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TECHNICAL GOVERNANCE AND LIFECYCLE MANAGEMENT OF PUBLIC PHOTOVOLTAIC SYSTEMS: EVIDENCE FROM BRAZILIAN O&M CONTRACTS

GOVERNANÇA TÉCNICA E GESTÃO DO CICLO DE VIDA DE SISTEMAS FOTOVOLTAICOS PÚBLICOS: EVIDÊNCIAS DE CONTRATOS BRASILEIROS DE O&M

GOBERNANZA TÉCNICA Y GESTIÓN DEL CICLO DE VIDA DE SISTEMAS FOTOVOLTAICOS PÚBLICOS: EVIDENCIAS DE CONTRATOS BRASILEÑOS DE O&M

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ABSTRACT: This study examines how public governance, accountability, and asset-management principles are incorporated into procurement and contractual instruments for the operation and maintenance of public photovoltaic systems. A qualitative, exploratory-descriptive approach was adopted based on documentary analysis of contracts, tender notices, terms of reference, and complementary documents retrieved from the Brazilian National Public Procurement Portal. The analysis considered service scope, responsibilities, monitoring, performance indicators, risk management, documentation, and lifecycle management. The results revealed substantial heterogeneity among the contracts, with a predominance of task-oriented arrangements, fragmented maintenance activities, and limited use of measurable performance indicators. More comprehensive contracts integrated continuous monitoring, technical reporting, preventive and corrective maintenance, and component supply. The findings indicate that stronger technical governance depends on clearly assigned responsibilities, traceable information, verifiable performance, and lifecycle-oriented decision-making. These elements can support more effective design, supervision, and long-term management of photovoltaic O&M contracts in public organizations and strengthen the preservation of asset value over time.

Keywords: Accountability. Asset management. Contractual governance. Photovoltaic operation and maintenance. Public procurement. Lifecycle management.

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RESUMO: Este estudo examina como princípios de governança pública, accountability e gestão de ativos são incorporados aos instrumentos de contratação e aos contratos de operação e manutenção de sistemas fotovoltaicos públicos. Adotou-se uma abordagem qualitativa, exploratório-descritiva, baseada na análise documental de contratos, editais, termos de referência e documentos complementares obtidos no Portal Nacional de Contratações Públicas. A análise considerou escopo dos serviços, responsabilidades, monitoramento, indicadores de desempenho, gestão de riscos, documentação e gestão do ciclo de vida. Os resultados revelaram forte heterogeneidade entre os contratos, com predominância de arranjos orientados a tarefas, atividades de manutenção fragmentadas e uso limitado de indicadores mensuráveis de desempenho. Os contratos mais abrangentes integraram monitoramento contínuo, relatórios técnicos, manutenção preventiva e corretiva e fornecimento de componentes. Os achados indicam que uma governança técnica mais robusta depende de responsabilidades claramente definidas, informações rastreáveis, desempenho verificável e tomada de decisão orientada ao ciclo de vida, contribuindo para maior efetividade na gestão pública dos ativos fotovoltaicos.

Palavras-chave: Accountability. Gestão de ativos. Governança contratual. Operação e manutenção fotovoltaica. Contratações públicas. Gestão do ciclo de vida.

RESUMEN: Este estudio examina cómo los principios de gobernanza pública, rendición de cuentas y gestión de activos se incorporan en los instrumentos y contratos de operación y mantenimiento de sistemas fotovoltaicos públicos. Se adoptó un enfoque cualitativo, exploratorio-descriptivo, basado en el análisis documental de contratos, pliegos de licitación, términos de referencia y documentos complementarios obtenidos del Portal Nacional de Contrataciones Públicas de Brasil. El análisis consideró alcance de los servicios, responsabilidades, monitoreo, indicadores de desempeño, gestión de riesgos, documentación y gestión del ciclo de vida. Los resultados mostraron heterogeneidad entre los contratos, con predominio de acuerdos orientados a tareas, mantenimiento fragmentado y uso limitado de indicadores medibles de desempeño. Los contratos más amplios integraron monitoreo continuo, informes técnicos, mantenimiento preventivo y correctivo y suministro de componentes. Los hallazgos indican que una gobernanza técnica más sólida depende de responsabilidades claramente definidas, información trazable, desempeño verificable y decisiones orientadas al ciclo de vida, favoreciendo una gestión pública más efectiva de los activos fotovoltaicos.

Palabras clave: Rendición de cuentas. Gestión de activos. Gobernanza contractual. Operación y mantenimiento fotovoltaico. Contratación pública. Gestión del ciclo de vida.

INTRODUCTION

The expansion of distributed renewable generation has led public organizations to increasingly incorporate photovoltaic (PV) systems into administrative buildings, educational institutions, healthcare facilities, courts, and other government-owned infrastructure. These systems are generally implemented to reduce electricity expenditures, improve the efficiency of public resource use, and contribute to environmental and sustainability goals. However, achieving these benefits depends not only on system installation, but also on the institutional capacity to preserve performance, reliability, and asset value throughout the operational life of the systems.

Although photovoltaic systems require relatively limited direct operation, their performance may be affected by soiling, shading, module degradation, inverter failures, electrical connection problems, protection-device faults, and deficiencies in monitoring systems. Some of these conditions produce gradual performance losses that may remain unnoticed without systematic monitoring. In public organizations, these technical requirements may be further complicated by the dispersion of photovoltaic assets across different administrative units and by the fragmentation of responsibilities for planning, procurement, contract supervision, budgeting, and asset management.

Within this context, operation and maintenance (O&M) contracts represent an important technical-governance mechanism. Through contractual instruments, public authorities can define responsibilities, monitoring procedures, reporting requirements, performance criteria, response times, acceptance conditions, and corrective measures. Contract design therefore influences not only service compliance, but also the ability of public organizations to monitor outcomes, manage risks, maintain technical information, and preserve the long-term value of photovoltaic assets.

A central challenge is that technically detailed contracts may remain predominantly task-oriented. Cleaning, inspection, or maintenance activities may be formally completed without evidence that they restored performance, reduced operational risks, or contributed to asset-life preservation. Therefore, contractual compliance does not necessarily imply effective asset management or preservation of the economic and environmental benefits expected from public photovoltaic investments.

Despite the growth of public photovoltaic generation, the literature has focused mainly on economic feasibility, energy performance, degradation, soiling, reliability, and maintenance strategies. Comparatively less attention has been given to O&M contracts and procurement documents as instruments of technical governance, accountability, and lifecycle management. In particular, limited evidence is available on how principles such as performance orientation, information traceability, risk management, and value preservation are translated into verifiable contractual requirements for publicly owned photovoltaic systems.

Against this background, this study addresses the following research question: How are public governance and asset-management principles translated into contractual and procurement instruments for the operation and maintenance of publicly owned photovoltaic systems?

The objective of this study is to assess the extent to which photovoltaic O&M procurement and contractual instruments incorporate principles of technical governance, accountability, and lifecycle asset management. Brazilian public procurement documents are examined with regard to service scope, responsibilities, monitoring practices, reporting requirements, performance indicators, risk management, technical documentation, and control mechanisms.

The study contributes by connecting contractual governance and asset management to the long-term management of public photovoltaic systems. From an applied perspective, it provides a structured assessment of procurement instruments and identifies governance elements that may support the design and oversight of photovoltaic O&M contracts in different public-sector contexts.

THEORETICAL FRAMEWORK

Public governance encompasses the structures, processes, and mechanisms through which public organizations are directed, coordinated, supervised, and evaluated. Its scope extends beyond legal and procedural compliance, involving the definition of public outcomes, allocation of responsibilities, monitoring of decisions, and institutional capacity to generate public value in a legitimate, efficient, and sustainable manner (Osborne, 2006; Almquist et al., 2013; Raschendorfer, Figueira and Furtado, 2023). In increasingly outsourced public-service environments, responsibilities are distributed among contracting authorities, managers, supervisors, service providers, technical professionals, and oversight institutions. Although specific activities may be delegated, the public authority remains responsible for defining objectives, supervising outcomes, and safeguarding the public interest (Osborne, 2006; Almquist et al., 2013).

Within this context, accountability requires actors to inform, explain, and justify their conduct before authorities capable of evaluating outcomes and assigning responsibility. Effective accountability therefore depends on identifiable responsibilities, reliable information, established evaluation criteria, and corrective mechanisms (Bovens, 2007; Koppell, 2005; Fontes Filho and Naves, 2014). Operational records, technical documentation, maintenance histories, and performance indicators become important governance mechanisms because they support traceability, reduce information asymmetry, and allow public organizations to assess whether contracted activities actually contribute to intended outcomes (Fontes Filho and Naves, 2014; Almquist et al., 2013).

This perspective is closely related to asset management, understood as the coordinated set of activities through which organizations derive value from physical assets throughout their lifecycle. Asset management involves balancing performance, costs, risks, and opportunities from planning and acquisition through operation, maintenance, renewal, and decommissioning (Schuman and Brent, 2005; El-Akruti, Dwight and Zhang, 2013; Giglio et al., 2018). A lifecycle perspective recognizes that decisions made during design, procurement, installation, and commissioning affect future maintenance requirements, technological compatibility, monitoring capability, and long-term asset performance (Schuman and Brent, 2005; El-Akruti and Dwight, 2013).

Risk management is therefore an essential component of lifecycle-oriented asset management. Failures, outages, degradation, accidents, and technological obsolescence may compromise the value generated by an asset, and decisions regarding inspection, repair, replacement, or upgrading should consider failure probability, consequences, and available alternatives (Maletič et al., 2020; El-Akruti and Dwight, 2013). Lifecycle cost analysis similarly expands the economic perspective by showing that the lowest initial acquisition or contracting cost may not represent the most advantageous option when operation, maintenance, downtime, replacement, modernization, and decommissioning costs are considered (Roda, Macchi and Albanese, 2020; Schuman and Brent, 2005).

Information management also plays a central role in lifecycle-oriented governance. Technical inventories, updated drawings, commissioning records, failure histories, inspection reports, replaced-component records, warranty information, and performance indicators form the technical memory required for informed decision-making. Without adequate traceability, organizations lose the ability to identify recurrent problems, evaluate previous interventions, compare alternatives, and preserve institutional knowledge over time (El-Akruti and Dwight, 2013; Maletič et al., 2020; Polenghi et al., 2021).

In public service delivery, contracts are among the main instruments through which governance and asset-management principles are translated into operational obligations. Contractual governance defines responsibilities, allocates risks, establishes control mechanisms, and connects service providers to public objectives (Brown and Potoski, 2003a;

Brown, Potoski and Van Slyke, 2006; Siwandeti, Mahuwi and Israel, 2023). Outsourcing does not eliminate the need for state capacity; instead, it increases the importance of procurement planning, specification development, contract monitoring, performance measurement, information systems, and technical competence among public managers and supervisors (Brown and Potoski, 2003a; Brown and Potoski, 2006; Yang et al., 2009).

The governance mechanisms required also depend on the characteristics of the contracted service. Simple and easily measurable activities may be controlled through direct verification of deliverables, whereas technically complex services characterized by uncertainty and information asymmetry require stronger monitoring, performance indicators, independent records, and acceptance criteria (Brown and Potoski, 2003a; Brown and Potoski, 2003b). Contract design should therefore combine clearly defined responsibilities with sufficient flexibility to address unforeseen technical conditions without compromising transparency, accountability, or legal certainty (Poppo and Zenger, 2002; Zheng, Roehrich and Lewis, 2008; Roehrich and Lewis, 2014).

Performance-oriented contractual governance requires verifiable outcomes rather than exclusive emphasis on task completion. Performance indicators, service levels, response times, reporting requirements, and acceptance criteria allow public organizations to assess whether contracted activities contribute to service quality, asset availability, continuity, and operational effectiveness (Brown and Potoski, 2003b; Brown, Potoski and Van Slyke, 2006). For long-lived public assets, these mechanisms should also support lifecycle management by connecting maintenance, monitoring, information management, risk assessment, and future decisions concerning renewal and replacement (Schuman and Brent, 2005; Jordan and Kurtz, 2013; El-Akruti, Dwight and Zhang, 2013).

In the case of public photovoltaic systems, this integration is particularly important because contractual compliance alone does not guarantee that the asset remains reliable, efficient, or capable of delivering the economic and environmental benefits that justified the original investment. Contracts that integrate accountability, technical information, performance monitoring, risk considerations, and lifecycle objectives provide a stronger institutional basis for sustainable public asset management and for the preservation of long-term photovoltaic asset value (Bovens, 2007; Brown, Potoski and Van Slyke, 2006; Maletič et al., 2020).

METHODOLOGY

This study adopted a qualitative, exploratory-descriptive approach based on documentary analysis. The unit of analysis was each public procurement process, considered as the set of documents associated with a specific contract, including contracts, tender notices, terms of reference, and complementary documents made available by the contracting authority.

The documents were retrieved from the Brazilian National Public Procurement Portal (Portal Nacional de Contratações Públicas – PNCP), using combinations of keywords related to photovoltaic cleaning, operation, and maintenance. The search included terms such as "photovoltaic plant", "photovoltaic system", "photovoltaic modules", "photovoltaic cleaning", "photovoltaic maintenance", "photovoltaic operation and maintenance", "preventive maintenance", and "corrective maintenance". Procurement processes were included when they involved a public contracting authority, an installed and operating photovoltaic system, a scope including cleaning, operation, or maintenance activities, and documentation with sufficient technical detail to identify contractual obligations, responsibilities, monitoring requirements, and control mechanisms. Processes referring exclusively to system supply or installation, isolated purchases of materials or components, duplicate records, small-scale installations without comparable operational characteristics, or cases with insufficient technical documentation were excluded.

For each selected procurement process, descriptive information was recorded, including contracting authority, contractual object, year, procurement modality, installed capacity, number of photovoltaic modules, execution period, contract term, and contract value. The documentary content was subsequently analyzed according to categories related to service scope, responsibilities, intervention planning, monitoring, performance indicators, risk and failure management, reporting and traceability, technical documentation, warranties, component replacement, contract supervision, environmental requirements, and lifecycle-value preservation. Coding was based exclusively on requirements explicitly established in the analyzed documents.

The analysis was conducted through individual examination of each procurement process followed by cross-case comparison. Each analytical element was classified as absent, partially incorporated, or clearly incorporated, according to the degree to which the documents established a verifiable requirement, procedure, criterion, or deliverable. The comparative analysis was used to identify recurring patterns and differences among the procurement instruments and to distinguish predominantly task-oriented arrangements from approaches with greater integration of monitoring, technical documentation, performance assessment, risk management, and lifecycle-oriented asset management.

RESULTS AND IMPLICATIONS

The comparative analysis presented in Table 1 revealed uneven incorporation of technical governance and lifecycle-management principles across public photovoltaic O&M procurement arrangements. The analyzed instruments ranged from isolated cleaning services to integrated solutions combining operation, monitoring, preventive maintenance, corrective maintenance, and component replacement. These differences concerned not only the number of activities included in each contract, but also the way responsibilities, information flows, risks, technical outcomes, and future asset-management decisions were structured.

Overall, traditional contract-management mechanisms—such as supervision, service acceptance, payment procedures, sanctions, and liability for damages—were more developed than mechanisms directly associated with long-term photovoltaic performance. Requirements concerning measurable energy-performance indicators, consolidated asset histories, risk-based prioritization, post-intervention assessment, and component-renewal planning were less consistently incorporated.

These findings indicate a relevant distinction between controlling the execution of contracted services and governing the performance of a public asset throughout its lifecycle. Procedural and contractual compliance remains necessary, but does not necessarily ensure that photovoltaic assets continue to deliver the technical, economic, and environmental benefits expected from the original investment.

Table 1 - Characterization of the analyzed procurement instruments

ID	Contracting authority	System characteristics	Predominant scope	Contractual nature
C1	Municipality of Ouro Verde do Oeste, Paraná (Contract 077/2025)	175 modules rated at 560 W, distributed across four public facilities	Eight scheduled cleaning services	Specific periodic service
C2	Administrative Base of the Brazilian Army Headquarters (Contract 03/2025)	6,086 photovoltaic modules	Technical cleaning and preventive maintenance of the modules	Continuous service
C3	Federal Institute of Rio Grande do Sul (Contract 224/2024)	Photovoltaic plants distributed across	Plant cleaning and preparation of technical documentation	Continuous service based on unit prices

		several campuses, totaling 1,593 kWp		
C4	Regional Council of Dentistry of Minas Gerais (Contract 050/2025)	One photovoltaic plant located at a regional facility	Preventive and corrective maintenance, cleaning, inspections, and technical reporting	One-time intervention
C5	City Council of Itajaí, Santa Catarina (Contract 01/2025)	168.40 kWp and 526 photovoltaic modules	Semiannual cleaning and preventive, predictive, and corrective maintenance	Integrated 12-month service
C6	Porto Alegre City Council, Rio Grande do Sul (Contract 1069/2025)	Photovoltaic plant requiring inverter replacement	Corrective maintenance, cleaning, executive design, and commissioning	Corrective intervention with partial asset renewal
C7	Court of Justice of the State of Acre (Electronic Auction 49/2025)	Four photovoltaic plants totaling 958.38 kWp	Operation, remote monitoring, maintenance, cleaning, testing, and supply of replacement parts	Integrated 13-month solution

The contracts with the narrowest scope were structured primarily around activities, quantities, frequencies, and execution methods. In these cases, the expected contractual outcome corresponded mainly to physical completion of the service, without explicit relationships between the intervention, the previous condition of the asset, and the performance achieved after completion.

The contract from Ouro Verde do Oeste illustrates this configuration. Its scope comprises eight cleaning interventions covering 175 photovoltaic modules distributed across four public buildings. The contractual instrument specifies execution deadlines, cleaning methods, permitted materials, and liability for damage, but does not associate the service with soiling-related losses, pre- and post-intervention energy generation, or other performance indicators.

The IFRS contract follows a similar logic, establishing cleaning as the core service and using installed photovoltaic capacity as the basis for measurement. Although it includes general requirements concerning contract supervision, project documentation, as-built records, and inspection reports, payment remains associated with quantities executed rather than with recovery or preservation of a predefined energy-performance level.

In both cases, cleaning is established in advance as a periodic requirement. This facilitates specification, measurement, and payment, but limits the ability to adapt interventions to the actual operating condition of each installation. Plants exposed to different environmental conditions may present distinct levels of soiling, shading, module inclination, and performance loss, making uniform schedules administratively convenient but not necessarily technically optimal.

This configuration reflects accountability centered mainly on evidence of activity completion. Contract supervision can verify whether the service was performed, but has limited contractual basis for assessing whether it was technically necessary, whether expected generation was restored, or whether the intervention generated sufficient value. This distinction is consistent with the difference between procedural compliance and results-oriented accountability (Bovens, 2007; Fontes Filho and Naves, 2014; Brown and Potoski, 2003b).

A task-oriented arrangement is not necessarily inadequate when the technical problem is clearly defined and the public authority has sufficient internal capacity to monitor asset condition and performance. The governance gap becomes more relevant when the contract itself is the main mechanism for managing the photovoltaic system but does not generate information connecting service execution, asset condition, and performance.

Maintenance Fragmentation

The analyzed instruments presented different levels of integration among cleaning, preventive maintenance, predictive maintenance, corrective interventions, monitoring, and component replacement. In some cases, these activities were treated separately through isolated procurement arrangements, while in others several activities were included within a broader scope without full integration into lifecycle-oriented management.

The CRO-MG contract includes general system inspection, module cleaning, tightening of electrical connections, maintenance of string boxes, cable ducts, and inverters, as well as preparation of a detailed technical report. Although broader than a cleaning-only contract, the scope corresponds to a single intervention rather than to a continuous maintenance process.

The Brazilian Army Headquarters contract connects module cleaning with preservation of module integrity, hotspot prevention, anti-reflective coating protection, and equipment longevity. However, its technical scope remains focused mainly on photovoltaic modules and does not integrate other subsystems to the same degree.

The Porto Alegre contract adopts a different logic because it originated from a previously identified corrective need. Its scope combines inverter replacement, corrective maintenance, cleaning, executive design, and commissioning tests. Technical responsibility documentation and warranties are also required, connecting diagnosis, intervention, and final verification, although without establishing continuous O&M.

The Itajaí contract represents a broader arrangement by explicitly combining semiannual cleaning with preventive, predictive, and corrective maintenance. However, the activities remain measured through separate contractual items and are not fully linked to a common set of performance indicators.

The fragmentation identified is both technical and temporal. Technical fragmentation occurs when different components or maintenance modalities are addressed separately, while temporal fragmentation arises when isolated interventions are procured without ensuring continuity among diagnosis, execution, monitoring, and subsequent decision-making.

This condition transfers to the public authority the responsibility for integrating technical outputs produced by different contractors and at different times. Where qualified personnel, information systems, and standardized documentation are limited, individually valid interventions may remain disconnected from a broader strategy for preserving asset performance and value.

Monitoring and Performance Indicators

Monitoring and the definition of performance indicators emerged as the most significant governance gap across the analyzed procurement instruments. Expressions such as “full operation,” “maximum efficiency,” “longevity,” “energy efficiency,” and “continuous performance” appeared in several documents, but in most cases they were not translated into measurable technical parameters.

Cleaning-oriented contracts generally did not require records of energy generation before and after the intervention, recovery rates, soiling levels, or condition-based activation criteria. Similarly, contracts that included preventive and corrective maintenance did not necessarily establish indicators such as system availability, specific yield, Performance Ratio, mean response time, or maximum periods for full restoration of energy generation.

This gap limits the ability of public organizations to determine whether contracted activities actually contribute to preserving the expected technical and economic benefits of photovoltaic assets. Without objective indicators, contract supervision tends to focus on whether an activity was performed rather than on whether the intervention improved system condition, restored performance, reduced risk, or protected long-term asset value.

The procurement instrument issued by the Court of Justice of the State of Acre (TJAC) represents the most comprehensive arrangement identified in the sample. It includes continuous remote monitoring of four photovoltaic plants, real-time performance analysis, and proactive detection of operational deviations. The proposed solution also requires monthly technical reports, visual and thermographic inspections, grounding tests, commissioning tests, instrument calibration, software updates, and the supply of replacement parts. Table 2 summarizes the degree to which the main technical-governance elements identified in the study were incorporated into each procurement instrument.

Table 2 - Comparative summary of technical governance elements

Procurement case	Integrated maintenance	Continuous monitoring	Technical reports	Performance indicators	Document management	Lifecycle orientation
C1 – Ouro Verde do Oeste	Absent	Absent	Absent	Absent	Absent	Absent
C2 – Brazilian Army Headquarters	Partial	Absent	Partial	Absent	Partial	Partial
C3 – IFRS	Partial	Absent	Present	Absent	Partial	Partial
C4 – CRO-MG	Partial	Absent	Present	Absent	Partial	Absent
C5 – Itajaí	Present	Partial	Present	Partial	Partial	Partial
C6 – Porto Alegre	Partial	Absent	Present	Partial	Present	Partial
C7 – TJAC	Present	Present	Present	Partial	Present	Present

"Present" indicates that the element was clearly incorporated through a verifiable contractual requirement, procedure, or deliverable; "Partial" indicates generic, incomplete, or limited incorporation; and "Absent" indicates that no corresponding requirement was identified in the analyzed documents.

The inclusion of remote monitoring in the TJAC procurement instrument expands the ability to identify partial failures and performance losses that do not result in complete system outages. The document explicitly links this mechanism to real-time performance analysis and rapid intervention when deviations are detected. It also establishes that monthly technical reports should support the monitoring of asset condition, services performed, and recommendations for improvement.

However, even the most comprehensive procurement instrument presents limitations. Although it refers to the assessment of performance indicators, complete reference values were not identified for availability, expected generation, Performance Ratio, response time, or energy recovery. Expressions such as “restore operation in the shortest possible time” communicate a desired priority, but do not constitute objectively measurable service levels.

This finding is important because monitoring does not automatically imply performance-based governance. Monitoring generates data; indicators organize and interpret those data; and contractual criteria determine how the resulting information affects acceptance, payment, corrective action, or accountability. When only the first element is present, the public authority gains greater technical visibility but does not necessarily acquire a stronger capacity to demand measurable outcomes.

For photovoltaic O&M contracts, this implies that technical reports should not merely document the activities performed. They should also enable verification of energy-generation trends, identified losses, downtime, affected components, probable causes, corrective measures, and post-intervention results. Such a structure would transform operational information into an instrument of accountability, continuous improvement, and lifecycle-oriented planning.

Document Management and Technical Memory

The analysis identified documentation requirements at different levels of detail. Required deliverables included technical reports, inspection records, professional responsibility documentation, executive designs, commissioning reports, inspection logs, and the archiving of as-built documentation. However, these elements generally appeared as isolated deliverables rather than as components of a continuous asset-information system.

The IFRS contract requires the archiving of designs, as-built documents, technical specifications, contracts, amendments, acceptance records, inspection reports, and formal notifications. This represents an advance over procurement arrangements limited to physical verification of service execution because it preserves information that may support future decisions. Nevertheless, the contract does not clearly establish an integrated structure linking these records to the historical performance and maintenance history of each photovoltaic plant.

In the CRO-MG contract, delivery of the final technical report is a condition for payment. The report may support diagnosis and accountability for the intervention performed, but because the service is a one-time intervention, its contribution to long-term technical memory depends on how the information is subsequently stored and connected to previous and future asset records.

In Porto Alegre, the combination of executive design, professional responsibility documentation, inverter replacement, and commissioning strengthens configuration management. The contract also establishes a one-year warranty for the services and a five-year warranty for the inverters, both of which are relevant to future maintenance and accountability decisions. In this case, the documentation not only provides evidence of service execution but also records a material change in the configuration of the photovoltaic plant.

The TJAC procurement instrument presents the most continuous documentation structure among the analyzed cases because it links monthly reports to asset condition, services performed, and recommendations for improvement. Software and firmware updates, intervention records, and the supply of replacement components also require greater control over the installed configuration.

Despite these advances, the analyzed procurement instruments did not consistently require a consolidated asset register containing information such as identification of key components, installation dates, active warranties, design modifications, failures, identified causes, interventions performed, replaced parts, test results, software versions, and the evolution of performance indicators.

The absence of such a structure reduces traceability and increases dependence on information held by service providers. When contractors change, relevant technical data may be lost or remain stored in platforms that are not fully controlled by the public authority. In such situations, the public organization may own the physical asset without necessarily retaining its complete technical memory.

For sustainable public infrastructure, maintaining this technical memory is particularly relevant because continuity of information supports long-term performance, reduces dependence on individual contractors, and strengthens the institutional capacity to preserve the value of renewable-energy investments across successive procurement cycles.

Relative Contractual Benchmark

Among the analyzed procurement instruments, the TJAC tender presented the most comprehensive translation of technical governance and asset-management principles. The procurement arrangement brings together four photovoltaic plants within a single service package, with a total installed capacity of approximately 958.38 kWp, and proposes an integrated solution covering operation, preventive and corrective maintenance, cleaning, remote monitoring, inspections, testing, technological updating, spare-parts logistics, and waste disposal.

This contractual design presents four main advances. First, it replaces isolated procurement of individual activities with an integrated service solution, reducing interfaces among different contractors and assigning broader responsibility to a single service provider. Second, it promotes information continuity through remote monitoring and monthly technical reporting. Third, it incorporates activities involving multiple subsystems, including photovoltaic modules, transformation stations, electrical panels, grounding systems, instruments, software, access areas, and vegetation management. Fourth, it assigns the contractor responsibility for the procurement and installation logistics of replacement parts, thereby reducing the risk of delays associated with separate purchasing procedures.

The decision to manage the four photovoltaic plants within a single contractual group also favors standardization across geographically distributed assets. For decentralized infrastructure, this type of arrangement enables common procedures to be applied, operational data to be consolidated, and performance across installations to be compared. The approach therefore moves closer to portfolio-oriented asset management rather than treating each photovoltaic plant as an isolated unit.

Nevertheless, the TJAC tender should be interpreted as a relative contractual benchmark, rather than as a complete or definitive model. First, the document represents contractual planning and does not constitute evidence of actual service execution or achieved performance. Second, several obligations remain based on predefined frequencies, such as scheduled cleaning activities, without explicit linkage to measured soiling levels, performance losses, or economic decision criteria. Third, although the tender refers to performance and rapid restoration of system operation, it does not establish a complete architecture of quantitative service levels or performance thresholds.

Table 3 summarizes the main practices identified in the TJAC procurement instrument, their contributions to technical governance, and the improvements that would still be required to strengthen lifecycle-oriented management.

Table 3 - Potential and limitations of the relative contractual benchmark

Dimension	Practice identified in the TJAC	Contribution to governance	Recommended improvement
Integration	Operation and maintenance of the four photovoltaic plants under a single contractual arrangement	Standardization of procedures and reduction of service fragmentation	Establish a structured transition process at the end of the contract
Monitoring	Continuous remote monitoring	Proactive detection of failures and performance deviations	Define minimum availability targets and data-quality requirements
Maintenance	Preventive and corrective maintenance with supply of replacement parts	Reduction of contractual interfaces and procurement delays	Establish asset criticality criteria and maximum response and restoration times by failure type
Reporting	Monthly reporting on asset condition and services performed	Supports contract supervision and preservation of technical memory	Standardize performance indicators and require trend analysis
Inspections and testing	Thermographic inspections, grounding tests, commissioning tests, and instrument calibration	Broader assessment of technical condition	Define acceptance criteria and procedures for addressing identified deviations
Lifecycle management	Explicit reference to energy efficiency and extension of equipment service life	Supports preservation of long-term investment value	Incorporate asset-renewal planning and lifecycle-cost considerations
Cleaning	Thirteen scheduled cleaning interventions during the contractual period	Provides operational predictability	Link cleaning decisions to soiling levels, measured performance losses, and economic feasibility
Software and configuration	Software and firmware updates	Reduces technological obsolescence and supports system reliability	Require records of software versions, configuration parameters, access credentials, and changes over time

The comparison between the relative benchmark and the other contracts shows that the advancement of technical governance does not depend solely on increasing the number of services included in the procurement scope. The central issue lies in the integration of activities, information, responsibilities, and expected outcomes. A technically comprehensive contract may still remain predominantly task-oriented if it lacks performance indicators or a structured technical memory. Conversely, monitoring, documentation, and measurable performance criteria can transform individual interventions into components of a broader decision-making process.

Overall, the results suggest three broad stages of contractual maturity. At the first stage, procurement focuses primarily on the control of specific tasks. At the second stage, different maintenance modalities are integrated, but performance orientation remains limited. At the third stage, contracts combine monitoring, information management, preventive and corrective actions, and component management, thereby moving closer to lifecycle-oriented governance. Among the analyzed cases, the TJAC procurement instrument represents the most advanced stage, although it still lacks fully defined quantitative indicators, risk-based criteria, and explicit mechanisms for asset-renewal planning.

The main empirical contribution of the analysis is to demonstrate that the isolated presence of contract supervision, technical reports, or preventive maintenance does not, by itself, constitute consolidated technical governance. Such governance emerges when contractual arrangements are able to connect four elements: clearly assigned responsibility, traceable information, verifiable performance, and lifecycle-oriented decision-making.

CONCLUSION

This study examined how contractual and procurement instruments for photovoltaic operation and maintenance incorporate principles of technical governance, accountability, and lifecycle management. The findings showed that such incorporation remains uneven, with a predominance of task-oriented arrangements, limited use of measurable performance indicators, and weak integration among maintenance, monitoring, documentation, and long-term decision-making.

The results therefore suggest that technical governance is strengthened when contractual arrangements connect four core elements: clearly defined responsibilities, traceable information, measurable performance, and lifecycle-oriented decision-making. Contracts that incorporate these elements are better positioned to support not only service compliance but also the long-term preservation of the technical, economic, and environmental value of public photovoltaic assets.

The study has two main limitations. First, it examined the formal content of procurement and contractual documents rather than the actual execution and operational outcomes of the contracts. Second, the analytical sample was not intended to provide statistical representativeness. Future research could relate contractual design to the effective technical and economic performance of photovoltaic systems, examine larger and more diverse sets of procurement arrangements, and further validate the proposed analytical categories across different institutional and national contexts.

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