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A TECHNICAL-REGULATORY FRAMEWORK FOR INTEGRATING PHOTOVOLTAIC SYSTEMS INTO MINE CLOSURE PLANS (PFM) IN BRAZIL

UM MARCO TÉCNICO-REGULATÓRIO PARA A INTEGRAÇÃO DE SISTEMAS FOTOVOLTAICOS EM PLANOS DE FECHAMENTO DE MINA (PFM) NO BRASIL

UN MARCO TÉCNICO-REGULATORIO PARA LA INTEGRACIÓN DE SISTEMAS FOTOVOLTAICOS EN PLANES DE CIERRE DE MINAS (PFM) EN BRASIL

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ABSTRACT

The management of mining liabilities, specifically Tailings Storage Facilities (TSFs), represents one of the most significant engineering and environmental challenges of the 21st century. This paper proposes a strategic solution for the energy transition through the "Functional Plan for the Recovery of Degraded Areas" (PRAD). We analyze the feasibility of converting inactive mining structures into utility-scale solar photovoltaic (PV) assets. Through a detailed exegesis of regulations from ANM, SEMAD-MG, and SEMAS-PA, this study demonstrates that Brazilian legislation supports "Technological Neutrality" in post-mining land use. The article concludes that solar integration is the most effective pathway to finance long-term monitoring and ensure the physical and chemical stability of tailings deposits.

Keywords: Tailing Dams. Mine Closure. Photovoltaic Energy. Energy Transition. Hybrid Infrastructure.

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RESUMO

A gestão de passivos minerários, especificamente das barragens de rejeitos (TSFs), representa um dos desafios mais significativos de engenharia e meio ambiente do século XXI. Este artigo propõe uma solução estratégica para a transição energética por meio do “Plano de Recuperação de Áreas Degradadas” (PRAD). Analisa-se a viabilidade de converter estruturas minerárias inativas em ativos solares fotovoltaicos de grande escala. Por meio de uma análise detalhada das regulamentações da ANM, SEMAD-MG e SEMAS-PA, o estudo demonstra que a legislação brasileira apoia a “neutralidade tecnológica” no uso do solo pós-mineração. O artigo conclui que a integração solar constitui o caminho mais eficaz para financiar o monitoramento de longo prazo e garantir a estabilidade física e química dos depósitos de rejeitos.

Palavras-chave: Barragens de Rejeitos. Fechamento de Mina. Energia Fotovoltaica. Transição Energética. Infraestrutura Híbrida.

RESUMEN

La gestión de pasivos mineros, específicamente de las presas de relaves (TSFs), representa uno de los desafíos más significativos de ingeniería y medio ambiente del siglo XXI. Este artículo propone una solución estratégica para la transición energética a través del “Plan de Recuperación de Áreas Degradadas” (PRAD). Se analiza la viabilidad de convertir estructuras mineras inactivas en activos solares fotovoltaicos a escala utilitaria. Mediante un análisis detallado de las regulaciones de ANM, SEMAD-MG y SEMAS-PA, el estudio demuestra que la legislación brasileña respalda la “neutralidad tecnológica” en el uso del suelo post-minero. El artículo concluye que la integración solar constituye la vía más eficaz para financiar el monitoreo a largo plazo y garantizar la estabilidad física y química de los depósitos de relaves.

Palabras clave: Presas de Relaves. Cierre de Minas. Energía Fotovoltaica. Transición Energética. Infraestructura Híbrida.

1 INTRODUCTION

The closure of mining activities in Brazil is subject to a dense and highly structured legal and regulatory framework, whose central objective is to ensure that the affected area is returned to a condition of physical stability, environmental safety, and socially acceptable land use. Brazilian environmental legislation does not conceive mine closure as a merely technical or administrative act, but rather as a substantive phase of the mining life cycle, in which the operator must demonstrate that the site will no longer pose risks to ecosystems, communities, or public infrastructure. [1] Within this context, the requirement to restore the area to a "productive and safe form of land use" [4] reflects the legislator's expectation that post-mining landscapes should fulfill a clear social and environmental function, avoiding abandonment, degradation, or latent hazards.

Historically, the *Plano de Recuperação de Áreas Degradadas (PRAD)* [5] has been implemented with a strong emphasis on revegetation, primarily aimed at erosion control, slope stabilization, and visual mitigation of environmental damage. While these measures remain essential, they often resulted in post-closure areas with limited ecological functionality and little or no economic or social integration into the surrounding territory. In many cases, revegetation was treated as an end in itself, rather than as a means toward a broader and more sustainable land-use strategy. This approach increasingly proves insufficient in light of contemporary environmental governance, which demands long-term resilience, efficient land use, and tangible contributions to sustainable development.

In recent years, a clear paradigm shift has emerged in the mining sector, both in Brazil and internationally. [8] Modern mine closure planning increasingly incorporates the expectation that post-exhaustion solutions should generate enduring value, whether environmental, social, or economic. This shift is closely aligned with the evolution of environmental law toward principles such as sustainability, intergenerational equity, and the rational use of already impacted areas [15]. Within this framework, innovation in land reuse is not merely permitted but implicitly encouraged, provided that it maintains or enhances environmental safety and complies with regulatory standards.

Inactive or decommissioned tailings dams represent a particularly relevant opportunity in this regard. These structures typically occupy vast, already deforested areas that are unsuitable for conventional agriculture or residential development due to geotechnical and environmental constraints. However, they often possess strategic logistical advantages, including proximity to transmission lines, substations, and access roads originally built to support mining operations. Replicating such infrastructure in greenfield renewable energy projects would entail significant financial costs and additional environmental disturbance. By contrast, reusing existing infrastructure embedded in mining landscapes exemplifies the principle of efficiency that underlies modern environmental regulation.

The installation of photovoltaic power plants on inactive tailings dams offers a compelling example of innovative land use compatible with PRAD objectives. From an environmental perspective, this approach avoids further land clearing, minimizes soil disturbance, and contributes to the reduction of greenhouse gas emissions by expanding the supply of renewable energy. From a regulatory standpoint, it transforms areas previously associated with environmental liability into assets that fulfill a clear and productive social function. Moreover, by injecting clean energy into Brazil’s National Interconnected System (Sistema Interligado Nacional – SIN), such projects align the mineral sector with national energy policies and global decarbonization commitments.

In this sense, the incorporation of photovoltaic facilities into PRAD strategies represents more than a technical alternative; it embodies a contemporary interpretation of the legislator’s expectations regarding mine closure. It reconciles environmental recovery with economic rationality, promotes innovation in the reuse of degraded areas, and reinforces the role of the mining sector as an active participant in the energy transition. Consequently, solar deployment on inactive tailings dams should be understood as a legitimate and forward-looking form of post-mining land use, capable of enhancing both environmental outcomes and societal value in the long term.

2 INTERNATIONAL REGULATORY & CASES BENCHMARK

International experience provides a robust empirical and regulatory foundation for assessing the feasibility of integrating photovoltaic (PV) facilities into post-mining landscapes, particularly in the context of inactive or decommissioned tailings storage facilities. Comparative analysis of foreign cases is especially relevant for Brazil, given the country’s complex mining geography, stringent environmental licensing procedures, and growing emphasis on innovative PRAD solutions. The international literature consistently demonstrates that renewable energy projects can be successfully deployed on mining residues and tailings structures, provided that site-specific geotechnical, environmental, and regulatory constraints are adequately addressed [11]. These cases serve not as direct blueprints, but as technical and conceptual benchmarks capable of informing adaptive strategies within the Brazilian legal and institutional context.

2.1 THE ELIZABETH MINE CASE (UNITED STATES): COVER ENGINEERING AND BALLASTED FOUNDATIONS

The remediation and reuse of the Elizabeth Mine in the state of Vermont (USA) is frequently cited as a reference case for the integration of solar energy generation into a highly sensitive post-mining environment. The site presented a critical environmental challenge due to the elevated potential for Acid Mine Drainage (AMD) generation, resulting from sulfide-rich tailings exposed to oxygen and water. In this context, environmental recovery efforts were primarily focused on isolating the reactive materials to prevent acidification of surface and groundwater systems, a concern that parallels conditions found in several Brazilian mining districts.

From a technical standpoint, the remediation strategy relied on the implementation of a multi-layer capping system designed to physically and chemically isolate the tailings. This system included, among other elements, a high-density polyethylene (HDPE) geomembrane, selected for its low permeability, chemical resistance, and long-term durability. The presence of this geomembrane introduced a critical constraint for any subsequent land use: direct anchoring or penetration of the cover system was strictly prohibited due to the risk of compromising its integrity and reactivating AMD processes [18].

To reconcile environmental protection with productive land use, a 5 MW photovoltaic facility was installed using a ballast-mounted racking system. Unlike conventional solar foundations that rely on pile driving or ground anchoring, ballast systems distribute loads through weighted structures resting on the surface of the capped area. This approach eliminated the need for subsurface disturbance and preserved the functionality of the environmental containment system.

From the perspective of fluid mechanics and structural engineering, the design of the ballast system was carefully calibrated to ensure that contact pressures remained below the yield strength of the HDPE geomembrane. Load distribution, friction coefficients, and wind uplift forces were all modeled to prevent localized stress concentrations that could lead to puncturing or long-term material fatigue. This level of engineering precision underscores the feasibility of combining environmental remediation with energy infrastructure, even in sites with severe contamination risks.

The relevance of this case to Brazil is particularly evident in states such as Minas Gerais, where numerous tailings dams incorporate liner systems to protect underlying aquifers and comply with increasingly strict environmental regulations. In such contexts, ballast-mounted PV systems emerge as a technically viable and regulatorily compatible solution, allowing PRAD objectives—namely, environmental safety and productive land use—to be fulfilled simultaneously without compromising protective barriers.

2.2 LOS BRONCES (CHILE): FLOATING PHOTOVOLTAICS (FPV) AND THERMODYNAMIC ADVANTAGES

Another internationally significant example is the implementation of a floating photovoltaic (FPV) system at the Los Bronces copper mine in Chile, operated by Anglo American. Located at approximately 3,300 meters above sea level, the project demonstrates the adaptability of solar technologies to extreme environmental conditions, including high solar irradiance, low atmospheric pressure, and substantial daily temperature variations. The FPV system was deployed on a tailings pond, transforming a mining-related water body into an energy-generating asset [3].

The initiative consists of 256 photovoltaic panels (330 watts each) installed on Las Tórtolas pond at Los Bronces copper mine, with the capacity to generate 86 kW. The panels are located on a floating island, and they are connected to a service room where the energy that the system generates will be monitored daily. This project will reduce CO2 emissions by 58 tonnes per year, generate 150,000 kWh/year of renewable electric power and reduce water evaporation in the area it covers by 80%.

The geotechnical and environmental implications of FPV systems are particularly noteworthy. By physically covering portions of the water surface, floating solar arrays reduce direct ultraviolet radiation exposure and attenuating wind-induced turbulence. These effects significantly decrease the evaporation rate (E), a factor of growing importance in water-scarce regions and under climate change scenarios. In mining operations, where water management is often a critical operational and regulatory issue, evaporation reduction contributes directly to water conservation and improved resource efficiency.

From a thermodynamic perspective, FPV systems also offer measurable gains in photovoltaic performance. Water bodies act as effective heat sinks, dissipating excess thermal energy from PV modules. Empirical studies indicate that for each degree Celsius reduction below the nominal operating cell temperature, photovoltaic efficiency increases by approximately 0.4% to 0.5%. In practical terms, this translates into higher energy yields and improved performance ratios when compared to equivalent land-based systems operating under high ambient temperatures.

These advantages are particularly relevant for Brazilian regions characterized by elevated temperatures and high solar irradiance, such as Pará and other states in the Amazon and Northeast regions. In such environments, thermal losses can significantly reduce the efficiency of conventional ground-mounted PV plants. Floating systems deployed on tailings ponds or water reservoirs associated with mining operations may therefore represent a competitive technological alternative, aligning energy production with water management and PRAD objectives.

Collectively, these international cases illustrate how regulatory compliance, environmental protection, and technological innovation can converge in post-mining land use strategies. They reinforce the argument that photovoltaic installations—whether ballast-mounted or floating—can be responsibly integrated into recovery plans, provided that they are supported by rigorous engineering, environmental safeguards, and alignment with the overarching values embedded in environmental legislation.

2.3 TRANSFORMING ABANDONED MINES INTO SOLAR FARMS

The mine-to-solar solution begins with a spatial screen that prioritizes abandoned mines featuring large contiguous areas, low slopes, favorable aspect, high insolation, and proximity to substations/lines; it then models generation with fixed-tilt and single-axis tracking layouts to estimate annual MWh and capacity factor. Applied to 18 sites (13 in Florida; 5 in Pennsylvania), this approach indicates that a prioritized portfolio could supply up to 22% of Florida's annual electricity, whereas the modeled contribution for Pennsylvania is ~0.017% a difference driven by irradiance and connectable land area. In higher-irradiance settings, tracking boosts yield and daytime coverage, while grid-adjacent siting shortens interconnections, reduces losses, and improves feeder voltage profiles, turning modeled output into deliverable MWh with less connection friction.

For communities, the financial upside stems from faster schedules (reduced intertie complexity), which bring forward local CAPEX, construction and O&M jobs, and procurement from local suppliers—without the land-use conflicts typical of greenfield builds. Florida is rapidly expanding utility-scale solar in a system still dominated by natural gas, which values local MWh and diversification; Pennsylvania, a major net exporter with sizable gas and nuclear shares, tends to see more granular benefits tied to node quality and connectable footprint around repurposed mines.

Investment levers combine federal and state instruments. Federally, the Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law (BIL) anchor the national emissions trajectory (targeting –50% to –52% by 2030) and unlock financing such as Powering Affordable Clean Energy (US$ 1 billion in partially forgivable loans for rural renewables and storage) and grid programs like GRIP (Grid Resilience & Innovation Partnerships, US$ 10.5 billion) for resilience, smart grid and interconnection—lowering capital cost and interconnection risk. At state level, Florida offers Voluntary Cleanup Tax Credits (VCTC), liability protections and expedited reviews for brownfields; Pennsylvania provides Industrial Sites Reuse, Pennsylvania First, Business in Our Sites, and the PENNVEST Brownfields Loan for assessment/cleanup and productive reuse—complemented by EPA/USDA brownfield and rural-energy support.

The study evaluated 13 non-overlapping mine sites in Florida, thereby avoiding interference with existing solar plants and preserving interconnection options. A Global horizontal irradiance (GHI) adding existing-plants overlay confirmed site aptitude and quantified two cases: Case 1 (utilizing panels with a capacity of 500 W) at 35–40 TWh/yr and ≈12.8–13.1 $MtCO_2$ avoided (≈3.2 million homes); Case 2 (utilizing panels with a capacity of 600 W) at 55–60 TWh/yr and ≈21.6 $MtCO_2$ avoided (≈5.3 million homes). Benchmarked against Florida's ≈260 TWh/yr of generation, these 13 sites correspond to ~17% of statewide output, concretely operationalizing the mine-to-solar logic of grid-adjacent siting to shorten intertie spans, improve deliverability, and align with the incentive stack discussed earlier. In Pennsylvania, the same workflow selected five sites, mapped against existing solar to demonstrate integration; slope excluded ~70% of candidates, reflecting the state's more restrictive topography. The GHI + existing-plants check validated the retained sites returned: Case 1 (utilizing panels with a capacity of 500 W) at 15–17 GWh/yr and ≈5.2 $ktCO_2$ avoided (≈1,500 homes); Case 2 (utilizing panels with a capacity of 600 W) at 40–45 GWh/yr and ≈13.4 $ktCO_2$ avoided (≈3,800 homes). While totals are smaller than Florida's—consistent with irradiance, siting geometry, and connectable area—the Pennsylvania portfolio still operationalizes mine-to-solar, concentrating gains where hosting capacity exists and leveraging the same IRA/BIL mechanisms alongside the state brownfield tools outlined previously.

The geographic dispersion of eligible sites in FL and PA mitigates local overload and maximizes resource use, aligning with solar-capacity growth and the need for battery storage and grid modernization to enhance integration reliability and capture system value. Deploying on abandoned mine lands cuts CO_2 versus state grids and reuses degraded land with minimal pressure on agricultural areas, delivering community-level co-benefits. In short, by distributing generation across hosting-capable nodes, stacking incentives, and pairing storage plus adding upgrades, mine-to-solar portfolios accelerate the clean-energy transition with measurable benefits in energy, emissions, and local development.

3 DEEP GEOTECHNICAL ANALYSIS: THE CRITICAL VARIABLE

The technical feasibility and long-term safety of installing photovoltaic facilities on inactive tailings dams are fundamentally dependent on a rigorous understanding of the geotechnical behavior of the deposited materials. From both an engineering and regulatory perspective, tailing dams cannot be treated as conventional construction sites [11]. They are man-made geological bodies, characterized by complex stratigraphy, heterogeneous material properties, and time-dependent mechanical behavior. Consequently, Brazilian environmental authorities and mining regulators increasingly expect PRADs to incorporate advanced geotechnical analyses capable of demonstrating not only present stability, but also the long-term performance of any proposed post-closure land use.

In this context, geotechnical assessment emerges as the critical variable that determines whether a solar plant constitutes a safe and acceptable form of land use under PRAD requirements. Issues such as consolidation, differential settlement, slope stability, and water flow dynamics directly influence both the structural integrity of photovoltaic systems and the residual risk profile of the dam itself. Failure to adequately address these aspects could undermine the very objectives of environmental recovery and risk reduction that PRADs are intended to achieve.

3.1 CONSOLIDATION AND DIFFERENTIAL SETTLEMENT OF TAILINGS DEPOSITS

Tailings materials, particularly fine-grained residues, typically exhibit high void ratios and low permeability, which results in a pronounced susceptibility to time-dependent consolidation. Total settlement (S_t) of a tailings deposit is generally understood as the sum of immediate (elastic) settlement, primary consolidation settlement driven by pore pressure dissipation, and secondary consolidation (creep) associated with the viscous behavior of fine particles [13]. While immediate settlement occurs rapidly after load application, primary and secondary consolidation may continue for years or even decades, depending on material characteristics and drainage conditions [12].

The classical theoretical framework for modeling primary consolidation in saturated fine-grained soils is provided by Terzaghi’s one-dimensional consolidation theory, expressed as:

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2} \qquad (1)$$

where u represents excess pore water pressure, t is time, z is the vertical coordinate, and C_v is the coefficient of consolidation, a parameter that reflects both soil permeability and compressibility. Although simplified, this model remains widely used in practice and is often required by regulators as a baseline for settlement predictions in tailings structures.

In Brazil, the relevance of consolidation behavior varies significantly according to the mineral commodity and tailings composition. In Minas Gerais, where iron ore mining predominates, tailings deposits frequently consist of a mixture of granular sands and fine slimes. While the granular fraction tends to consolidate relatively quickly due to higher permeability, the fine slimes may retain excess pore pressures for extended periods. This disparity leads to differential settlements across the dam surface, which is particularly problematic for photovoltaic installations that rely on precise alignment and structural continuity.

Differential settlement poses a direct risk to solar trackers and support structures, as uneven vertical displacements can induce torsional stresses, misalignment, and ultimately mechanical failure. In the context of PRAD evaluation, such risks are not limited to energy infrastructure performance; they also raise concerns regarding the integrity of the dam surface, potential cracking of cover systems, and localized water infiltration pathways.

In Pará, where bauxite mining generates tailings with high clay content and elevated plasticity, consolidation challenges are even more pronounced. These materials exhibit extremely low permeability and significant secondary compression, making natural consolidation an excessively slow process. In such cases, the use of vertical drainage systems, such as prefabricated vertical drains (wick drains), becomes a critical precondition for solar installation [14]. Regulatory best practice increasingly demands that a substantial degree of consolidation—often on the order of 90% of primary consolidation—be achieved prior to the construction of any permanent or semi-permanent structures. This requirement reflects the legislator’s expectation that post-mining land uses must be compatible with long-term geotechnical stability rather than short-term expediency.

3.2 SLOPE STABILITY, FACTOR OF SAFETY, AND LOAD INTERACTIONS

Beyond settlement behavior, slope stability constitutes a central pillar of any geotechnical assessment associated with tailings dams [11]. The installation of photovoltaic panels introduces additional static loads and, more critically, dynamic loads resulting from wind action on the panel surfaces. These forces act as surcharges on the dam structure and must be explicitly incorporated into stability analyses to ensure compliance with safety criteria established by Brazilian mining and environmental authorities [2].

Slope stability is commonly evaluated using limit equilibrium methods, with the Morgenstern–Price method being one of the most robust and widely accepted approaches due to its ability to satisfy both force and moment equilibrium. The Factor of Safety (FS) can be expressed as:

$$FS = \frac{\sum[c' \cdot \Delta l + (W + q - u \cdot \Delta l)\tan\,\phi'] \cdot \frac{1}{M(\alpha)}}{\sum W \sin\,\alpha} \qquad (2)$$

where $c'$is the effective cohesion, $\phi'$is the effective friction angle, Wrepresents the weight of the soil slices, $q$denotes the surcharge imposed by the photovoltaic installation, $u$is the pore water pressure, $\Delta l$is the length of the slice base, and $M(\alpha)$is a function related to interslice force inclination. The explicit inclusion of the surcharge term $q$is essential, as it captures the incremental stresses introduced by panel supports, ballast systems, and maintenance loads.

In regulatory terms, Brazilian authorities expect PRADs to demonstrate that the proposed post-closure land use does not reduce the Factor of Safety below acceptable thresholds, even under adverse conditions such as extreme rainfall or maximum wind loading. This expectation reflects a precautionary approach rooted in recent dam failure incidents and the resulting tightening of safety standards.

Equally important is the analysis of water flow and infiltration patterns. The presence of photovoltaic panels alters surface runoff by intercepting rainfall and redistributing concentrated flows along panel edges and support structures. If not properly managed, these altered flow paths can lead to the formation of erosion channels or “gullies” on the dam surface. Such features are particularly dangerous, as they can trigger regressive erosion, undermine cover systems, and ultimately compromise the dam crest [3].

Accordingly, a robust PRAD must integrate hydraulic and geotechnical design solutions, such as drainage channels, energy dissipation structures, and surface protection measures, directly into the layout of the photovoltaic plant. By doing so, the solar installation becomes part of a holistic recovery strategy, reinforcing rather than weakening the dam’s long-term stability.

Taken together, consolidation behavior, differential settlement, slope stability, and flow dynamics illustrate why deep geotechnical analysis is not merely a technical requirement, but a central regulatory and conceptual pillar for the integration of photovoltaic facilities into PRADs. These analyses ensure that innovation in post-mining land use remains firmly aligned with the fundamental objectives of environmental safety, structural integrity, and sustainable land management envisioned by Brazilian legislation.

4 COMPARATIVE BRAZILIAN REGULATORY ANALYSIS: MG VS. PA

Brazil’s federative system grants states significant autonomy in regulating environmental licensing and land-use planning, particularly with respect to mining activities and post-closure obligations. While federal legislation establishes general principles and minimum standards, state-level norms and administrative practices often introduce distinct interpretative frameworks and procedural requirements. A comparative analysis of Minas Gerais (MG) and Pará (PA) illustrates how divergent regulatory priorities shape both constraints and opportunities for such projects.

4.1 MINAS GERAIS AND THE “MAR DE LAMA NUNCA MAIS” LAW (LAW NO. 23.291/2019)

In Minas Gerais, the regulatory landscape governing tailings dams is profoundly influenced by Law No. 23.291/2019, popularly known as the “Mar de Lama Nunca Mais” law [9]. Enacted in the aftermath of major tailings dam failures, the statute reflects a strong precautionary and risk-averse approach, prioritizing the elimination of structures perceived as posing residual hazards to human life and the environment [2]. Within this framework, the licensing of any post-mining use on tailings dams—including photovoltaic facilities—is intrinsically linked to the process of decharacterization.

From a legal standpoint, decharacterization entails the complete cessation of a dam’s containment function. This requires the physical reconfiguration of the structure so that it no longer retains tailings, water, or slurry, and cannot revert to such use in the future. The law thus redefines the dam not merely as an inactive structure, but as a transformed landform whose stability and function are comparable to natural terrain. In this context, the photovoltaic project must be formally presented to the Fundação Estadual do Meio Ambiente (FEAM) as the “planned final use” of the area, integrated into the PRAD and aligned with the decharacterization strategy [6].

A careful legal exegesis of Law No. 23.291/2019 reveals that the legislator’s intent extends beyond risk elimination to encompass the promotion of socially acceptable and economically rational post-closure outcomes. Although the law does not explicitly mandate productive reuse, it creates a regulatory environment in which mere abandonment is no longer acceptable. Consequently, photovoltaic generation can be interpreted as a legitimate and coherent final land use, provided that it does not reintroduce containment characteristics or compromise geotechnical stability [7].

From an economic and policy perspective, this regulatory rigidity also opens a significant opportunity. Decharacterization processes in Minas Gerais are notoriously costly, often representing one of the largest financial burdens of mine closure. By integrating solar energy generation into the final land-use plan, mining companies may partially amortize these environmental costs through self-consumption, or fiscal mechanisms such as tax offsets and energy compensation schemes. In this sense, photovoltaic projects function not as substitutes for environmental obligations, but as complementary instruments that enhance the economic viability of compliance while preserving the law's underlying safety objectives.

4.2 PARÁ AND SEMAS INSTRUCTION MANUAL NO. 01/2020

In contrast to Minas Gerais, the regulatory approach in Pará is strongly shaped by the state's ecological context, particularly the presence of extensive tropical forests and the centrality of biodiversity conservation in environmental policy. SEMAS Instruction Manual No. 01/2020, which guides PRAD formulation and evaluation, places a pronounced emphasis on the recovery of native vegetation and the reestablishment of ecological functions in degraded areas [10]. Within this paradigm, proposals to install photovoltaic plants on tailings dams may initially encounter skepticism, as they appear to replace "biomass" and potential forest regeneration with anthropogenic infrastructure.

This perceived land-use conflict represents one of the principal regulatory challenges in Pará. Environmental authorities may question whether the substitution of revegetation efforts with solar panels undermines the core objectives of environmental recovery, particularly in a biome of global ecological significance. However, this tension also creates space for more sophisticated legal and technical argumentation within PRAD submissions.

A central strategic concept in this context is Land Use Efficiency. The proponent can demonstrate that allocating renewable energy infrastructure to already degraded and deforested mining areas reduces the need to clear native vegetation elsewhere for energy projects. In other words, by intensifying the productive use of impacted land, photovoltaic installations indirectly contribute to the preservation of intact forests and biodiversity in other regions of the state. This argument aligns with broader sustainability principles and with the logic of avoiding additional environmental externalities.

Furthermore, SEMAS Instruction Manual No. 01/2020 implicitly adopts a stance of technological neutrality. Rather than prescribing specific recovery techniques, it focuses on outcomes—namely, chemical stability, physical integrity, and the absence of environmental risk. [8] Under this interpretation, productive anthropic structures, including solar plants, may be deemed compatible with PRAD objectives as long as they demonstrably ensure long-term stability and do not generate new sources of contamination or degradation.

In practical terms, this means that a photovoltaic project in Pará must be framed not as a deviation from environmental recovery, but as an alternative and complementary form of land use that fulfills the functional expectations of PRAD legislation. By grounding the proposal in rigorous geotechnical, environmental, and land-use efficiency analyses, proponents can reconcile energy generation with the state’s strong conservation ethos.

Taken together, the comparison between Minas Gerais and Pará underscores the importance of context-sensitive regulatory strategies. While Minas Gerais emphasizes risk elimination and structural transformation through decharacterization, Pará prioritizes ecological recovery and forest conservation. In both cases, however, the integration of photovoltaic facilities into PRADs remains legally plausible and conceptually coherent, provided that projects are carefully tailored to state-specific regulatory expectations and supported by robust technical evidence.

5 SOCIOECONOMIC IMPACT AND THE "JUST TRANSITION"

The closure of mining operations has consequences that extend far beyond the physical rehabilitation of degraded land. In many regions, mining activities constitute the primary economic engine of local communities, shaping labor markets, public revenues, and regional infrastructure [17]. Within this context, the concept of a “Just Transition” has gained prominence in international environmental and labor policy debates, emphasizing that the shift toward more sustainable economic models should not impose disproportionate social costs on workers or mining-dependent towns [11]. Applied to mine closure, this principle requires that environmental recovery efforts be designed in a manner that avoids abrupt economic decline and supports alternative pathways for local development [15; 16].

In the Brazilian context, PRADs increasingly function as instruments not only of environmental compliance but also of territorial planning. Legislators and environmental authorities implicitly expect mine closure strategies to consider socioeconomic continuity, particularly in remote or mono-industrial municipalities where alternative sources of employment and income are scarce.

5.1 ENERGY SECURITY AND REGIONAL INFRASTRUCTURE RESILIENCE

One of the most significant socioeconomic benefits associated with the installation of solar plants on inactive tailings dams lies in their contribution to local and regional energy security. Mining operations are frequently located at the “end of the line” of the electrical grid, far from major consumption centers and often supplied through long transmission lines that are susceptible to voltage drops, losses, and service interruptions. When mining activities cease, the associated electrical infrastructure—substations, transmission lines, and access corridors—often remains underutilized, despite having been designed for high-capacity energy flows.

By injecting renewable energy into the grid at these remote nodes, photovoltaic plants can improve voltage regulation and power quality for surrounding rural and peri-urban communities. Distributed generation in such locations reduces transmission losses and enhances grid stability, particularly in regions with weak or overstretched distribution networks. From a public policy perspective, this outcome aligns with broader national objectives related to energy reliability, universal access, and the modernization of the electricity sector.

Moreover, the reuse of existing electrical infrastructure reinforces the rational use of public and private investments made during the operational phase of the mine.

5.2 HUMAN CAPITAL RETENTION AND WORKFORCE TRANSITION

A second and equally important dimension of the Just Transition relates to employment and human capital. Mine closure often results in the sudden displacement of a skilled workforce, leading to unemployment, outmigration, and the erosion of local technical expertise. This dynamic can have long-lasting social consequences, including reduced municipal revenues, increased demand for social assistance, and the weakening of community structures.

The operation and maintenance (O&M) of photovoltaic plants, while less labor-intensive than mining operations, nevertheless require a qualified workforce with expertise in electrical systems, automation, instrumentation, and industrial maintenance. Many of these competencies are already present among mining employees, particularly those involved in process control, mechanical maintenance, and electrical operations. As a result, solar projects create a concrete opportunity for workforce retraining and professional reallocation, allowing former mine workers to remain economically active within their communities.

From a regulatory and ethical standpoint, this workforce continuity is consistent with the values underlying the Just Transition framework. It recognizes that environmental progress should be accompanied by social inclusion and capacity building, rather than labor displacement. In the context of PRAD evaluation, the inclusion of retraining programs, local hiring commitments, and partnerships with technical education institutions can significantly strengthen the legitimacy and social acceptance of photovoltaic projects on tailings dams.

Taken together, the contributions to energy security and human capital retention demonstrate that the socioeconomic impacts of solar installations extend well beyond energy generation itself. They position photovoltaic reuse of mining areas as a strategic tool for managing the social dimensions of mine closure, reinforcing the idea that environmental recovery, economic resilience, and social justice are not competing objectives, but mutually reinforcing components of a sustainable post-mining transition.

6 CONCLUSION

This article sustains the thesis that inactive and decommissioned tailings dams in Brazil can—and, under contemporary environmental and regulatory paradigms, should—be repurposed as photovoltaic parks within the framework of PRADs. Far from constituting a speculative or marginal proposal, this approach is grounded in demonstrable technical feasibility, rigorous geotechnical engineering, and a legally coherent interpretation of Brazilian environmental and mining legislation [1]. When properly designed, solar installations on tailings structures are compatible with the fundamental objectives of mine closure: long-term physical stability, environmental safety, and the attribution of a socially productive land use.

From a technical standpoint, the international case studies and geotechnical analyses discussed throughout this work demonstrate that the principal challenges associated with tailings dams—such as consolidation behavior, differential settlement, slope stability, and water management—can be effectively addressed through established engineering solutions. Ballasted foundations, floating photovoltaic systems, advanced drainage strategies, and continuous monitoring technologies illustrate how renewable energy infrastructure can be adapted to the unique constraints of post-mining environments. These solutions do not circumvent geotechnical risks; rather, they internalize them as design variables, reinforcing the stability and safety of the reclaimed structure.

Legally, the proposed reuse aligns with the evolving expectations embedded in PRAD regulation at both federal and state levels. [5] Brazilian environmental law increasingly favors outcomes over prescriptive methods, emphasizing demonstrable safety, functional land use, and the prevention of future liabilities. Whether under the risk-focused framework of Minas Gerais or the conservation-oriented regulatory culture of Pará, photovoltaic projects can be legitimately framed as compliant final land uses, provided they are supported by robust technical evidence and integrated into comprehensive recovery plans. In this sense, solar deployment does not dilute environmental obligations; it enhances their durability by embedding recovery within a productive and economically viable system.

More broadly, the conversion of tailings dams into solar parks represents a conceptual transition in engineering and environmental governance. It marks a shift from traditional “dam civil engineering,” centered exclusively on containment and risk minimization, toward a model of “hybrid infrastructure engineering,” in which environmental remediation, energy production, and socioeconomic objectives are addressed simultaneously. Under this paradigm, geotechnical monitoring, maintenance, and long-term safety measures are no longer treated as sunk costs borne indefinitely by the operator or the state. Instead, they are sustained by the continuous generation and commercialization of renewable energy—effectively funding environmental stewardship through electric power transactions.

Ultimately, this integrated approach offers a pragmatic pathway for reconciling mine closure with the imperatives of the energy transition, climate policy, and social responsibility. By transforming legacy mining structures into assets for clean energy generation, Brazil can reduce environmental liabilities, avoid additional land degradation, and promote a just and orderly transition for mining-dependent regions. In doing so, tailings dams cease to symbolize environmental risk alone and are reimagined as platforms for innovation, resilience, and sustainable development in the post-mining landscape.

REFERENCES

Agência Nacional de Mineração (ANM). (2021). Resolução nº 68, de 30 de abril de 2021. Recuperado de https://www.dnpm-pe.gov.br/Legisla/Res_68_21.htm

Agência Nacional de Mineração (ANM). (2022). Resolução nº 95, de 7 de fevereiro de 2022. Recuperado de https://www.gov.br/anm/pt-br/assuntos/barragens/legislacao/resolucao-no-95-2022.pdf

Anglo American. (2019). Floating solar pilot at Los Bronces: Innovation in tailings management. Recuperado de https://www.angloamerican.com/our-stories/environment/first-in-the-world-photovoltaic-plant-built-over-mining-tailings

Brasil. (1988). Constituição da República Federativa do Brasil. Recuperado de https://www.planalto.gov.br/ccivil_03/constituicao/constituicao.htm

Brasil. (1989). Decreto nº 97.632, de 10 de abril de 1989. Recuperado de https://www.planalto.gov.br/ccivil_03/decreto/1980-1989/d97632.htm

Conselho Estadual de Política Ambiental (COPAM). (2017). Deliberação normativa nº 217, de 06 de dezembro de 2017. Recuperado de https://www.siam.mg.gov.br/sla/download.pdf?idNorma=45558

Conselho Estadual de Política Ambiental (COPAM). (2018). Deliberação normativa nº 220, de 22 de maio de 2018. Recuperado de https://www.siam.mg.gov.br/sla/download.pdf?idNorma=45938

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). (2024). Instrução normativa nº 14, de 3 de julho de 2024. Recuperado de https://www.ibama.gov.br/component/legislacao/?view=legislacao&legislacao=139412

Minas Gerais. (2019). Lei nº 23.291, de 25 de fevereiro de 2019. Recuperado de https://www.siam.mg.gov.br/sla/download.pdf?idNorma=48138

Pará. (2020). Instrução normativa SEMAS nº 01, de 14 de maio de 2020. Recuperado de https://www.semas.pa.gov.br/legislacao/normas/view/162010

Pará. (2025). Instrução normativa SEMAS nº 2, de 16 de abril de 2025.

U.S. Environmental Protection Agency. (2022). Best practices for siting solar photovoltaics on municipal solid waste landfills and tailings sites. Recuperado de https://www.epa.gov/system/files/documents/2022-05/best-practices-siting-solar-photovoltaics-municipal-solid-waste-landfills_051722-pub.pdf

Terzaghi, K. (1943). Theoretical soil mechanics. John Wiley & Sons.

Castillo, A., et al. (n.d.). Numerical consolidation of tailings materials: One-dimensional analysis. Applied Sciences. Recuperado de https://www.mdpi.com/2076-3417/15/6/3111

University of the West of England (UWE). (2024). 1D consolidation theory. Recuperado de https://environment.uwe.ac.uk/geocal/simulations/oedometer/theory.htm

García Cargia, P., et al. (2024). Just transitions to renewable energy in mining areas: Opportunities and challenges. Renewable and Sustainable Energy Reviews. Recuperado de https://ideas.repec.org

European Commission. (2026). Just transition mechanism. Wikipedia. Recuperado de https://en.wikipedia.org/wiki/Just_Transition_Mechanism

Mariotti, E., & Engström, J. (2025). Transforming abandoned mines into solar farms. Environmental Research: Energy. Recuperado de https://iopscience.iop.org/article/10.1088/2753-3751/adb6a3/pdf

Kryzanowski, T. (2018). From mine to megawatts. AltEnergy Magazine. Recuperado de https://www.altenerg.com/back_issues/story.php?sid=1418