plant, establishes the baseline for the photovoltaic asset. It collects information such as installed capacity, system topology, arrangement and inverter configuration, geographic location, environmental characteristics, commissioning date, and required technical documentation. This axis is essential because it links the operational phase to the design and commissioning conditions, enabling technical traceability and future performance comparison.

The second axis, monitoring and performance indicators, forms the analytical core of PMOC Solar. It calls for systematic monitoring of the plant using energy, operational, maintenance, and financial indicators, including specific yield, Performance Ratio (PR), operational availability, expected versus generated energy, failure frequency, mean time to repair, and O&M cost per unit of power or energy. In this way, the plan transcends the limited practice of evaluating plants solely by monthly energy generated and introduces an objective basis for diagnosis, oversight, and decision-making(Thakfan and Bin Salamah, 2025).

The third axis, preventive and predictive maintenance planning, organizes intervention routines in stages. The proposal includes visual inspections, scheduled cleaning or cleaning triggered by indicators, verification of electrical connections, thermographic inspections, analysis of operational data, and remote monitoring to identify trends in failure and degradation. Thus, PMOC Solar shifts management from a predominantly corrective approach to a preventive and predictive approach that better aligns with the reliability required for public assets(Pratticò et al., 2025a).

The fourth axis, operational and document management, directly addresses a recurring weakness in the public contracts analyzed: the low standardization of records and evidence. In this axis, PMOC

Solar establishes the need for maintenance plans and schedules, inspection and intervention reports, records of failures and unavailability, energy performance history, and consolidated reports for oversight and auditing. The result is a model with greater transparency, traceability, and institutional control capacity.

The fifth axis, continuous evaluation and performance improvement, gives PMOC Solar an evolutionary character. The proposal states that indicator results, technical inspection findings, and operational audits will be used to revise procedures, adjust maintenance plans, update contracts, and incorporate new monitoring technologies. Thus, the plan not only standardize routines but also creates a permanent mechanism for feedback and improvement in photovoltaic asset management.

Table 3 summarizes the structure of the PMOC Solar by linking each proposed axis to the relevant technical standards, adopted performance indicators, and empirical evidence used in mapping and diagnosing of photovoltaic power plants in public agencies. This integrated approach aligns regulatory requirements, technical monitoring, operation and maintenance practices, thereby strengthening performance management throughout the life cycle of these installations.

Table 3. Macro-structure of the PMOC Solar

PMOC Solar Axis	Associated Standards and Technical References	Performance Indicators	Evidence Used in the Diagnosis
1. Plant Characterization and Technical Registration	ABNT NBR 16690 (2019); (IEC 62548); ABNT NBR 16274 (2014) (IEC 62446); Law No. 14,300/2022	Installed capacity (kWp); system configuration; commissioning date; generation baseline	Detailed engineering designs; electrical diagrams; commissioning reports; public agency asset records
2. Monitoring and Performance Indicators	ABNT NBR IEC 61724 (2017); (Dhimish, 2020; Rediske et al., 2024a, 2024b)	Specific yield (kWh/kWp); Performance Ratio (PR); operational availability; expected vs. generated energy	Monitoring system data; monthly/annual generation records; fault histories; operational reports
3. Preventive and Predictive Maintenance Plan	ABNT NBR 16274 (inspections); international O&M literature; (Abdulla et al., 2024; Jordan and Kurtz, 2013; Praticò et al., 2025b; Rajput et al., 2024)	Inspection frequency; mean time to repair (MTTR); number of recurring failures; preventive vs. corrective interventions	Visual and thermographic inspection reports; cleaning records; work orders; intervention history
4. Operational and Documentary Management	ABNT NBR 16274 (documentation); public asset management principles	Compliance with the O&M plan; documental completeness; traceability of actions	Maintenance plans; O&M contracts; technical reports; administrative and inspection records
5. Continuous Performance Evaluation and Improvement	ABNT NBR IEC 61724;(Dhimish, 2020; Rediske et al., 2024a)	PR trend; avoided losses; O&M cost per kWh; performance before/after interventions	Comparative time-series analyses; consolidated performance reports; financial and energy indicators

Accordingly, this PMOC Solar axis is based on the principle of continuous improvement applied to photovoltaic asset management, inspired by Lean approaches originally developed for production process management but gradually adapted to the energy sector. Applying Lean principles in solar projects enables the identification of operational waste, reduction of recurring failures, and promotion of ongoing cycles of technical and managerial performance improvement (Pingulkar et al., 2024). In public photovoltaic power plants, such waste appears, for example, as prolonged equipment unavailability, lack of feedback from performance data, and repeated occurrence of previously identified failures. Therefore, Axis 5 of the PMOC Solar is structured as a permanent feedback mechanism, using the results of performance indicators, technical inspections, and operational audits for the periodic review of procedures, updating of maintenance plans, and improvement of contractual and governance instruments, in line with the concept of continuous improvement advocated by (Pingulkar et al., 2024).

4.3 Indicators and operational criteria incorporated into PMOC Solar

A distinguishing feature of PMOC Solar is the central role given to performance indicators as the foundation for management and oversight. The proposal includes energy, operational, maintenance, and financial indicators aligned with technical standards and the reviewed literature. Among these, the Performance Ratio (PR) stands out, identified in the source material as a high-impact, low-effort indicator suitable for operation and maintenance contracts and for ongoing assessment of plant performance. However, the plan acknowledges that while PR is strategic, it is not sufficient on its own to explain all losses, so it is incorporated into a broader monitoring system.

In addition to the energy dimension, PMOC Solar includes operational and financial indicators for asset governance. The proposed structure covers failure frequency, mean time to repair, compliance with the maintenance plan, O&M cost per kWp, cost per kWh generated, and the financial impact of unavailability. This combination expands diagnostic capacity and enables the correlation of technical performance with economic rationality, which is especially important in the public sector, where contract oversight and cost-effectiveness are essential.

One of the most original results of PMOC Solar is the proposal of a specific indicator to trigger module cleaning services, replacing the fixed schedule used in some of the contracts analyzed. This proposal is based on the understanding that soiling should not be managed solely by schedule, as losses depend on local variables such as rainfall, dust type, environment, and seasonality. Therefore, the plan recommends using the Soiling Ratio (SR) as an objective and auditable metric to support cleaning decisions, rather than relying only on overall efficiency drops. Cleaning is triggered at two complementary levels. The first is a technical trigger, based on the persistence of relevant soiling loss, avoiding decisions based on daily fluctuations. The second is an economic trigger, grounded in the balance between recoverable energy and total intervention cost. This approach allows cleaning to be treated as a technical, operational, and contractual issue, integrating monitoring, cost-effectiveness, and auditing under a single decision criterion. This analysis is particularly relevant because it addresses a limitation identified in the documentary diagnosis: the adoption of periodic cleaning without specific indicators. By proposing the use of SR and benefit–cost criteria, PMOC Solar improves intervention decisions and reduces the risk of excessive cleaning during rainy periods or delayed cleaning during dry periods, contributing to greater operational efficiency and better service governance.

Although the use of the Soiling Ratio (SR) through dedicated soiling monitoring stations represents the most robust technical approach for isolating soiling losses, its full adoption may not be proportionate or economically justified for all public photovoltaic plants, particularly small-scale systems installed in schools, administrative buildings, or other low-capacity facilities. In such cases, requiring a dedicated station may raise implementation and operating costs to a level inconsistent with the size of the asset, thereby undermining the economic rationale of the management strategy. Under this ap-

proach, small-scale plants may rely on simplified arrangements, such as clean reference modules combined with performance history and meteorological data; medium-scale plants may adopt intermediate solutions based on paired reference and exposed modules with standardized comparison routines; and large-scale or strategically critical plants are more suitably monitored through dedicated soiling stations, given their greater technical robustness, traceability, and contractual usefulness (Agbogla et al., 2025). Table 4 summarizes cleaning strategies proposed based on photovoltaic plant size.

Table 4. Proportional implementation levels of the Soiling Ratio (SR) monitoring

Criterion	Small-scale plants	Medium-scale plants	Large-scale plants
Indicative installed capacity	up to 75 kWp	75 to 300 kWp	above 300 kWp
Recommended monitoring level	Simplified	Intermediate	Advanced
Recommended SR approach	Clean reference module, standardized visual comparison, historical generation analysis, and local/regional meteorological data	Clean reference module plus exposed module, standardized comparison routine, integration with plant monitoring, meteorological records, and performance time series	Dedicated soiling monitoring station with a clean reference device and an exposed device, integrated into the monitoring system
Practical application	Support cleaning decisions based on performance-loss trends, absence of effective rainfall, and periodic field inspection	Enable approximate SR calculation and support technical-economic cleaning decisions	Support formal SR calculation, cleaning-threshold definition, contractual auditing, and prioritization across multiple plants
Main advantages	Low cost, easy implementation, and better suitability for small public assets	Better balance between cost and reliability; feasible for medium-sized public contracts	Higher accuracy, traceability, and robustness for contractual decision-making and oversight
Main limitations / precautions	Lower metrological accuracy; greater risk of confounding with other loss sources; requires standardized documentation and conservative interpretation	Requires routine maintenance of the reference module and greater operational discipline; still less robust than a dedicated station	Higher installation and operating costs; requires metrological maintenance and proper cleaning of the reference device

Another relevant result of the study is the proposal of a PMOC Solar assessment matrix, designed as a diagnostic tool to evaluate the degree of technical, operational, and managerial compliance of public photovoltaic plants. The matrix links assessment criteria, normative and technical references, corresponding indicators, and verifiable evidence, using a scoring scale from 0 to 4. This structure translates the plan's principles into a practical instrument for institutional application.

The suggested assessment scale is:

0 – Nonexistent;

1 – Insufficient;

2 – Partially met;

3 – Met;

4 – Met and systematically documented.

Thus, the evaluated axes can be assessed according to the matrix presented in Table 5.

Table 5. Assessment matrix for solar plants

Axis	Assessment criterion	Normative/ technical reference	Associated indicator	Score (0–4)	Verified evidence
1. Technical Registration	Complete and updated executive design	ABNT NBR 16690 (IEC 62548)	Existence of design compliant with the standard		Design, diagrams
	Commissioning report available	ABNT NBR 16274 (IEC 62446)	Formalized commissioning		Technical report
	Asset registration of the plant	Law No. 14,300/2022	Plant registered as an asset		Agency inventory
2. Monitoring and Performance	Active monitoring system	ABNT NBR IEC 61724	System availability (%)		SCADA platform
	Periodic calculation of PR	ABNT NBR IEC 61724	Performance Ratio		Monthly reports
	Comparison of generated vs. expected energy	(Ahmed Murtaza et al., 2024; Rediske et al., 2024b)	Percentage deviation (%)		Historical series
3. Preventive Maintenance	Formal preventive maintenance plan	PV O&M literature	Inspection frequency		Documented plan
	Periodic module cleaning	Costa et al. (2021)	Soiling losses (%)		Service orders
	Thermographic inspections	(Abdulla et al., 2024; Ahmed Murtaza et al., 2024; Rajput et al., 2024)	Number of anomalies		IR reports
4. Predictive Maintenance	Use of data to detect failures		Anticipated failures		Data logs
	Trend analysis of performance	(Jordan and Kurtz, 2013)	Annual degradation (%)		Time series

5. Operational Management	Designated manager	technical O&M best practices	Formal responsibility	Administrative order/contract
	Record of failures and interventions	ABNT NBR 16274 (IEC 62446)	MTTR / failure frequency	Technical history
6. Document Management	Periodic O&M reports	PMOC Solar (proposed)	Document regularity	Annual reports
	Traceability of actions	Asset management	Document completeness	File system
7. Assessment and Improvement	Periodic performance assessment	ABNT NBR IEC 61724	PR evolution	Comparative reports
	Corrective actions implemented	PMOC Solar (proposed)	Avoided losses	Improvement plan

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Based on the total score, the plant can be classified into maturity levels, ranging from nonexistent or critical management to structured management aligned with PMOC Solar. This classification enables prioritization of interventions, comparison of plants, and support for public management decisions in solar energy. Thus, the matrix broadens the scope of the plan by not only organizing conceptual guidelines but also providing an objective mechanism for diagnosis and monitoring.

4.5 PMOC Solar as a continuous management model

From a conceptual and managerial perspective, PMOC Solar also stands out for explicitly incorporating Lean philosophy and the PDCA cycle as the foundation of its operational logic. In the Plan phase, technical registration, normative requirements, indicators, and contractual instruments are defined; in the Do phase, operation and maintenance routines are executed; in the Check phase, results are verified through indicators, audits, and diagnoses; and in the Act phase, corrections, procedure reviews, and plan updates are implemented. This structure reinforces the systemic nature of the proposed result, positioning PMOC Solar not merely as a technical checklist but as a continuous management model for public photovoltaic assets.

Thus, PMOC Solar is more than an isolated operational proposal. It provides a structured response to a technical, economic, contractual, and institutional problem. Another way to understand the continuous improvement process within PMOC Solar is through the development of the PDCA cycle based on Lean philosophy, as shown in Figure 1. PMOC Solar is structured around the PDCA (Plan–Do–Check–Act) continuous improvement cycle, which is widely used in management systems and adapted to Lean principles for solar projects. In the Plan phase, normative requirements, plant technical registration, performance indicators, and contractual instruments are defined. The Do phase involves executing preventive and predictive operation and maintenance activities, including monitoring and technical inspections.

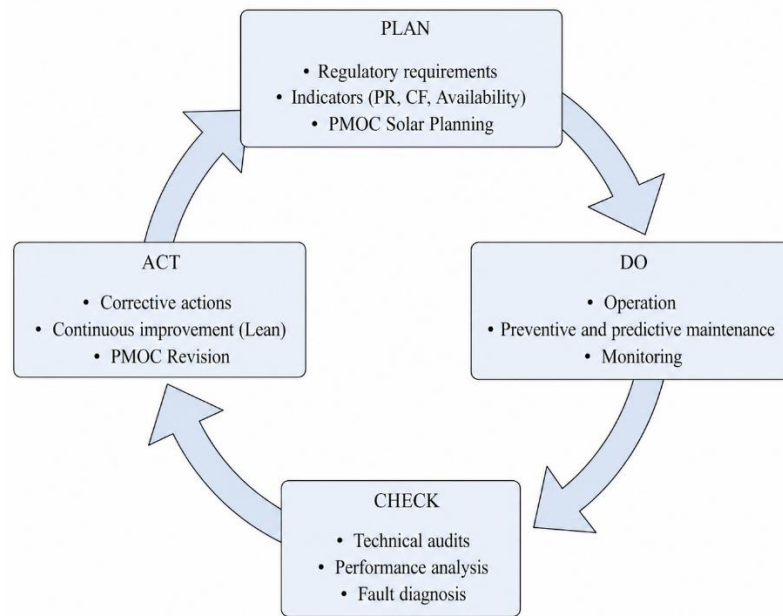


Figure 1. PMOC SOLAR PDCA cycle (author)

In the Check axis, systematic verification of plant performance is conducted using technical indicators, audits, and operational diagnoses. The Act axis consolidates corrective actions and continuous improvement by promoting adjustments to maintenance plans, incorporating lessons learned, and periodically reviewing PMOC Solar. This cycle reinforces the dynamic and evolving nature of public photovoltaic plant management, in line with the continuous improvement principles (Bucea-Manea-Țoniș et al., 2020; Pingulkar et al., 2024; Vieira et al., 2026).

In practical terms, the PMOC Solar is designed to serve as a strategic guideline for procuring and managing contracts with specialized companies responsible for operating, maintaining, and controlling public decentralized photovoltaic power plants. Under this approach, the contracted company must, at the start of the contract, prepare a plant-specific PMOC Solar based on the structure proposed in this article. This plan should define routines, procedures, responsibilities, monitoring methods, and inspection and intervention frequencies according to the technical, operational, and environmental characteristics of each installation. Therefore, instead of being a generic document, the PMOC Solar should be implemented as an integrated and customized management plan for each power plant, guiding service execution, supporting oversight, and ensuring that contractual performance aligns with technical requirements, operational reliability, and long-term economic efficiency.

In terms of public policy implications, the PMOC Solar proposal may contribute to the development of national or state-level public procurement guidelines by promoting a shift in focus: from procurement centered solely on the immediate object to procurement guided by performance, life-cycle cost, and contract execution control mechanisms. This direction is consistent with the international literature, which shows, on the one hand, that performance measurement systems in public procurement increase effectiveness, efficiency, and the diagnostic capacity of contract management (Patrucco et al., 2016; Silva et al., 2024; Wang et al., 2025); on the other hand, that experience in sustainable public procurement favors the internalization of Life Cycle Costing approaches, thereby broadening the incorporation of economic and environmental criteria into tendering processes (Casalta et al., 2024; Patrucco et al., 2016); and, furthermore, that the presence of guidelines, regulatory support, and specific institutional structures is one of the main drivers for the adoption of green procurement practices in the public sector (Singh et al., 2024). In this sense, PMOC Solar could support state regulations, reference manuals, and

standardized procurement documents by establishing minimum parameters for technical asset registration, monitoring, maintenance, inspection, provision of spare parts and consumables, and the technical-economic triggering of cleaning, thereby strengthening the governance of photovoltaic power plant procurement within Public Administration.

5. Conclusions

The study achieved its general objective by proposing and structuring PMOC Solar as a technical-managerial tool for managing the operation, maintenance, and control of decentralized photovoltaic plants in public agencies. The specific objectives were also satisfactorily met: diagnosing existing contracting models, identifying technical and governance weaknesses, selecting indicators for performance monitoring, and organizing these elements into an integrated management model. The results show that the analyzed contracts are heterogeneous, lack technical standardization, and often do not include objective performance indicators, availability targets, or consistent oversight criteria, confirming the need for the proposed tool. In this context, the study's main finding is that PMOC Solar integrates technical registration, monitoring, preventive and predictive maintenance, document management, and continuous evaluation within a single structure, providing a coherent response to the normative and operational gaps identified in the public sector.

Scientifically, the study contributes by shifting the discussion on public photovoltaic plants from an emphasis on installation to a focus on asset life cycle, operational performance, and contractual governance. Methodologically, it advances by combining documentary diagnosis, normalized cost-energy proportionality indicators, a technical-economic trigger for cleaning based on the Soiling Ratio, and a management maturity assessment matrix, transforming scattered evidence into an applicable artifact. Empirically, it demonstrates that the relationship between contractual cost and energy benefit can reach critical amplitudes, with significant dispersion among contracts and indications of a lack of uniform parameters for scope, measurement, and verification. Practically, PMOC Solar can be used by public managers, contract inspectors, audit bodies, and O&M teams to improve bidding documents, standardize routines, strengthen traceability of actions, and support decisions based on performance and cost-effectiveness, promoting the progressive implementation of more efficient and auditable management of public photovoltaic plants.

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