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Closing Legal Loopholes in Public-Private Partnership Schemes for Waste Management in Indonesia

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ABSTRACT

In recent years, Public-Private Partnership (PPP) schemes have been increasingly used in Indonesia. PPP schemes attract foreign investment because they are cost-efficient. However, the waste-management sector has not reaped these benefits due to a gap in sectoral regulation. This paper addresses the issues of legal loopholes and proposes fundamental elements that should be included in future waste-management PPP legislation. The results of this paper are intended to assist legislators in developing future regulations for the sector. We employed a qualitative research method, specifically through a normative legal approach by relying on international standards and comparative provisions across jurisdictions. Our analysis identifies three main aspects that future legislation should include. First, waste-management PPPs require an explicit legal and policy framework that governs financing schemes, including clear and investor-friendly principles and options. Second, tax incentives are essential. To enable effective participation, legislation should provide tax and customs incentives (e.g., tax holidays and exemptions). Third, incentives related to local content requirements (TKDN) are highly required. One persistent barrier to market entry in PPP projects is strict TKD requirements and high import costs. Therefore, we propose TKDN mechanisms that incentivize investors to participate in the projects by reducing TKDN thresholds in the sector.

Keywords: Legal Loopholes; Tax Incentives; TKDN Incentives; Waste-Management PPP

ABSTRAK

Dalam beberapa tahun terakhir, skema Kerja Sama Pemerintah dan Badan Usaha (KPBU) telah banyak digunakan di Indonesia. Skema ini menarik investasi asing karena efisiensi biaya. Namun, belum ada regulasi sektoral di sektor pengelolaan limbah. Banyaknya peluang yang ditawarkan di sektor ini tidak diakomodasi secara memadai karena kesenjangan hukum. Oleh sebab itu, tulisan ini bertujuan untuk mengembangkan aspek-aspek utama yang harus dimasukkan dalam regulasi KPBU pengelolaan limbah dan berfungsi sebagai pertimbangan bagi legislatif. Kami menggunakan pendekatan hukum normatif sebagai metodologi penelitian, dengan mengandalkan standar internasional dan ketentuan perbandingan di yurisdiksi lain. Temuan utama kami meliputi tiga aspek utama untuk perundangan di masa depan. Pertama, Undang-Undang di sektor KPBU pengelolaan limbah memerlukan kerangka kerja yang jelas untuk skema pembiayaan yang diizinkan, termasuk skema yang jelas dan ramah investor, serta prinsip dan skema pembiayaan utama. Kedua, agar investor dapat berpartisipasi secara efektif, insentif pajak dan kepabeanan perlu mendapat perhatian serius dalam Undang-Undang (misalnya terkait pembebasan pajak dan bea masuk). Terakhir, insentif untuk Tingkat Kandungan Dalam Negeri (TKDN) merupakan salah satu masalah utama dalam proyek KPBU karena sulitnya masuk ke pasar akibat ketatnya persyaratan TKDN dan tingginya biaya impor. Kami mengusulkan mekanisme TKDN yang mendorong partisipasi investor melalui pelonggaran persyaratan TKDN di sektor ini.

Kata Kunci: Insentif Pajak; Insentif TKDN; Kekosongan Hukum; KPBU Pengelolaan Limbah

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INTRODUCTION

The preparation and implementation of infrastructure development in Indonesia require substantial financial resources, largely due to the country's vast geographic scope and sizable population. To address infrastructure needs and ensure equitable distribution across regions, effective solutions is needed to meet these extensive financing demands. The Indonesian government employs specific schemes to allocate sufficient funds for these development objectives (Alfianto & Gayo, 2021).

A funding gap also exists in the waste-management sector, which necessitates financial regulatory mechanisms that enable cooperation between the government and the private sector through Public-Private Partnerships (PPPs) (Vassileva, 2022). An assessment of the PPP legal framework in developing countries such as Indonesia reveals many legal loopholes that can hinder these partnerships, including ambiguity in the legal framework, taxation issues, and local incentives. This paper aims to identify and analyze these legal loopholes and proposes changes aimed at achieving an ideal and enforceable legal framework that protects the public interest while encouraging private-sector participation in PPP schemes, particularly in waste management.

THEORETICAL FRAMEWORK

PPPs are a widely used and viable financing scheme for large-scale infrastructure projects and are often used as the primary financing solution. By definition, PPPs are collaborations between public authorities and private entities to provide and manage infrastructure (Asian Development Bank, 2023). They typically involve long-term contracts under which the private sector and the government develop public assets and services; the private sector bears significant risks and management responsibilities as well as remuneration related to performance, maintenance, and/or demand or use of the asset or service (World Bank, 2021).

In Indonesia, the PPP framework initially appeared in specific sectors such as electricity and highways, which were considered to be closely linked to public assets or services (Saputra, 2024). Starting from regulations such as Law No. 15 of 1985 concerning Electricity and Government Regulation No. 8 of 1990 concerning Toll Roads, it then began to develop into regulations on cooperation between the government and the private sector in Presidential Decree No. 7 of 1998 concerning Cooperation between the Government and Private Enterprises in the Development and/or Management of Infrastructure. In 2015, Indonesia made crucial revisions in

PPP laws by aligning PPP practices with global standards and ensuring that financing is carried out sustainably across the country. Despite this progress, significant institutional and implementation challenges are still commonly found (Saputra, 2024).

Within this framework, there are two methods for implementing PPP projects: government-"proposed" projects and "unproposed" projects. The government will prioritize "proposed" projects, which are initiated based on public and national interests, rather than the "unproposed" projects of private entities (Yun et al., 2015). However, PPP outcomes do not always align with theoretical expectations (Siagian et al., 2019). For example, in the waste-management sector, which in theory should enable efficient delivery, PPPs have at times failed to provide essential infrastructure (Kakeu–Tardy & Véron, 2019).

To address these challenges and continue attracting private investment, the concept of project guarantees is frequently employed. In Indonesia, for instance, special State-Owned Enterprises (SOEs) known as State-Owned Special Mission Vehicles (SMVs) support both the government and the private sector. SMVs are designed to protect the interests of all parties in the event of unforeseen project circumstances. One of such SMVs, namely Indonesia Infrastructure Guarantee Fund (IIGF), acts as a guarantor and plays a crucial role in supporting the PPP ecosystem (Pambudi et al., 2023).

Waste Management Using a Public-Private Partnership (PPP) Framework

The main legal framework for waste management in Indonesia includes Law No. 18 of 2008 on Solid Waste Management, Law No. 32 of 2009 on Environmental Protection and Management, and Government Regulation No. 27 of 2020 on the Management of Certain Types of Waste. Upon closer examination, this framework remains inadequate to attract private investment through PPPs. The framework still lacks detailed provisions on long-term financing structures and risk-sharing mechanisms, which creates legal uncertainty, particularly for waste-management PPPs. As a consequence, the current framework does not ensure that PPPs in waste management operate within an ideal and enforceable legal system.

Fostering the Indonesian Government's Plan and Policy

In accordance with specific PPP regulations, Indonesia has committed to implementing Law No. 16 of 2016 concerning the Ratification of the Paris Agreement to the United Nations Framework Convention on Climate Change, which is operationalized through the National Energy Policy (KEN) and the Electricity Supply Business Plan (RUPTL). The strategic objectives of KEN are outlined in the National Electricity Master Plan (RUKN), which was established through Decree of the Minister of Energy and Mineral Resources No. 85.K/TL.01/MEM.L/2025. This framework is intended to provide a strategic foundation for integrating renewable energy and Waste-to-Energy (WtE) projects into the national development agenda.

RESEARCH METHODOLOGY

This study employs qualitative methods with a normative legal analysis. The object of analysis focuses on legal norms applied as positive law. Data sources include legislation, government policies in Indonesia, and international best practice legal instruments in waste management that can inform implementation in Indonesia. The study seeks to identify and critically examine legal loopholes and inconsistencies in the

existing regulatory structure and to formulate recommendations that can be applied within the Indonesian legal framework to make it more coherent and enforceable:

1. **Research locus.** The primary locus is Indonesia, with its legislation governing PPPs, environmental protection, and the infrastructure development life-cycle. To strengthen the analysis, selective comparisons to international best practices are used as references for identifying ideal regulatory approaches and adapting them to Indonesia's regulatory framework.

2. **Identification of legal gaps**. The analysis addresses unregulated areas (legal gaps or vacuums), incomplete laws, and overlapping regulations that collectively produce an imperfect and difficult-to-implement framework. These weaknesses hinder the development, financing, and implementation of PPPs in the waste-management sector.

3. **Data sources and analysis.** The sources include legislation, government reports, policy documents, scholarly literature, and PPP evaluations from existing projects within the aforementioned best practice jurisdictions. Analytical techniques include doctrinal analysis, examination of regulatory texts, or evaluation of other countries' regulations related to PPP implementation.

4. **Limitation.** The scope of this paper is limited to the legal and regulatory dimensions of PPPs in waste management. This study recognized the value of practical insights regarding contextual interpretation; however, the research did not include formal interviews with stakeholders such as regulatory bodies or private entities. The analysis is grounded in Indonesia's legal and institutional policy framework and would require adaptation to local legal and policy contexts elsewhere. Technical, financial, and operational aspects of waste-management systems are outside the scope, except where they intersect with legal considerations.

DISCUSSION

Regulating an Investor-Friendly Financing Scheme for Waste-Management PPPs

The source of funding is vital to a project's success. In general, Presidential Regulation No. 38 of 2015 on Public-Private Partnership (PR 38/2015) provides that PPP financing schemes may combine private and government funds. Whether a project is initiated by the government (solicited) or by private parties (unsolicited) influences the project's financing structure. This approach is reinforced by Article 2(1) of Ministry of Finance Regulation No. 68 of 2024 on Government Incentive for Infrastructure Finance through PPP Schemes (MFR 68/2024). As a result, under PPP schemes, the project's originator is typically responsible for financing the project (Dewar, 2015).

Although financing schemes depend on the originator, government funding plays a pivotal role in projects, particularly those designed for public purposes (Dewar, 2015). This situation underscores the need for cost-efficiency and minimal strain on public budgets (OECD, 2012). For waste-management projects, the government is likely to initiate the project and thus serve as the originator (solicited) (Dewar, 2015). This implies a significant impact on the governmental budget for establishing such projects. Although this responsibility accords with the government's fiduciary obligations, the approach does not align with the efficiency principles under PR 38/2015.

Another regulatory gap is the absence of specific provisions on financing energy inputs for projects (Fleta-Asín & Muñoz, 2021). Both PR 39/2015 and MFR 68/2024 are silent on the matter. In contrast, the National Energy Policy (KEN) and the Electricity Supply Business Plan (RUPTL) imply opportunities to adapt financial schemes in particular for Waste-to-Energy (WtE) PPP projects (PT PLN (Persero), 2025). This regulatory dissonance generates uncertainty in application. Accordingly, future legislation should explicitly address financing for energy procurement in waste-management projects (Adam, 2025). Mechanisms such as Power Purchase Agreements (PPAs) could support long-term financial viability (Steelyana & Aulia, 2024).

In the context of waste-management PPPs, the absence of sectoral PPP regulations means that the reliance on PR 38/2015 and MFR 68/2024 does not provide legal certainty for both the government and the investors. This problem arises for three main reasons:

1. **Overlapping regulation.** Developing a sectoral regulation is needed to mitigate conflicts among regulations applicable for specific projects (Maolana, 2018). Decentralization of the regulatory framework could lead to incoherence across government levels, which in turn creates information asymmetries regarding which regulation applies (OECD, 2012).

2. **Lack of sectoral consideration.** Both PR 38/2015, and MFR 68/2024 only govern general infrastructure projects and do not account for sector-specific technical considerations (OECD, 2012). For example, to determine the success of a project, economic productivity metrics are typically used. However, practitioners note that such metrics may overlook sectoral business cycles (Low & Pheng, 2021).

3. **Disincentivizing investors.** As previously mentioned, sectoral regulation plays a pivotal role in legal certainty (OECD, 2012). Having sectoral regulation can boost investors' or private parties' interest in participating in a waste-management project. Posner (1973) argues that regulations can create incentives that lead to entry into related markets. In this context, the absence of sectoral PPP regulation discourages investors from participating. For instance, there is no provision for financing energy inputs for projects. Although KEN and RUPTL emphasize the strategic nature of waste-management, particularly WtE projects and the need for priority treatment in financing (PT PLN (Persero), 2025), PR 38/2015 and MFR 68/2024 remain silent on the matter, thereby amplifying uncertainty of financial schemes.

To close such gaps, establishing a dedicated regulatory framework for waste-management PPPs is required. One such aspect is the financial scheme. The private sector's involvement in financing waste-management PPPs can strengthen its compliance under the efficiency principles. The World Bank reports that private sector involvement can provide access to cost-efficient financing, offer flexible financing options, contribute technical expertise, and reduce state spending (APBN) (Cointreau-levine & Coad, 2000). Furthermore, cost reductions can also enable the government to leverage resources for other projects (Karsayuda et al., 2023).

As a consideration for the legislature, future legislation for waste-management PPP schemes must adhere to the following principles:

1. **Value for Money (VfM).** The concept of VfM is closely related to a project's bankability. The United Nations Commission on International Trade Law (UNCITRAL) Legislative Guide on PPP states that VfM aims to maximize economy (UNCITRAL, 2021). Achievement of VfM can be measured by assessing concession terms and the performance of both the public and private sectors (Son, 2012). According to the Ministry of National Development Planning (Bappenas), financial planning for a Project must meet the VfM criteria to ensure its success (Bappenas, 2025). Regulating a flexible financing system for PPP that includes the participation of private sectors can enable VfM (Karsayuda et al., 2023). To achieve the aim, the Organization for Economic Co-operation and Development (OECD) recommends that the legislature include a VfM test to determine the project's financial capability and long-term sustainability (OECD, 2012).

2. **Cost-efficiency.** Under the principles of effectiveness and efficiency in PP 38/2015, PPPs must increase public utility and adequately finance infrastructure. This approach is supported by the OECD, which emphasizes that PPP financing must be designed, managed, and evaluated effectively and efficiently (OECD, 2012). Furthermore, ensuring efficiency and effectiveness in structuring a project's financial plan can trigger long-term success (Gatti, 2008).

3. **Sustainability and climate mitigation.** For a project to secure proper financing, the sustainability of the project must be taken into consideration. To achieve this, the project should gain significant public support by demonstrating its benefits to society and improvements to better quality of life (UNCITRAL, 2021). In this regard, waste-management PPPs aim to reduce the growing volume of waste, particularly in Indonesia, where infrastructure for the public interest carries significant weight (Gatti, 2008). For example, waste-management projects can employ green financing or bonds to support climate-change mitigation (Maphosa, 2024). Moreover, Incorporating sustainability and climate change principles can also provide both public and private sectors with access to governmental incentives.

4. **Transparency.** Formulating a sectoral regulatory framework that is accessible and establishes efficient procedures for financing waste-management PPPs can attract investors and provide legal certainty (UNCITRAL, 2021). In this case, regulating a sectoral waste-management PPP may foster transparency between public and private parties.

Furthermore, waste-management PPP regulations should explicitly enumerate the financing schemes permitted to the parties. For comparison, Governor Regulation of the Special Capital Region of Jakarta No. 18 of 2018 on PPP for Waste Management in Intermediate Treatment Facility (GRDKIJ 18/2018) explicitly lists the financing schemes that include:

1. Equity from the project company or the Regional Governmental Entities (APBD);
2. Debt from financial institutions, the project company, or the regional governmental entities;
3. Debt securities or obligations;
4. Non-binding sponsors; and
5. Other forms of financing schemes permitted under relevant regulations.

Hence, future legislation must explicitly state the permitted financing schemes. Along with the foregoing principles, we propose the financing schemes that align with the following principles.

1. **Creative financing.** Ministry of Finance Regulation No. 220/PMK.08/2022 on Government Incentives through Creative Financing for Public-Private Partnerships in Ibu Kota Nusantara (MFR 220/2022) establishes the basis for what constitutes creative financing. It encompasses a mixture of public and private participation in infrastructure financing. Article 1(6) of MFR 220/2022 defines creative finance as a financing scheme that relies on a combination of government funds, the private sector, and other stakeholders to fund infrastructure.

2. **Climate-change or green financing.** Green financing refers to funding provided by national or international financial institutions for projects that support sustainable growth (Nursahla et al., 2023). In this case, waste-management projects play a pivotal role in combating climate change and protecting the environment (Maphosa, 2024). This is further supported by RUPTL which highlights that waste-management projects reinforce Indonesia's climate-change initiatives (PT PLN (Persero), 2025). Hence, green financing should be included in future legislation.

3. **Islamic Financing.** The core idea of Islamic finance refers to commercial and financial activities that comply with Islamic law (Dewar, 2015). Its use in PPPs is enshrined under the UNCITRAL Legislative Guide on PPP (UNCITRAL, 2020). In Indonesia, Islamic financing has been applied in various PPP Projects, such as the Singkawang Airport (which uses Government Islamic Securities) and the Makassar-Parepare Railway (which employs Islamic finance for construction and operations) (Bappenas, 2025). The inclusion of Islamic finance within waste-management PPP legislation would incentive parties to utilize this modality in their projects.

Investor-Friendly Tax Incentives on Waste-Management PPPs

The legal regulatory framework for PPP in Indonesia is based on the Presidential Regulation No. 38 of 2015 on Public Private Partnerships, which establishes a framework for private sectors to participate in building state infrastructure based on universal PPP principles, such as partnership, risk allocation, and sustainable provision on infrastructure. However, this Presidential Regulation is general in nature and does not provide a suitable legal framework when applied specifically to waste-management PPPs. Private sectors participating in PPP schemes would need an incentive to make the waste-management projects feasible and bankable. Taxes and customs duties are fees that are accountable when a project is going to be financed.

The Indonesian Tax and Customs fee regulation states that private sectors undertaking PPPs may incur, among others, corporate income tax (PPh), Value-Added Tax (PPn), and import duties (S. Bella & Yudianto, 2021). These taxes and custom fees may be charged to private sectors in a PPP scheme. These billable taxes and fees can render a waste-management PPP infeasible. To support private sector participation and ensure feasible project financing in the waste-management PPPs, the government should issue specific regulations that facilitate private-sector involvement. Since PPPs in waste management have a high

and distinctive risk profile, investors need to consider several challenges, including:

1. **High capital requirements (CAPEX).** Building infrastructures that are capable of accommodating waste to energy conversion requires substantial capital, potentially up to trillions of rupiah, because the necessary technology in these PPP projects are scarce and often has a high price ceiling.

2. **Income and affordability risk.** The primary revenue for investors in waste-management PPPs will come from tipping fees (fees charged per unit of waste managed) paid by the local governments. The risk of this payment creates uncertainty on the tipping fees billed by investors.

3. **Long period of return on investment.** Waste-management projects structured as PPPs typically require a high period of investment, which may require up to 15 to 25 years of investing. Such long durations make PPPs vulnerable to political risks, regulatory changes, and macroeconomic fluctuations.

4. **Non-financial risks.** Waste-management PPPs, particularly on waste-to-energy projects, have certain risks investors may encounter, such as rejection of the project by the citizens and environmental regulations that strictly adheres to carbon emission requirements.

This analysis indicates that the waste-management PPPs present a high-risk profile that can create worries for investors. To reduce risks and enhance feasibility, the government support is necessary, including fiscal incentives in the form of tax or fee relief (Alifia et al., 2024). The forms of incentives given to investors undertaking waste-management PPPs include the following (Rahardjo & Farudin, 2025):

1. **Tax holiday.** A tax holiday is an incentive given by the government towards the corporate income tax. The incentive is usually a 100% tax exemption for a certain amount of time that can last between 5-20 years. The amount of time for the tax exemption is based on the value of the investment (S. Bella & Yudianto, 2021). When the exemption period expires, the corporation may still receive a 50% tax reduction for the subsequent two years. This incentive can significantly assist investors who seek to participate in waste-management PPPs. The legal basis of a tax holiday is the Minister of Finance Regulation No. 130/PMK.010/2020.

2. **Tax allowance.** A tax allowance differs from a tax holiday, in which tax allowance provides a set of tax reliefs, including (Surbakti et al., 2023):

   a. a reduction of net income by 30% of the total investment value, charged evenly over six years;

   b. accelerated depreciation and amortization of assets;

   c. extended fiscal loss compensation (up to ten years);

   d. a 10% withholding tax under Article 26 on dividends paid to foreign tax subjects, or a lower rate in accordance with applicable double taxation-avoidance.

   These tax reliefs are based on Law No. 36/2008 on Income Tax, as amended by Law No. 7/2021 on Harmonization of Tax Regulation, and Government Regulation No. 78/2019 on Income Tax Facilities for Investment in Certain Business Fields and/or in Certain Regions.

3. **Exemption of customs duties.** Customs-duty exemption may be granted for imports of capital goods, machinery, and tools used directly in the construction or development of infrastructure. The legal basis for customs-duty exemption is found in the Minister of Finance Regulation No. 171/PMK.04/2019.

4. **Exemption from VAT charges.** In addition to customs relief, the government may provide incentives by giving a Value-Added Tax (VAT) facility so that imported Taxable Goods, such as machinery and factory equipment otherwise subject to VAT, are exempted (R et al., 2024).

These four mechanisms can be recommended for incentivizing investors in waste-management PPPs (Shannia Angelia Rahardjo & Muhamad Farudin, 2025). If it were to be compared with the PPP schemes in the transportation sector, a specified regulation can be found, i.e., Minister of Transportation Regulations No. 58/2018 on the Procedures for Implementing PPP in the Provision of Transportation Infrastructure within the Ministry of Transportation. That regulation includes government support in the form of tax incentives for PPP projects, thereby providing investors with greater flexibility in project financing. Consequently, a sector-specific regulation for waste-management PPPs is urgently needed to create legal certainty for investors considering entry into this sector.

Providing fiscal incentives is not merely a means of reducing the capital burden on investors; such incentives can fundamentally change a project's financial feasibility (Patu & Akhmadi, 2021). For investors, decisions to make capital investments on long-term infrastructure projects are based on the metric, quantitative financial analysis (Citrazalzabilla & Suyatno, 2024). Each incentive described in this chapter has its own impacts that complete each other and structurally support the financial close of this project, including:

1. **Exemption from import customs duties and VAT.** The impact of this incentive will provide relief to investors during the early stages of a project by reducing total investment costs (CAPEX). Lower CAPEX means the project requires less debt and equity. The implications will be that the interest expenses during construction and operations are less burdensome and likely to help generate free cash flow in the first year of operations.

2. **Tax holiday.** This facility, as explained, will give an exemption from the corporate income tax during the incentive period. This will drastically increase the profits after being taxed, and, most importantly, generate free cash flow for investors. The impact of this incentive is most evident in the early stages of operations, which is a critical time stamp of the project where the investors need to pay back the debt and interest of the loan. A tax holiday will also support the main business activities of a WtE project that enters into a PPA, aligning with Indonesia's RUPTL (PT PLN (Persero), 2025).

3. **Tax allowance.** Although the impact of a tax allowance is generally less significant than that of a tax holiday incentive, it still contributes positively to the project. Accelerated depreciation allows companies to recognize larger non-cash expenses in the early years, thereby reducing taxable income and, consequently, the income tax payable. The reduction in net income also directly lowers the tax base.

Under the current regulations of Indonesian taxes, projects in the PPP sectors may be subject to taxation at various phases. Accordingly, the government needs to establish specific regulations that address investors' needs for incentives related to taxable items across a PPP's life cycle. These tax incentives may take the form of tax holidays, tax allowances, exemptions from custom duties, and exemptions from VAT.

These incentives will trigger creativity towards the Project Implementing Entity's options for structuring financing schemes to return the investments, under the assumption that such incentives are provided in a regulation specific to PPPs in waste management.

Enhancing Incentives through Reduction of Local Content Requirements (TKDN)

Local Content Requirements (LCR) or *Tingkat Komponen Dalam Negeri* (TKDN) are strategic policies that strengthen local industries by requiring a specified percentage of domestic components or value in goods or services, including materials, overhead, labor, and related production processes. Based on the provisions of Law of the Republic of Indonesia No. 3 of 2014 on Industry, the government states that to empower domestic industries, the government should increase the use of domestic products, particularly in state agencies, ministries, non-ministerial government agencies, state-owned enterprises, regional-owned enterprises, and private business entities, in the procurement of goods/services financed by the state budget, regional budgets, and/or cooperation between the government and private business entities and/or the exploitation of state-controlled resources.

Law of the Republic of Indonesia No. 29 of 2018 on Industrial Empowerment provides that domestic products comprise goods and services, including design and engineering, that are produced or worked on by companies investing and operating in Indonesia, using all or part Indonesian labor and raw materials or components derived wholly or partially from within the country. Accordingly, TKDN is implemented to foster the development of Indonesia's domestic industries and reduce dependence on foreign investment or imports. In the infrastructure domain, this policy aims to increase the use of local products in government projects, with the expectation of strengthening domestic industries, creating employment opportunities, and decreasing reliance on imported products (Hidayat et al., 2024).

Nevertheless, the implementation of TKDN, particularly in infrastructure sectors, is crucial yet challenging. The challenges are primarily due to the limited capacity of domestic supporting industries, which have yet to sufficiently enhance development-based technology, as well as the absence of a fully established upstream raw material industry capable of sustaining comprehensive industrial needs from upstream to downstream (Ravianti, 2024). Additionally, infrastructure development requires substantial procurements, and limitations in local resources—and their quality—that often fail to meet the required standards have become a major problem.

Indonesian regulation on Industry, namely Presidential Regulation (Perpres) No. 16 of 2018 on Government Procurement of Goods and Services, as amended by Presidential Regulation No. 12 of 2021 and Presidential Regulation No. 46 of 2025, mandates the use of domestic products with a minimum TKDN threshold of 40% for the combined TKDN and Company Benefit Weight (or *Bobot Manfaat Perusahaan*, BMP), with a fallback minimum TKDN of 25% if not applied in the

project. Strict adherence to this threshold may hinder project feasibility due to the absence of local suppliers for key components.

The application of TKDN incentive provision across Indonesia's infrastructure sectors, particularly in solar module or solar photovoltaic (PLTS) projects, presents a notable example of regulatory flexibility. Under Minister of Energy and Mineral Resources (MEMR) Regulation No. 11/2024, domestic and foreign solar module manufacturers that commit to local production and TKDN compliance by 31 December 2025 are granted a relaxation from the obligation to use domestic products. This incentive specifically applies to projects whose Power Purchase Agreements (PPAs) are signed by 31 December 2024 and that are scheduled to reach commercial operation by 30 June 30 2026, with eligibility determined through coordination by the Coordinating Minister for Maritime Affairs and Investment. (Partners, 2024). In contrast, the Waste to Energy (WtE) projects under PPP schemes face challenges in meeting the TKDN threshold, such as limited domestic capacity for advanced waste-management technologies. The lack of a comparable relaxation mechanism for TKDN in WtE projects risks hindering private sector engagement and delaying project realization, unlike the more flexible solar sector regulation.

While intended to develop domestic industry in Indonesia, the implementation of TKDN in the context of PPP projects, especially in waste management, still poses considerable challenges. In PPPs, these difficulties can be categorized as the main factors affecting the feasibility of waste-management PPPs in Indonesia:

1. **Limited domestic production capacity.** A strict TKDN threshold may create barriers to investment and the entry of advanced technologies into Indonesia. Domestic industries in Indonesia have not yet developed sufficient capacity, particularly in waste-disposal technologies. The majority of WtE Facilities heavily rely on sophisticated technologies such as incineration and gasification systems, which must meet TKDN threshold. This mandatory compliance can affect investors' interests because they must maintain project feasibility while covering large investment and operational costs (Azis et al., 2021).

2. **Key implications for the project's budget, procurement schedule, and bankability.** As discussed previously, Indonesia's TKDN threshold applies within the PPP schemes, which also includes the WtE sector. This threshold has a significant impact on project feasibility and financing. Because WtE technologies are not locally produced in Indonesia, project developers are either compelled to localize production to satisfy TKDN or to import technologies, which directly increases project costs due to the TKDN requirement. Procurement schedules often experience delays stemming from prolonged tender procedures and legal uncertainties, which raise investor costs and slow financial close. Bankability is likewise weakened by high capital expenditures and stringent regulations. In sum, private investors' interest in WtE PPPs decreases when significant TKDN thresholds are imposed without complementary policies that provide fiscal incentives and capacity building.

3. **Investor reluctance.** Excessively high TKDN thresholds may be perceived as economically restrictive, discouraging both domestic and foreign investors from participating in project tenders. Some investors are not interested in proceeding due to difficulties in obtaining locally produced components that meet the regulated standards. Investors also take into account the high cost and risk of overruns and the possibility of delays in the procurement process.

   A similar situation has been observed in several developing regions, including the Middle East, where PPP schemes are commonly used to enhance the efficiency of infrastructure development (Tamošaitienė et al., 2021). Observations from the Middle East cases indicate that efforts to attract investors often face similar obstacles, such as insufficient availability of suitable technology and equipment to meet project specifications. This comparison is relevant to Indonesia's WtE projects, where overly strict TKDN requirements may discourage participation by private and foreign investors and, in turn, undermine overall feasibility (Tamošaitienė et al., 2021).

Further insights can be drawn from the People's Republic of China (PRC), which has encountered similar challenges. The PRC's WtE sector has adopted PPP schemes, such as municipal solid waste-to-energy plants, that rely on investor funding to procure essential equipment, including incineration technology, while maintaining substantial local involvement in construction, operations, and workforce participation (Cui et al., 2020). This method increased the overall completion of the project, promoted effective transfer of knowledge, and improved both the financial viability and the ability to develop the domestic industry.

An examination of China's and Indonesia's WtE approaches indicates clear differences in how each manages the use of foreign technologies while cultivating local expertise. In China's case, it follows a step-by-step progression that initially focuses on adopting advanced technology from abroad to stimulate its industrial growth. Over time, the experience gained from this adoption phase is used to strengthen domestic research capacity, adjust the technology to match local waste characteristics, and gradually develop national production for specialized incineration equipment. (Cui et al., 2020). China employed this strategy to overcome domestic content restrictions by utilizing imported technology as a transitional tool to cultivate and strengthen its own sustainable innovation capabilities over the long term.

Conversely, Indonesia's focus on TKDN requirements tends to create barriers for the adoption of advanced technologies such as the incineration system. This limitation weakens the ability of WtE plants to process waste with high moisture and low caloric value, which impedes the broader progress of waste-management infrastructure development (Azis et al., 2021). Reducing or relaxing the TKDN threshold has the potential to expand opportunities for adopting advanced technologies.

Although both Indonesia and China rely on PPP schemes to address waste challenges, China's gradual and pragmatic policy direction has proven more effective in accelerating industrial growth. In Indonesia, maintaining rigid TKDN standards may slow the progress. Providing incentives through more adaptable TKDN policies could facilitate access to imported technologies capable of managing wet and low-calorific waste. With consistent policy support, effective implementation, and greater public participation, such an approach could

enhance the feasibility of WtE initiatives and reduce investment risk.

Relaxing TKDN requirements may serve as an effective approach to encourage greater participation from the private sector in waste-management infrastructure development. Lowering these thresholds can ease initial investment barriers and create a more feasible environment for implementing WtE projects. Such regulatory flexibility enables projects to begin with reduced financial pressure while progressively supporting the growth of local industries.

Based on Article 5(1)(g) of Law No. 30/2009 on Electricity, the Indonesian government holds the authority to grant permits for cross-border electricity trade, including PPAs with other countries. However, rather than prioritizing electricity imports or direct overseas procurement, a more contextually relevant policy would revise the TKDN threshold applicable to technologies used in the WtE industry. Such an adjustment would facilitate the use of advanced technologies that are not yet domestically manufactured, while simultaneously serving as a strategic mechanism to strengthen Indonesia's industrial capabilities, especially in WtE. Thus, the relaxation of TKDN requirements may be viewed as a transitional policy instrument consistent with national objectives to boost domestic technological development and secure long-term energy sustainability.

CONCLUSION

This Manuscript concludes that there is an urgency for Indonesia to create a specific, investor-friendly scheme for waste-management PPPs. The current scheme is slightly hindered by general PPP regulations, principally the Presidential Regulation No 38/2015, which do not address specific PPPs for waste management and thereby contribute to regulatory overlap, legal uncertainty, and a discouraging environment for private investors. Challenges also arise from the nature of the waste-management sector, including high capital requirements, long return-on-investment periods, and uncertain income from tipping fees.

Indonesia needs a more investor-friendly regulatory framework. This paper has analyzed regulatory and fiscal reforms from different perspectives and approaches. The first step is for the government to create a specific regulation on financing schemes for waste-management PPPs. This regulation should be grounded in the principles of value for money, cost-efficiency, sustainability, and transparency. There is also a need to include financing mechanisms, such as PPAs, to support stable financial viability. In addition, innovative funding mechanisms, including creative financing, green financing, and Islamic financing, should be regulated to broaden access to capital for private investors.

The second step is to include explicit provisions on fiscal incentives in the specific regulation on waste-management PPPs. These incentives include:

1. Tax holidays: A short-term 100% exception from corporate income tax to improve early-stage cash flow.

2. Tax allowances: Tax relief from net-income reductions and accelerated asset depreciation.

3. Exemption of customs duties and VAT: The exception towards customs fees and VAT on imported machinery and capital goods to reduce investment costs.

Finally, this paper looks towards the soft restriction of investment arising from local content requirements (*Tingkat Komponen Dalam Negeri*, TKDN). The current TKDN

threshold, i.e., 40% domestic components, poses challenges because Indonesia's domestic capacity for WtE technologies remains limited. Consequently, the policy increases project costs and deters investors. A reduction in the TKDN threshold is proposed as a crucial incentive to attract private investors, lower investment barriers, and enable technology transfer to Indonesia, similar to policies implemented in the solar energy sector. Although the electricity law permits cross-border PPAs, a targeted reduction of the TKDN threshold is more relevant for technologies used in the WtE sector and for the development of Indonesia's WtE industry. It is strongly recommended that the Indonesian government provide regulatory support to strengthen TKDN-related incentives for waste-management infrastructure, particularly WtE projects. By implementing these integrated reforms, Indonesia can create a more predictable and financially viable environment for private investment in critical waste-management infrastructure.

ABOUT THE AUTHORS

The authors of this paper bring a combination of academic and professional backgrounds. The authors are three final-year law students from Brawijaya University and a Law Graduate who is working as a legal officer at Panin Dubai Sharia Bank. The authors have a strong interest in the legal framework of waste-management PPPs, which is also supported by their legal backgrounds. The authors' main goal is to recommend solutions for creating an investor-friendly PPP regulation that provides legal certainty and attractive investment opportunities for private investors.

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Flood Damages in an Infrastructure Climate Risk Stress Test: A Case Study of a Solar Power Plant Project

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ABSTRACT

Climate change presents significant risks not only to the environment but also to financial systems. In response, climate risk stress testing (CRST) has become an important tool for regulators and financial institutions. However, most applications of CRST to date have focused on real estate and mortgage exposures, with little attention given to infrastructure assets. This paper addresses that gap by exploring methodologies to analyze flood-related physical risk for infrastructure in the context of CRST. The study applies the hazard–vulnerability–exposure approach by combining global flood hazard data from the Aqueduct tools, depth-damage functions, and simplified assumptions on asset exposure. A case study on an anonymized solar power plant project in Indonesia is conducted to demonstrate the methodology. The analysis produces estimates of financial loss using both single-event damage and Expected Annual Damage (EAD), which can then be integrated into project-level financial stress tests. The results show that this framework provides a practical and transparent way to quantify climate-induced flood risk for infrastructure, offering a starting point for regulators, development finance institutions, and multilateral development banks. At the same time, several weaknesses are identified, including the coarse resolution of global hazard maps, generic vulnerability functions are not calibrated for local conditions, and the absence of considerations for flood protection and indirect financial impacts.

Keywords: Flood Damage; Climate Risk Stress Test; Infrastructure Finance; Vulnerability Assessment

ABSTRAK

Perubahan iklim menghadirkan risiko yang serius tidak hanya bagi lingkungan, tetapi juga bagi sistem keuangan. *Climate Risk Stress Testing* (CRST) menjadi salah satu instrumen bagi regulator dan lembaga keuangan untuk mengantisipasi risiko tersebut. Namun, sebagian besar penerapan CRST saat ini lebih berfokus pada properti dan hipotek, tidak pada aset infrastruktur. Penelitian ini mencoba mengisi kesenjangan tersebut dengan mencari pendekatan yang cocok untuk menakar kerugian fisik akibat banjir di proyek infrastruktur. Analisis dilakukan menggunakan kerangka *hazard–vulnerability–exposure* dengan memanfaatkan peta bahaya banjir dari Aqueduct Tools, *depth–damage function*, serta asumsi paparan proyek. Perhitungan menghasilkan dua nilai utama, yaitu kerugian dari kejadian tunggal berdasarkan periode banjir dan *Expected Annual Damage* (EAD). Nilai kerugian ini dapat digunakan sebagai dasar untuk melakukan *stress test* terhadap arus kas proyek. Hasil penelitian menunjukkan bahwa kerangka ini dapat digunakan untuk mengalkulasi risiko banjir akibat perubahan iklim pada infrastruktur, serta menawarkan titik awal bagi regulator, *development finance institution*, dan *multilateral development bank*. Meski demikian, terdapat beberapa kelemahan dalam pendekatan ini, termasuk resolusi peta banjir global yang masih kasar, fungsi kerentanan yang bersifat umum dan belum dikalibrasi dengan kondisi lokal, serta belum adanya pertimbangan mengenai proteksi banjir dan dampak tidak langsung dari adanya banjir.

Kata Kunci: Climate Risk Stress Test; Kerusakan Banjir; Pembiayaan Infrastruktur; Penilaian Kerentanan

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INTRODUCTION

Climate change is one of the greatest challenges of our time (Boros, 2020). This challenge manifests through multiple transmission channels, including finance. It is, therefore, not an overstatement to argue that climate change constitutes a financial risk (Netto et al., 2021), and poses a significant threat to global financial stability (UNEP, 2024). Addressing those challenges has become increasingly urgent.

Over the past decades, awareness of climate risks has grown, including within the financial and banking industries. As a result, significant efforts have been made to examine and analyze financial risks arising from climate change and the transition to a low-carbon economy (Reinders et al., 2023).

This trend is also evident in Indonesia, with regulations and guidance published by the Financial Services Authority (*Otoritas Jasa Keuangan*, OJK). An example is the Climate Risk Management Scenario (CRMS), published in 2024 (OJK, 2024a). The document guides on implementing the Climate Risk Stress Test (CRST), which builds on a pilot CRST conducted by OJK and 11 major banks in Indonesia back in 2023 (OJK, 2024a).

However, despite these efforts, relatively few studies have focused on developing CRST methodologies for the infrastructure asset class. Furthermore, existing CRST methodologies found in national regulations or central bank guidelines are typically limited to the mortgage asset class. For example, it is outlined in the recent OJK Climate Risk Management and Scenario Analysis (CRMS) framework, which primarily focuses on flood-related physical risks for residential properties. The knowledge gap is critical for at least two reasons: First, infrastructure assets are inherently exposed to climate risks, particularly physical risk such as coastal and riverine flooding (Assab, 2025). Second, some organizations manage portfolios that are largely composed of infrastructure assets, such as development finance institutions and multilateral development banks.

This paper seeks to address the gap outlined above. However, given the extensive scope of climate risk stress testing, it will be limited to the physical risk of flooding arising from climate change. Additionally, the analysis focuses solely on the direct physical damage caused by flooding. This focus is important because there has been comparatively less attention in the literature on physical climate-related financial risk (Ranger et al., 2022).

Accordingly, the research question addressed in this paper is: "How can climate-induced flood-related physical damage to infrastructure assets be analyzed and considered in climate risk stress testing?" Specifically, this paper seeks to examine methodologies for estimating potential financial losses resulting from flooding in the infrastructure asset class.

A solar power plant project has been selected as a case study to apply the proposed flood-risk quantification framework within the infrastructure CRST context. This asset type is particularly relevant for two main reasons. First, solar power plants are physically exposed to flood hazards due to their extensive ground coverage and low-lying installation sites. Second, the availability of project-level technical and financial data allows a quantitative assessment of how physical damage translates into financial loss. As such, the solar power plant serves as a representative case to test the applicability and practical value of the proposed methodology for infrastructure assets.

LITERATURE REVIEW

The main challenge of CRST is linking climate-induced flood risk with financial risk, as outlined in the introduction, is scarcely addressed in the literature. Most literatures focus on mortgages. For example, Krijgsman (2021) highlighted the need of standardized flood risk assessment framework for financial institutions and examined methods for estimating the flood damage to real-estate portfolios. Building on this, Wu et al. (2024) outlined a similar methodology for analyzing flood risk but placed greater emphasis on its financial implications. They argued that two major financial risks in real-estate portfolios are market risk (referring to potential property loss) and credit risk (referring to an increased likelihood of mortgage default). Similarly, Auzepy and Bannier (2025) discussed the European Central Bank's (ECB) CRST, which focused on banks' mortgage exposures to flood risk and assessed the resulting impacts on credit risk.

As noted in the previous paragraph, flood risks in CRST predominantly address mortgages, and this is also evident in guidelines provided by national banks and financial authorities for commercial banks. In Indonesia, for example, OJK (2024b), provides technical recommendations for flood analysis in the mortgage sector, assigning percentage of asset value as the impact of flood in IDR, based on the location (city/regency level) of the mortgage and its flood risk level.

Bank Negara Malaysia/BNM (2024) offers similar guidance for the mortgage sector, but with more detailed technical specifications. In the technical guideline, BNM requires banks to analyze a 1-in-200-year flood event with assessments conducted at a minimum resolution of postcode level. Similarly, De Nederlandsche Bank (DNB) in its working paper (Caloia & Jansen, 2021) requires flood risk analysis in the real estate sector using flood maps provided by the Dutch Government. These maps provide inundation depths for specific locations at the postcode level, ranging from 1 to 5 meters for 50, 500, and 2,000 year return periods. Hong Kong Monetary Authority (2021) adopts a similar approach but allows banks greater flexibility in assumptions and methodologies, providing only projected mean sea level rise as a reference.

To further examine the methodology widely used in flood risk analysis in CRST, this paper adopts the IPCC risk framework. As explained by Krijgsman (2021) and expanded by Wu et al. (2024), risk can be expressed in the following formula:

$$R = H \; x \; V \; x \; E$$

Where *R* is risk or the expected value loss; *H* represents the *hazard*, which is the intensity of flooding; *V* represents vulnerability, which refers to the degree to which an asset or system is prone to harm from the hazard; and finally, *E* represents exposure, which is the level of the asset exposed to the hazard.

This conceptual definition of flood risk is applied in CRST by several authors (Assab, 2025; Krijgsman, 2021; Wu et al., 2024), although its direct linkage to financial risk remains underexplored in the literature. The analytical structure based on hazard (probability), vulnerability, and exposure builds upon the general framework for assessing climate risk in infrastructure proposed by Dawson et al. (2018). Since flood events are probabilistic in nature, the associated damage must also be represented as probabilistic outcomes. Accordingly, the return period becomes a critical variable in estimating expected damage.

Within the CRST context, expected damages can be derived by integrating the potential flood depths across multiple return periods (Assab, 2025). The resulting financial value does not represent an actual or guaranteed monetary loss, but rather an indicative measure of the magnitude of potential financial impact that a project may face under different flood scenarios. One way to interpret this value is by comparing it with a flood insurance premium. Ideally, the project proponent should ensure that the premium paid remains lower than the expected damage value to optimize cost efficiency in risk mitigation (Mühlhofer et al., 2024). This metric serves as a bridge between physical flood risk and financial stress testing, providing a quantifiable basis for evaluating asset vulnerability to climate-induced shocks.

The following subsections review existing methodologies in the literature according to hazard, vulnerability, and exposure.

Hazard

In the context of climate risk, a hazard refers to the occurrence of an extreme climate event (Field et al., 2012). This paper focuses on flooding as the hazard. Several approaches to analyzing flood hazard are discussed in the literature. The first approach involves advanced hydrological modeling, as demonstrated in studies by Kondrup et al. (2022) and Becher et al. (2023). While this method produces highly analytical results, it requires significant resources, which makes it less practical for CRST applications. The second approach utilizes available flood maps provided by governmental entities, as seen in studies by Caloia & Jansen (2021), Hong Kong Monetary Authority (2021), OJK (2024b) and Bank of England (2022). While this approach is more practical, these maps often lack granularity and typically only indicate risk levels without specifying flood intensity, such as inundation depth, as highlighted in OJK (2024b). This limitation reduces their utility for infrastructure asset analysis, which requires more precise data to estimate potential financial losses.

The third approach is the use of open-source flood models or maps, particularly the Aqueduct Flood Tool (Ward et al., 2020). This tool has been employed in several studies, including Assab (2025); Krijgsman (2021); Netto et al. (2021); and Wu et al. (2024). Aqueduct provides data on inundation depth (measured in meters) and probabilities across different return periods, making it more suitable for infrastructure asset analysis. This study adopts the last approach.

Vulnerability

Vulnerability in climate risk refers to the susceptibility of exposed assets to experience negative impacts from a hazard (Field et al., 2012). In CRST, vulnerability assessment is essential as it converts the physical value of a hazard into the expected financial value of resulting physical damage. The literature on this particular aspect is relatively limited. Some central banks provide flexibility for financial institutions to assess expected damage, as seen in the guidelines of Bank Negara Malaysia (2024) and the Hong Kong Monetary Authority (2021). Other institutions, such as DNB, recommend the use of impact functions in vulnerability analysis (Caloia & Jansen, 2021). Impact functions correlate monetary loss from physical damage with inundation depth from a hazard (Slager & Wagenaar, 2017). A similar approach is adopted by Assab (2025) and Krijgsman (2021), who rely on impact functions or depth–damage functions, most commonly using the global depth–damage dataset from Huizinga et al. (2017). We found that this depth-damage function is widely referenced in the literature (Assab, 2025). The dataset from Huizinga et al. (2017) is based on a global literature review and allows for adjustments based on continent and country. Therefore, this approach is selected for the present study.

Exposure

According to IPCC, exposure refers to the presence of people, livelihoods, economic assets, social and cultural assets, investment, infrastructure, services, ecosystems, and species that are subject to potential climate hazards (Field et al., 2012). Since this paper focuses on physical damage to infrastructure, the exposure analysis follows the simplification employed by Assab (2025), which estimates the proportion of the infrastructure assets directly exposed to flooding. For example, when assessing road infrastructure, instead of considering the entire length of a highway, only a representative segment (e.g., a 500-meter stretch) might be analyzed as being exposed to flood risk.

ANALYSIS

As discussed in the literature review, the flood analysis will be conducted by following a combination of tools identified in the literature, as illustrated in Figure 1.

For the case study, an anonymized project was selected to ensure confidentiality. The project is a ground-mounted solar power plant located in the Province of West Nusa Tenggara, Central Indonesia. The site is identified as being at risk of flooding using the Aqueduct tool.

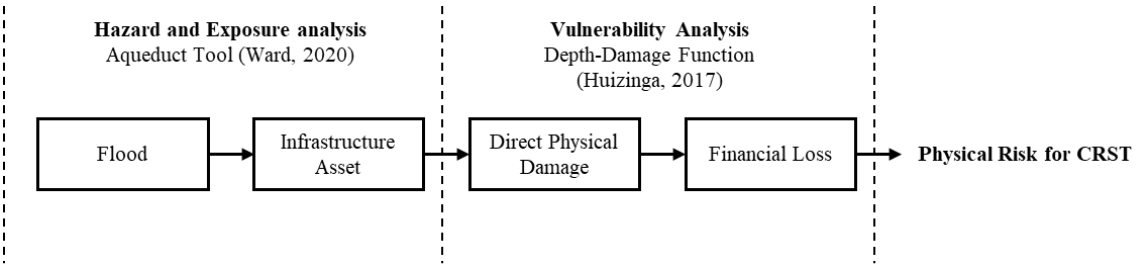

Figure 1. Flood Analysis Framework

The site represents a typical ground-mounted solar power installation in Indonesia, typically situated in lowland coastal areas that are exposed to flood hazards driven by sea level rise and land subsidence. This type of project was chosen because flooding and storms are major climate events that impact solar power plants (Silva et al., 2021). Aqueduct distinguishes between two types of flooding: coastal and riverine. This project is primarily exposed to coastal flooding driven by sea level rise and land subsidence.Figure 2 presents the flood map, where the dark pixels indicate flood hazards, with the project located within the mapped area.

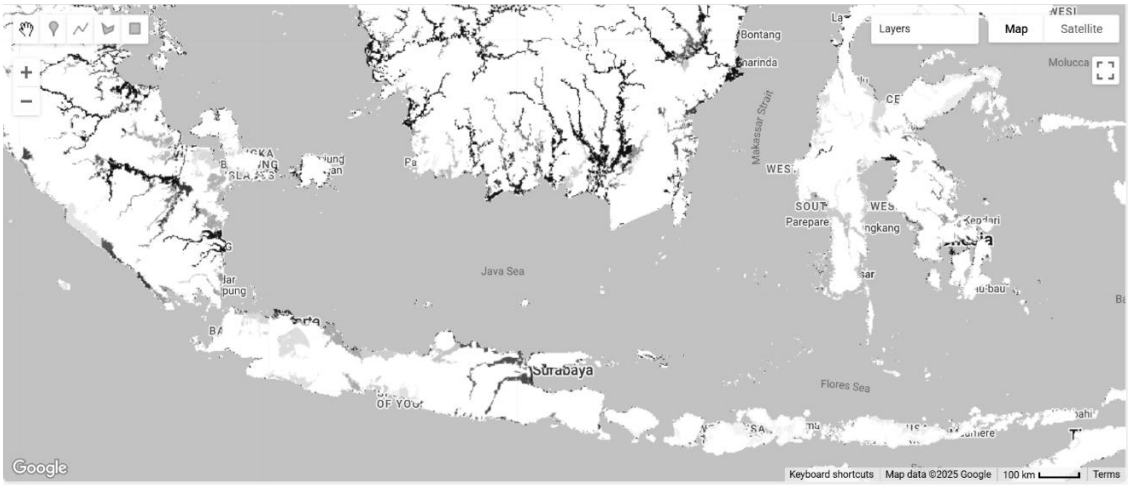

Figure 2. Flood Hazard Map

From the flood intensity shown in Figure 2, the exposure and vulnerability analysis can be carried out. The project area covers approximately 37.7 hectares; however, it is assumed that only a minor yet significant portion, namely the solar panels, is affected. Based on this assumption, the exposure is estimated to be 10% of the total project area. For the vulnerability assessment, the depth–damage function proposed by Huizinga et al. (2017) is applied, as shown in the following Table 1.

Table 1. Example of Depth-Damage Function

Depth (m)	0	0,5	1	1,5	2	3	4	5	6
Damage	0,00	0,21	0,37	0,60	0,71	0,81	0,89	0,97	1,00

From the Aqueduct tool, the flood hazard intensity data can be exported in table format. As noted earlier, the project is expected to be impacted by coastal flooding. The model provides multiple scenarios for 2030 and 2050; for the purposes of this paper, the high-emission scenario (RCP 8.5 from the IPCC) combined with land subsidence in 2050 is selected to illustrate the magnitude of the risk. The flood intensity—expressed as inundation depth and probability of occurrence—is presented in Figure 3.

By combining the depth-damage function and flood intensity, the expected damage from flooding on the project can be determined. For CRST applications, two approaches exist: one that estimates the expected damage from a single event and another that estimates the expected annual damage (EAD) (Wobus et al., 2019).

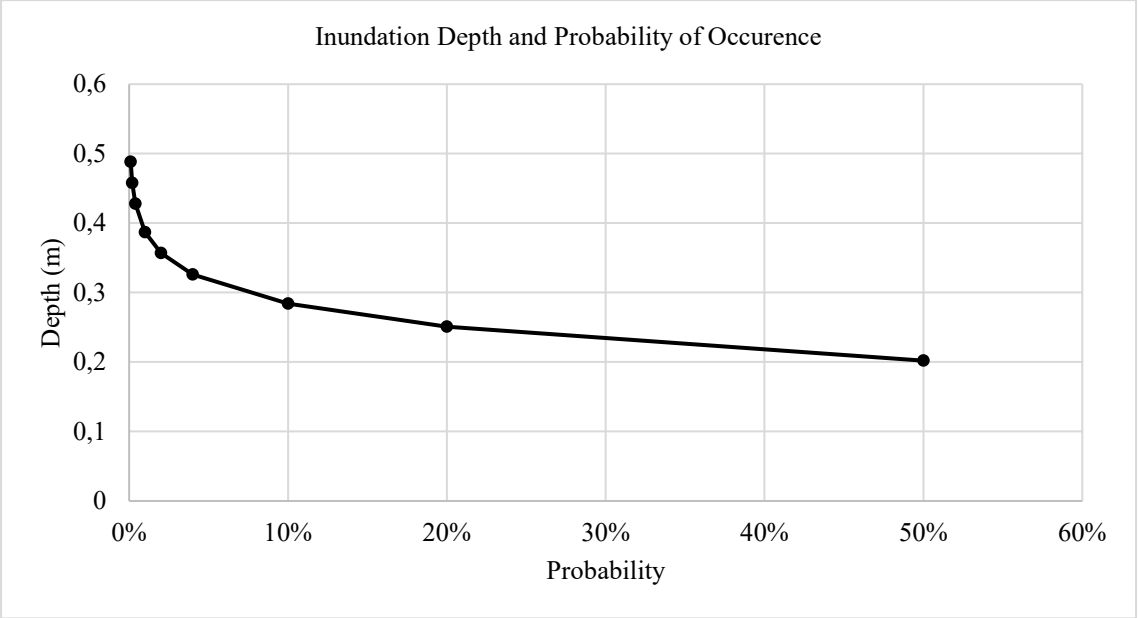

Figure 3. Flood Inundation Depth and Probability of Occurrence

The first approach is to select a return period and analyze the damage from that particular event. For example, the return period might be chosen to be 100 years, reflecting the intensity of the flood hazard. The inundation depth corresponding to the 100-year return period is 0.387 meters. The expected damage from the depth-damage function provided by Huizinga et al. (2017) can be calculated using the formula below:

$$Expected\ Damage = D(l)\ \times Max\ Damage$$

In this formula, D represents the percentage of direct physical damage from flooding, l is the inundation depth in meters, and Max Damage refers to the maximum potential loss per square meter, adjusted for country and asset class, expressed in euros. Using an inundation depth of 0.387 meters, along with the project area and the assumed exposure, the estimated physical damage amounts to IDR 98,651,609,197 or USD 5,989,392 (with max damage of IDR 2,616,754/m^2).

The second approach is to calculate annual damage based on all return periods, rather than just a single return period. This method is similar to the analysis conducted by Assab (2025). The expected damage can be expressed as an integral by the following formula:

$$Expected\ Damage = \int p(l)D(l)dl$$

where p(l) is the probability of flooding at depth l, and D(l) represents the corresponding physical damage. Since the Aqueduct tool provides flood hazard data at discrete return periods, the formula can be adapted into a summation:

$$Expected\ Damage = \left(\sum_j p_j\ \times D(d_j)\right) \times M$$

Here, j denotes the flood return periods (ranging from 2 to 1000 years in Aqueduct), pj is the probability of flood occurrence at return period j, D(dj) is the damage associated with inundation depth dj, and M represents the maximum damage value from Huizinga et al. (2017), as expressed in €/m². The resulting calculation of direct flood damage for the project is presented in the following Table 2.

Table 2. Project Flood Damage Calculation

Return Period	Probability	Inundation Depth (m)	Damage Percentage	Base Damage (IDR/m2)	Project Damage (IDR)
2	50%	0,202	11%	1.365.851	51.492.571.209
5	20%	0,251	14%	1.697.171	63.983.343.433
10	10%	0,284	16%	1.920.305	72.395.496.155
25	4%	0,326	18%	2.204.294	83.101.872.347
50	2%	0,357	20%	2.413.904	91.004.197.631
100	1%	0,387	22%	2.616.754	98.651.609.197*
250	0,4%	0,428	24%	2.893.981	109.103.071.670
500	0,2%	0,458	26%	3.096.830	116.750.483.236
1000	0,1%	0,488	28%	3.299.679	124.397.894.801
				Expected Annual Damage (IDR/year)	**52.707.489.993**

** First approach calculation*

Table 2 shows that the Expected Annual Damage (EAD) is estimated to be IDR 52,707,389,993, equivalent to approximately USD 3,200,000. This value represents the annualized loss from climate-induced flooding under the modeled scenarios. In the context of a Climate Risk Stress Test (CRST), the EAD can serve as the baseline financial impact used to evaluate the project's resilience to flood risk and its ability to withstand long-term climate pressures.

For example, this financial value can be used to stress test the project's cashflow. Assuming that the damage is absorbed as a reparation budget for the project, this amount would increase annual operating expenses, thereby decreasing the Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA). Since part of the project's funding is through debt, this would weaken the debt servicing capacity of the project, typically calculated using the debt service coverage ratio (DSCR) and loan life coverage ratio (LLCR).

The analysis yields two key values: single-event losses based on a selected flood return period and the Expected Annual Damage (EAD). Drawing from the literature, it is recommended that both values be used for stress testing. The single-event approach captures the impact of an extreme flooding scenario, testing the project's resilience under severe conditions. In contrast, the EAD reflects the average annual burden of climate-induced flooding, providing insight into the project's capacity to sustain such risks over its entire lifecycle.

The analysis shows how flood risk can be systematically quantified for CRST by breaking it down into hazard, vulnerability, and exposure components, which can be assessed separately and then integrated. The primary objective of this framework is to provide a method that is both simple and robust for estimating financial losses resulting from climate-induced flooding. The approach developed in this paper is sufficiently practical to be applied or adapted by financial institutions conducting CRST for infrastructure assets. Its primary strength lies in its explicit linkage of climate and financial risk analysis, moving beyond the purely engineering-based perspective that dominates much of the existing literature. Nevertheless, several limitations remain unaddressed and are discussed below.

The first limitation concerns the relatively low resolution of Aqueduct's flood hazard maps. The underlying data have a spatial resolution of approximately 10 km × 10 km (resized to 1 km × 1 km for visualization) (Ward et al., 2020). This resolution is too coarse for asset-level analysis, where the objective is to assess how flooding physically affects specific infrastructure components. In this case study, the flood hazard was treated as directly affecting the project site, but it was not possible to distinguish whether the inundation would impact, for instance, the solar panels, control rooms, or other supporting facilities.

This limitation also complicates exposure analysis: due to the coarse resolution of the hazard map, the proportion of the project considered exposed can only be assumed, which makes the resulting financial loss estimates highly sensitive to these assumptions. This issue becomes even more pronounced for linear infrastructure, such as roads and railways, where it is difficult to determine which segments are truly exposed.

Recognizing this limitation, several CRST guidelines, such as those from Bank Negara Malaysia (2024) and Caloia & Jansen (2021), require flood hazard analysis at a minimum of postcode-level resolution. Future research should, therefore, prioritize developing higher-resolution climate-induced flood models that can provide inundation depths at an asset-relevant scale to improve the robustness of CRST.

The second limitation is related to the oversimplification of vulnerability analysis when using Huizinga et al. (2017). While the depth–damage functions they provide are practical and widely cited, they are based on a global review of literature, which limits their precision at the level of specific infrastructure types and local conditions. The functions are limited to six broad asset classes (i.e., residential, commercial, transportation industrial, agricultural, and infrastructure), which means that assets outside these categories must rely on approximations.

In this study, for instance, the solar farm was treated as "industrial," even though its characteristics and susceptibility to flooding may differ significantly from those of other categories. Furthermore, the maximum damage values from Huizinga et al. (2017) are expressed in 2010 euros, requiring both currency conversion and adjustment to 2025 Indonesian prices. These layers of approximation and adjustment reduce the accuracy of the vulnerability analysis. To strengthen future CRST applications, locally calibrated depth–damage functions should be developed for Indonesia, ideally tailored to a broader range of infrastructure asset classes, including renewable energy facilities.

The third weakness involves the omission of flood protection measures in the analysis. Climate adaptation measures, such as protection against flood events, has often been overlooked in renewable energy discussion (Silva et al., 2021). In this paper, flood protection refers to design standards or physical structures that reduce the intensity of flooding, such as land grading and construction of dikes in power plant projects (Silva et al., 2021).

Unlike some studies (Krijgsman, 2021; Wu et al., 2024), this paper did not account for existing defenses or adaptation measures, which likely led to an overestimation of risk. By assuming that even low-return-period floods could cause serious damage, the results may exaggerate the project's vulnerability. Although there is a growing body of research on the role of flood protection and climate adaptation (Assab, 2025; Krijgsman, 2021), this area remains underdeveloped, particularly for application in CRST.

In practice, protection levels are often defined by the return period of flood events they are designed to withstand. Incorporating this information would allow for a more realistic estimation of Expected Annual Damage (EAD). For instance, if the project were assumed to have protection against a 10-year flood, the loss estimates in Table 2 would shift significantly compared to a no-protection scenario, as shown in Table 3 and Figure 4. The expected damage using flood protection results in IDR 1,350,532,882 per year, or approximately USD 82,000 annually.

Table 3. Project Flood Damage Calculation with Flood Protection

Return Period	Probability	Inundation Depth (m)	Damage Percentage	Base Damage (IDR/m2)	Project Damage (IDR)
2	50%	0	0%	-	-
5	20%	0	0%	-	-
10	10%	0	0%	-	-
25	4%	0,042	2%	283.989	10.706.376.192
50	2%	0,073	4%	493.600	18.608.701.476
100	1%	0,103	6%	696.449	26.256.113.042
250	0,4%	0,144	8%	973.676	36.707.575.515
500	0,2%	0,174	10%	1.176.525	44.354.987.081
1000	0,1%	0,204	12%	1.379.374	52.002.398.646
				Expected Annual Damage (IDR/year)	**1.350.532.882**

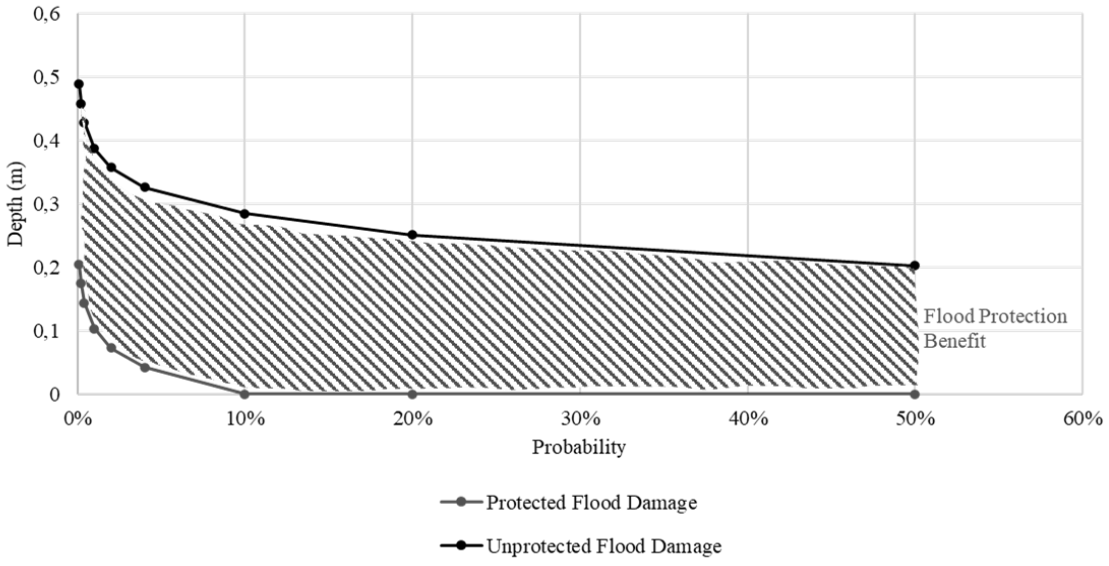

Figure 4. Protected and Unprotected Flood Damage with 10-Year Flood Protection

To contextualize this figure, the result can be compared with the typical insurance premium for solar power plants that includes flood coverage. Based on industry data, the average premium ranges from USD 4–10 per kW per year (Schwab et al., 2020). For a project with an installed capacity of 26 MW, this translates to an annual insurance cost of approximately USD 182,000, or between USD 104,000–260,000 across the typical range. Thus, the estimated premium exceeds the expected annual damage, which is reasonable since insurance premiums generally cover a wider set of hazards beyond direct flood impacts. Hence, this comparison suggests that the calculated expected damage is realistic and provides a credible basis for assessing flood-related financial risk within the CRST framework.

Finally, this paper does not account for the indirect impacts of flooding. In CRST, physical damage represents only one channel of risk transmission. Flooded infrastructure can trigger broader socioeconomic consequences, e.g., supply chains, disruptions to communities, or regional economies. For revenue-generating assets, flooding can also lead to prolonged income losses, even when physical repairs are relatively minor.

By limiting the scope to direct physical damage, this analysis underestimates the full financial implications of flood events. Moreover, the study does not extend the stress testing to capture the broader set of financial risks—such as credit risk, operational risk, market risk, and liquidity risk—which banks typically assess. Future research should, therefore, expand the framework to integrate both direct and indirect impacts, linking physical risk to the wider financial system.

So, incorporating these broader considerations would make CRST more comprehensive, practical, and valuable for banks, regulators, and development finance institutions.

CONCLUSION

This paper set out to explore how flood-related physical risk can be analyzed for infrastructure assets in the context of CRST. Through a combination of literature review and a case study of an anonymized solar power project, the study applied the hazard–vulnerability–exposure framework to estimate potential financial losses from climate-induced flooding.

The review showed that most existing guidance and applications of CRST remain focused on real estate and mortgage portfolios, leaving a clear gap for infrastructure assets. By applying tools such as Aqueduct flood maps and Huizinga et al.'s (2017) depth-damage function, this paper demonstrated a practical method to quantify both single-event losses and expected annual damages at the project level. Importantly, the methodology allows for a direct link between climate hazards and financial outcomes, a connection that remains limited in current practices.

However, the analysis also highlighted several limitations that need to be addressed in future studies. The resolution of global flood maps remains too coarse for asset-level analysis. While the depth-damage function is widely used, it is generic and not tailored to Indonesian infrastructure. Assumptions about exposure introduce uncertainty, and the absence of flood protection measures or consideration of indirect impacts from flooding likely leads to over-/under-estimate real risks. Furthermore, the financial stress

testing in this study was limited to direct damage, leaving out other important risk channels such as credit and market risk.

In addition, the scope of this study is intentionally narrow. The analysis focuses on a single solar power plant project, selected to illustrate the methodological application rather than represent the full diversity of infrastructure assets. As such, the results are not directly generalizable to other sectors or geographies without adjustment. Furthermore, the financial translation of physical damage relies on simplified assumptions regarding asset value and replacement cost, serving only as an indicative estimate rather than a precise valuation. These limitations define the exploratory nature of this study and should be considered when interpreting the results.

Despite these weaknesses, the paper provides an initial step in extending CRST methodology for infrastructure assets. For regulators, MDBs, and development finance institutions, the proposed framework can serve as a baseline that can be further adapted, localized, and scaled up. Future research should aim to develop country-specific damage functions, improve the granularity of hazard data, and integrate flood protection standards. In addition, further research is needed to link physical losses to credit, operational, and market risks to further enhance the value of the framework for financial institutions and regulators.

In short, while the approach presented in this paper is not definitive, it offers a practical pathway to bridge the gap between climate-related flood risk and financial stress testing for infrastructure assets, an area that will only grow in importance in the years ahead.

ABOUT THE AUTHORS

The authors are part of the Environmental, Social, and Technical Evaluation Division at PT SMI. Their primary responsibilities include evaluating the Environmental, Social, and Governance (ESG) aspects of infrastructure investments within PT SMI. In addition to evaluation tasks, the authors are also actively involved in developing frameworks and methodologies related to climate change analysis at PT SMI, ensuring that climate risks are systematically integrated into investment decision-making processes.

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Estimasi Kerugian Fisik Akibat Gempa Bumi pada Infrastruktur Jalan dan Jembatan: Studi Kasus *Fly Over* di Kota Bandung

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ABSTRACT

Indonesia's geographical location, which is prone to earthquakes and high economic losses in the infrastructure sector, requires a quantitative approach to support post-disaster financial resilience. This study aims to estimate earthquake losses to road and bridge infrastructure in a flyover in the City of Bandung using the HAZUS method developed by FEMA in the United States. The research methodology involved analyzing losses on the 550-meter flyover at the Jakarta street, the City of Bandung, which consisted of road and bridge segments. Estimates were made based on eight earthquake scenarios with different recurrence periods, using seismic parameters from the 2017 Indonesian Earthquake Map correlated to meet annual physical loss requirements (AAL). The analysis components included hazard (PGD and S1), fragility curves, and cost variables for each damage level. The results showed that the AAL values for sections AB, BC, and CD were IDR 23.46 million, IDR 14.29 million, and IDR 28.67 million, respectively. These findings indicate that the HAZUS method can be used to systematically map potential road infrastructure losses and support the planning of Disaster Pool Funding (PFB) allocations. Despite limitations in local data and design parameters, this study provides a strong basis for the development of more contextual and applicable loss estimation models in Indonesia.

Keywords: Bridge; Disaster Poll Funding; Earthquake; HAZUS; Road

ABSTRAK

Lokasi geografis Indonesia yang rawan gempa dan tingginya kerugian ekonomi pada sektor infrastruktur meniscayakan perlunya pendekatan kuantitatif untuk mendukung ketahanan finansial pascabencana. Kajian ini bertujuan untuk mengestimasi kerugian gempa bumi pada infrastruktur jalan dan jembatan di *fly over* Kota Bandung dengan menggunakan metode HAZUS—yang dikembangkan oleh FEMA di Amerika Serikat. Metodologi penelitian melibatkan analisis kerugian pada ruas *fly over* Jalan Jakarta Kota Bandung sepanjang 550 meter, yang terdiri dari segmen jalan dan jembatan. Estimasi dilakukan berdasarkan delapan skenario gempa dengan periode ulang berbeda, menggunakan parameter seismik dari Peta Gempa Indonesia 2017 yang dikorelasikan untuk memenuhi kebutuhan kerugian fisik tahunan (AAL). Komponen analisis mencakup *hazard* (PGD dan S1), kurva fragilitas, dan *cost variable* untuk tiap tingkat kerusakan. Hasil menunjukkan bahwa nilai AAL untuk ruas AB, BC, dan CD masing-masing sebesar Rp23,46 juta, Rp14,29 juta, dan Rp28,67 juta. Temuan ini menunjukkan bahwa metode HAZUS dapat digunakan untuk memetakan potensi kerugian infrastruktur jalan secara sistematis dan mendukung perencanaan alokasi dana *Pool Funding* Bencana (PFB). Meskipun terdapat keterbatasan pada data lokal dan parameter desain, studi ini memberikan dasar kuat bagi pengembangan model estimasi kerugian yang lebih kontekstual dan aplikatif di Indonesia.

Kata Kunci: Gempa Bumi; HAZUS; Jalan; Jembatan; *Pool Funding* Bencana

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PENDAHULUAN

Indonesia terletak pada zona tektonik kompleks, yaitu pertemuan tiga lempeng tektonik besar: Lempeng Eurasia, Lempeng Indo-Australia, dan Lempeng Pasifik (Pribadi et al., 2023). Dengan kondisi geografis tersebut, Indonesia menjadi salah satu negara di dunia yang sangat rawan ditimpa bencana gempa bumi. Berdasarkan data historis kebencanaan, bencana gempa bumi berpotensi menyebabkan kerusakan dan kerugian ekonomi pada infrastruktur yang paling vital dibandingkan bencana lainnya (BNPB, 2021; UNDRR, 2011).

Salah satu strategi penanggulangan dampak bencana adalah perencanaan ketahanan finansial untuk pulih kembali lebih cepat (The World Bank, 2019). Perencanaan ketahanan finansial sendiri memerlukan studi estimasi kerugian yang akan dihadapi. Beberapa studi sebelumnya telah melakukan upaya estimasi kerugian di wilayah Indonesia, namun estimasi tersebut lebih berfokus pada infrastruktur gedung (Aulady & Fujimi, 2019; Roi Milyardi, Pribadi, Abduh, Meilano, Lim, Wirahadikusumah, et al., 2025; Wibowo et al., 2024). Studi estimasi kerugian infrastruktur jalan dan jembatan masih sangat minim dilakukan, dan sering kali terbatas pada studi indeks risiko bencana gempa bumi (Direktorat Jenderal Bina Marga, 2014). Sementara itu, pembangunan dan pengembangan infrastruktur jalan dan jembatan masih terus berjalan dan menjadi prioritas pembangunan nasional (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2023).

Dalam konteks kebijakan publik, strategi ketahanan finansial telah diinisiasi melalui Peraturan Presiden Nomor 75 Tahun 2021 tentang Dana Bersama Penanggulangan Bencana dan Peraturan Menteri Keuangan Nomor 205/PMK.05/2021 Tahun 2021 tentang Pengakumulasian Cadangan *Pooling Fund* Bencana (PFB) pada Sisa Lebih Pembiayaan Anggaran Tahun Anggaran 2021. Skema tersebut diharapkan dapat mengurangi beban keuangan negara dalam proses rekonstruksi pasca bencana. Namun, dalam pelaksanaannya, PFB tidak dapat berdiri sendiri tanpa adanya metode estimasi kerugian bencana yang bertujuan menentukan besarnya kebutuhan PFB (Khotimah, 2024). Belum adanya metode baku dalam penentuan estimasi kerugian menjadi kendala pada proses realisasi PFB.

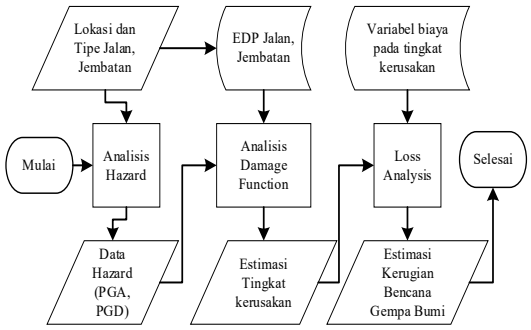
Penelitian ini bertujuan untuk mengestimasi kerugian gempa bumi pada infrastruktur jalan dan jembatan dengan studi kasus pada *fly over* Jalan Jakarta di Kota Bandung. Proses dan hasil studi ini diharapkan dapat memberi gambaran adopsi metode yang dapat digunakan untuk kontribusi PFB di Indonesia. Estimasi kerugian dilakukan melalui salah satu metode yang telah lama dikembangkan dan digunakan di berbagai

negara, yaitu metode HAZUS (FEMA-NIBS, 2020). Analisis estimasi dilakukan pada studi kasus ruas *fly over* Jalan Jakarta Kota Bandung. Hasil studi ini dapat memberikan gambaran alternatif metode estimasi kerugian bencana pada infrastruktur jalan dan jembatan pada kontribusi PFB di Indonesia.

KERANGKA TEORI

Metode HAZUS dikembangkan oleh Federal Emergency Management Agency (FEMA) pada tahun 1992 untuk memberikan perkiraan kerugian potensial akibat gempa bumi di Amerika Serikat (FEMA-NIBS, 2020). Metode ini telah dikembangkan dan diaplikasikan di beberapa negara di luar Amerika Serikat (Milyardi et al., 2025).

Salah satu keunggulan metode HAZUS ini adalah bahwa ia dapat membantu menghitung parameter teknikal, atau *Engineering Demand Parameter (EDP),* dengan simplifikasi sesuai tipe jalan maupun jembatan yang ditinjau, tanpa melalui analisis yang rigid (Milyardi et al., 2023). Hal tersebut dapat mempercepat proses estimasi pada skala luas. Pada modul estimasi kerugian jalan dan jembatan, terdapat tiga komponen analisis, yaitu *hazard, damage function,* dan *loss analysis,* sebagaimana ditunjukkan pada Gambar 1.



Gambar 1. Metode Estimasi Kerugian Gempa Bumi Hazus untuk Modul Jalan Dan Jembatan

Pada objek jalan, data *hazard* yang digunakan adalah *Peak Ground Deformation* (PGD). Nilai PGD didapat berdasarkan estimasi skenario magnitude gempa yang akan terjadi pada suatu ruas jalan yang dihitung melalui Persamaan 1 dan 2. Nilai *Peak Ground Acceleration* (PGA) dan nilai percepatan spektral respons horizontal di batuan dasar pada periode 1,0 detik, S1 yang merupakan basis *hazard* untuk jembatan didapatkan berdasarkan peta gempa lokal (dalam studi kasus ini berdasarkan Peta sumber dan bahaya gempa Indonesia 2017) (PUSGEN, 2017). Pada data sumber gempa 2017, terdapat keterbatasan dalam ketersediaan data, yaitu hanya tersedia periode ulang 2500 tahun, sementara data yang dibutuhkan adalah minimal 8 periode ulang dalam menentukan kerugian tahunan (*Average Annualized Losses, AAL*) sesuai metode HAZUS. Oleh sebab itu, penghitungan dilakukan dengan menggunakan persamaan korelasi parameter seismik sebagai berikut.

$$E[PGD_{SC}] = K_{\Delta} \times E[PGA / PL_{SC}] \quad (1)$$

$$K_{\Delta} = 0.0086M^3 - 0.0914M^2 + 0.4698M - 0.9835 \quad (2)$$

$$\frac{a_g}{a_{gR}} = \left(\frac{T}{T_R}\right)^k \quad (3)$$

Di mana:

K_{Δ} = faktor koreksi pergeseran yang diberikan oleh Persamaan 2

M = skenario magnitude gempa

a_g = nilai percepatan gempa yang dicari

a_{gR} = nilai referensi percepatan gempa

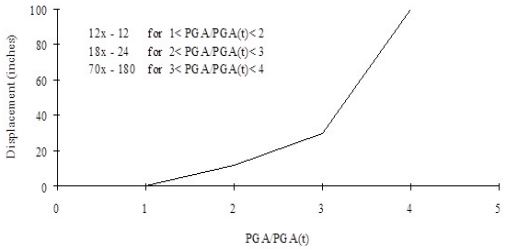
T = nilai periode ulang gempa yang dicari

T_R = nilai referensi periode ulang

k = koefisien seismik diambil 0,4

$E[PGA / PL_{SC}]$ = pergeseran tanah permanen yang diharapkan untuk kategori kerentanan tertentu pada tingkat getaran tanah yang dinormalisasi yang ditentukan Gambar 2.

PGA(t) = percepatan tanah ambang batas yang diperlukan untuk memicu likuefaksi, diambil 0.26 gram untuk kategori kerentanan *very low*



Gambar 2. Hubungan Pergeseran Penyebaran Lateral (FEMA-NIBS, 2020)

Pada komponen analisis kerusakan, dilakukan konstruksi kurva fragilitas yang dihitung berdasarkan Persamaan 4 untuk objek jalan, dan Persamaan 5 untuk objek jembatan. Penentuan EDP Persamaan 4 dan 5 yang digunakan berdasarkan tipe jalan dan jembatan yang ditinjau ditunjukkan pada Tabel 1 untuk jalan, dan Tabel 2 untuk jembatan. Pada *damage function* ini terdapat 4 tingkat kerusakan, yaitu *slight, moderate, extensive,* dan *complete.*

$$P_{Road}\left[ds \mid S_d\right] = \Phi\left[\frac{1}{\beta_{road}} \times ln\left(\frac{PGD}{\overline{PGD}}\right)\right] \quad (4)$$

$$P_{Bridge}\left[ds \mid S_d\right] = \Phi\left[\frac{1}{\beta_{bridge}} \times ln\left(\frac{S_1}{\overline{S_1}}\right)\right] \quad (5)$$

Di mana:

$P_{Road}[ds \mid S_d]$ = probabilitas tingkat kerusakan untuk jalan

$P_{bridge}[ds \mid S_d]$ = probabilitas tingkat kerusakan untuk jembatan

Φ = fungsi distribusi kumulatif normal standar

$\overline{PGD}$ = Nilai median dari PGD jalan untuk tingkat kerusakan tertentu

$\overline{S_1}$ = Nilai median dari S_1 jalan untuk tingkat kerusakan tertentu

β_{road} = standar deviasi dari logaritma natural dari PGD untuk jalan

β_{bridge} = standar deviasi dari logaritma natural dari S_1 untuk jembatan

Tabel 1. Komponen Analisis Estimasi Kerugian Gempa Bumi HAZUS untuk Modul Jalan Tipe HRD2 (*Urban Road*)

Komponen		Parameter		
Tingkat kerusakan		*Slight*	*Moderate*	*Extensive/ Complete*
Hazard		*Peak Ground Deformation* (PGD)		
Damage Function	$\overline{PGD}$ (mm)	150	600	1500
	β_{road}	0.7		
Loss Analysis (Cost variable)		0.05	0.20	0.7

Tabel 2. Komponen Analisis Estimasi Kerugian Gempa Bumi HAZUS untuk Modul Jembatan Tipe HWB4 (*Single Span-Seismic Design*)

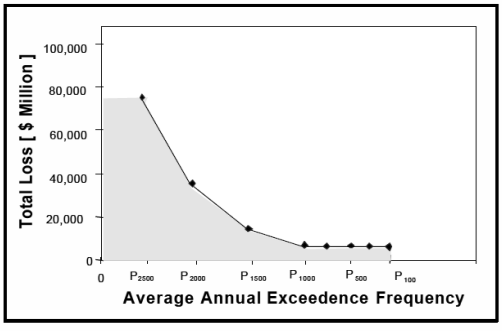
Komponen		Parameter			
Tingkat kerusakan		*Slight*	*Moderate*	*Extensive*	*Complete*
Hazard		*Peak Ground Deformation* (PGD)			
Damage Function	$\overline{S_1}$ (g)	0.8	1.0	1.2	1.7
	β_{bridge}	0.6			
Loss Analysis (Cost variable)		0.03	0.08	0.25	1

Nilai probabilitas kerusakan tiap tingkat kerusakan dikalikan dengan *cost variable,* yang dikalikan dengan nilai jembatan untuk mendapatkan nilai estimasi kerugian pada tiap skenario gempa yang ditinjau. Lingkup estimasi yang dihasilkan adalah kerugian fisik jalan dan jembatan saja, atau kerugian langsung (*direct loss*). Nilai estimasi tiap

skenario gempa menjadi dasar untuk penyusunan kurva ALL, sebagaimana ditunjukkan pada Gambar 3. Nilai AAL dihitung dari luasan area yang diarsir.

Implementasi metode HAZUS dalam konteks Indonesia memerlukan adaptasi yang cermat terhadap kondisi geologis dan karakteristik infrastruktur lokal. Keunggulan utama metode ini terletak pada pendekatan modular yang memungkinkan analisis terpisah namun terintegrasi antara komponen *hazard, damage function*, dan *loss analysis*, sehingga memfasilitasi perubahan berdasar ketersediaan data dan karakteristik regional. Metode HAZUS telah terbukti memberikan hasil yang konsisten dalam berbagai studi internasional, dengan tingkat akurasi yang dapat diterima untuk perencanaan strategis bencana, meskipun memerlukan validasi lokal untuk parameter-parameter kritis seperti kurva *fragilitas* dan *cost variable*.

Dalam konteks Indonesia, adopsi metode ini menjadi relevan mengingat standar desain infrastruktur nasional masih banyak mengacu referensi internasional, utamanya Amerika Serikat, sehingga parameter *Engineering Demand Parameter (EDP)* yang tersedia dapat diaplikasikan dengan penyesuaian minimal namun tetap memerlukan verifikasi empiris untuk kondisi spesifik Indonesia.



Gambar 3. Perhitungan *Average Annualized Earthquake Loss* Kurva Kerugian Probabilistik (FEMA-NIBS, 2020)

METODOLOGI

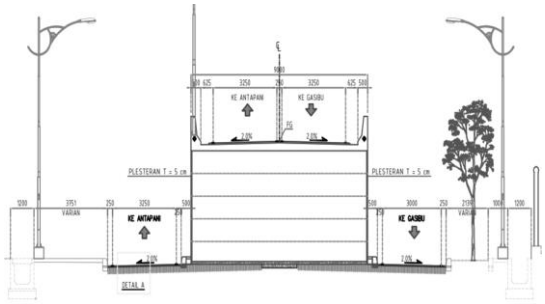
Penelitian dilakukan dengan melakukan perhitungan estimasi kerugian pada ruas jalan studi kasus. Estimasi kerugian dilakukan berdasarkan 8 skenario gempa untuk mendapatkan nilai AAL ruas jalan. Kasus yang dipilih pada kajian ini adalah *fly over* Jalan Jakarta Kota Bandung dengan total panjang 550 meter, terdiri dari objek jalan dan jembatan (sebagaimana terlihat pada Gambar 4 dan Tabel 4).

Detail perkerasan tipikal dan struktur jembatan ditunjukkan pada Gambar 5. Untuk ruas jalan terdiri dari 2 jalur dan 4 lajur.

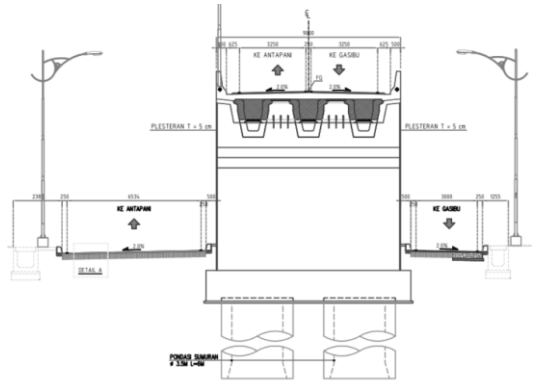
Gambar 4. Ruas Jalan *Fly Over* Jalan Jakarta Kota Bandung

Tabel 4. Data Ruas Jalan *Fly Over* Jalan Jakarta Kota Bandung

Ruas	Panjang (m)	Objek	Klasifikasi	Nilai Objek (Juta Rupiah)
A-B	225	Jalan	HRD2	7967
B-C	50	Jembatan	HWB4	6853
C-D	275	Jalan	HRD2	9737



Gambar 5a. Potongan Tipikal Objek Jalan



Gambar 5b. Potongan Tipikal Objek Jembatan

HASIL

Berikut hasil dari tiap komponen analisis metode HAZUS, yang terdiri dari komponen analisis *hazard*, kerusakan, dan kerugian.

Analisis *Hazard*

Hasil analisis *hazard* dapat dilihat pada Tabel 5. Nilai acuan parameter seismik (PGA, S_S, S_1) diambil berdasarkan data PUSGEN pada skenario gempa periode ulang 2500 tahun, dengan ketujuh periode ulang lainnya ditentukan berdasarkan Persamaan 3. Sementara itu, parameter seismik PGD ditentukan berdasarkan Persamaan 1 dan 2.

Tabel 5. Komponen Analisis *Hazard*

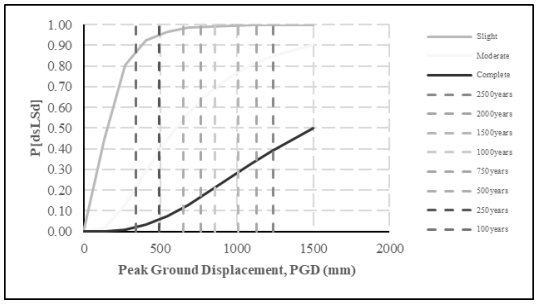
Parameter Seismik (Amplified)	Skenario Periode Ulang							
	2500	2000	1500	1000	750	500	250	100
PGA	0.62	0.57	0.51	0.43	0.39	0.33	0.25	0.17
Ss	1.42	1.30	1.16	0.98	0.88	0.75	0.57	0.39
S1	0.76	0.70	0.62	0.53	0.47	0.40	0.30	0.21
PGD (mm)	1238.50	1132.75	1009.62	858.46	765.15	650.59	493.06	341.76

Penentuan parameter seismik dalam analisis *hazard* merupakan tahapan kritis yang memerlukan pendekatan sistematis untuk memastikan akurasi estimasi kerugian. Dalam studi ini, tantangan utama yang dihadapi adalah keterbatasan data periode ulang gempa pada Peta Gempa Indonesia 2017 yang hanya menyediakan data untuk periode ulang 2500 tahun, sementara metode HAZUS memerlukan minimum delapan periode ulang berbeda untuk perhitungan AAL yang komprehensif.

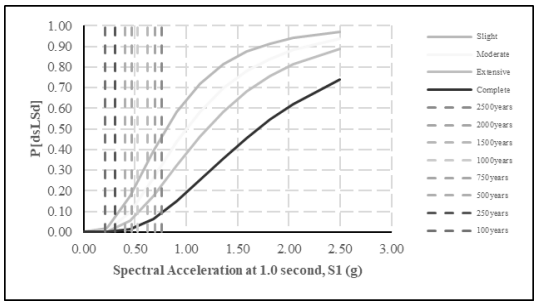
Untuk mengatasi keterbatasan tersebut, dilakukan interpolasi menggunakan persamaan korelasi parameter seismik dengan koefisien seismik k=0,4 yang telah terbukti valid untuk kondisi Indonesia. Proses ini memungkinkan transformasi data tunggal menjadi spektrum *hazard* multi-periode yang diperlukan, meskipun tetap membawa potensi deviasi terhadap kondisi seismik aktual di lapangan.

Analisis Kerusakan

Tingkat kerusakan dapat ditentukan dari hasil plot *hazard* pada kurva fragiltias, sebagaimana ditunjukkan pada Gambar 6 dan Tabel 6 untuk objek jalan (Ruas AB, dan CD), dan pada Gambar 7 dan Tabel 7 untuk objek jembatan (Ruas BC).



Gambar 6. Plot Kurva Fragilitas untuk Objek Jalan (Ruas AB dan CD)



Gambar 7. Plot Kurva Fragilitas untuk Objek Jembatan (Ruas BC)

Konstruksi kurva fragilitas dalam analisis kerusakan menunjukkan pola respons yang berbeda antara infrastruktur jalan dan jembatan terhadap intensitas getaran gempa yang sama. Objek jalan dengan klasifikasi HRD2 (*Urban Road*) menunjukkan tingkat kerentanan yang relatif tinggi terhadap deformasi tanah permanen (PGD), dengan probabilitas kerusakan *slight* mencapai 37.10% pada periode ulang 100 tahun, sementara kerusakan *extensive/complete* masih signifikan pada 15.02% untuk skenario yang sama.

Sebaliknya, objek jembatan tipe HWB4 (*Single Span - Seismic Design*) menunjukkan karakteristik kerentanan yang berbeda, dengan tingkat kerusakan *complete* yang dominan mencapai 31.50% pada periode ulang 2500 tahun, namun menurun drastis menjadi 10.49% pada periode ulang 100 tahun. Perbedaan pola ini mengindikasikan bahwa jembatan memiliki ambang batas kerusakan yang lebih tinggi dibandingkan jalan, namun ketika ambang tersebut terlampaui, tingkat kerusakannya cenderung lebih parah.

Analisis Kerugian

Estimasi nilai kerugian langsung (kerugian fisik) probabilitas tingkat kerusakan dilakukan melalui perhitungan kerugian dengan perkalian *cost variable* dan nilai objek infrastruktur yang ditinjau, sebagaimana ditunjukkan pada Tabel 8. Dari perhitungan estimasi kerugian langsung dari tiap skenario *hazard* kemudian dilakukan perhitungan AAL, sebagaimana ditunjukkan pada Gambar 8 dan Tabel 9. Pemetaan estimasi kerugian langsung ditunjukkan pada Gambar 9.

Tabel 6. Estimasi Tingkat Kerusakan pada Objek Jalan (Ruas AB dan CD)

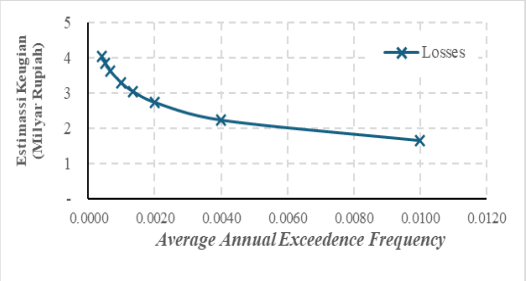
Tingkat Kerusakan	Skenario Periode Ulang Gempa							
	2500	2000	1500	1000	750	500	250	100
Slight	23.62%	24.97%	26.68%	29.00%	30.54%	32.52%	35.22%	37.10%
Moderate	24.74%	24.97%	25.13%	25.10%	24.88%	24.32%	22.73%	19.66%
Extensive/Complete	44.67%	42.21%	39.08%	34.80%	31.87%	27.94%	21.80%	15.02%

Tabel 7. Estimasi Tingkat Kerusakan pada Objek Jembatan (Ruas BC)

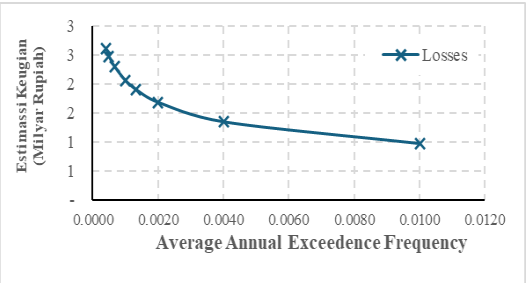
Tingkat Kerusakan	Skenario Periode Ulang Gempa							
	2500	2000	1500	1000	750	500	250	100
Slight	5.31%	5.28%	5.21%	5.08%	4.96%	4.75%	4.33%	3.66%
Moderate	4.26%	4.20%	4.12%	3.96%	3.84%	3.63%	3.24%	2.67%
Extensive	7.75%	7.59%	7.35%	6.97%	6.67%	6.22%	5.41%	4.31%
Complete	31.50%	29.62%	27.28%	24.15%	22.04%	19.27%	15.05%	10.49%

Tabel 8. Estimasi Kerugian pada Objek Jalan dan Jembatan

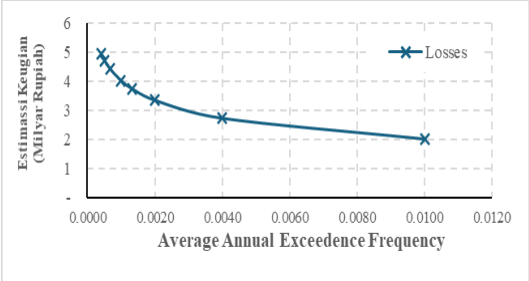
	Estimasi Kerugian (Milyar Rupiah)							
Skenario Periode Ulang Gempa	2500	2000	1500	1000	750	500	250	100
Ruas AB	4.05	3.86	3.62	3.29	3.06	2.74	2.24	1.66
Ruas BC	2.61	2.47	2.30	2.06	1.90	1.69	1.35	0.97
Ruas CD	4.95	4.72	4.43	4.02	3.74	3.35	2.74	2.03



Gambar 8a. Kurva AAL Ruas AB



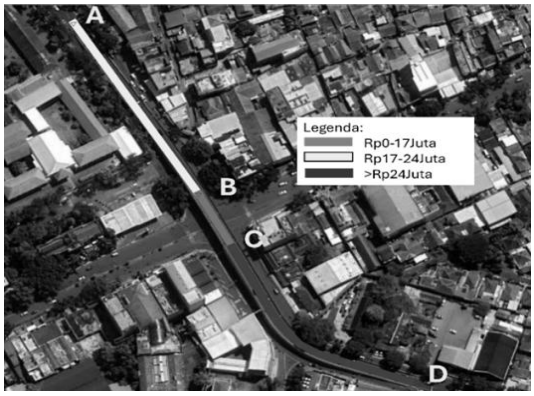
Gambar 8b. Kurva AAL Ruas BC



Gambar 8c. Kurva AAL Ruas CD

Tabel 9. Estimasi Kerugian Tahunan (AAL)

Ruas	Tipe	AAL (Juta Rupiah)
AB	Jalan	23.46
BC	Jembatan	14.29
CD	Jalan	28.67



Gambar 9. Pemetaan Kerugian Tahunan (AAL)

Konstruksi kurva fragilitas dalam analisis kerusakan menunjukkan pola respons yang berbeda antara infrastruktur jalan dan jembatan terhadap intensitas getaran gempa yang sama. Objek jalan dengan klasifikasi HRD2 (*Urban Road*) menunjukkan tingkat kerentanan yang relatif tinggi terhadap deformasi tanah permanen (PGD), dengan probabilitas kerusakan *slight* mencapai 37.10% pada periode ulang 100 tahun, sementara kerusakan *extensive/complete* masih signifikan pada 15.02% untuk skenario yang sama.

Sebaliknya, objek jembatan tipe HWB4 (*Single Span - Seismic Design*) menunjukkan karakteristik kerentanan yang berbeda, dengan tingkat kerusakan *complete* yang dominan mencapai 31.50% pada periode ulang 2500 tahun, namun menurun drastis menjadi 10.49% pada periode ulang 100 tahun. Perbedaan pola ini mengindikasikan bahwa jembatan memiliki ambang batas kerusakan yang lebih tinggi dibandingkan jalan, namun ketika ambang tersebut terlampaui, tingkat kerusakannya cenderung lebih parah.

DISKUSI

Hasil pemetaan estimasi kerugian langsung pada ruas jalan di studi kasus menunjukkan bahwa metode HAZUS dapat berkontribusi pada pemetaan kerugian infrastruktur akibat gempa di wilayah Indonesia. Tantangan yang dihadapi adalah pada adopsi EDP untuk tipe jembatan dan jalan yang diobservasi. EDP yang disediakan HAZUS adalah EDP yang merepresentasikan karakteristik infrastruktur di Amerika Serikat.

Pada penerapannya di infrastruktur Indonesia, masih relevan dengan acuan standar desain jalan dan jembatan masih banyak mengacu pada standar desain Amerika Serikat (Simanjuntak et al., 2023). Beberapa studi sebelumnya menunjukkan bahwa adopsi seluruh EDP HAZUS untuk wilayah Indonesia menghasilkan deviasi yang minim berdasarkan analisis yang komprehensif pada infrastruktur (Milyardi et al., 2025).

Adanya potensi penerapan metode HAZUS pada infrastruktur jalan dan jembatan dapat mendukung ketahanan bencana di Indonesia secara lebih luas dan cepat. Hal tersebut mendukung kebijakan terkait ketahanan bencana PFB sehingga kebijakan publik yang berbasis data kerugian dapat diukur dengan lebih efektif dalam mengalokasikan dana dan merespons dampak bencana secara sistematis (Rachman et al., 2025). Salah satu keterbatasan utama dalam studi ini adalah ketergantungan pada parameter seismik dari Peta Gempa Indonesia 2017 yang hanya menyediakan data untuk satu periode ulang (2500 tahun).

Upaya untuk memenuhi kebutuhan analisis AAL sesuai metode HAZUS dilakukan melalui interpolasi menggunakan persamaan korelasi parameter seismik, yang meskipun valid secara teknis, tetapi membawa potensi deviasi terhadap kondisi aktual. Selain itu, kurva fragilitas dan *cost variable* yang digunakan masih mengacu pada standar Amerika Serikat sehingga belum sepenuhnya merepresentasikan karakteristik infrastruktur lokal Indonesia. Keterbatasan ini menunjukkan perlunya pengembangan

basis data lokal yang lebih komprehensif agar estimasi kerugian dapat dilakukan dengan lebih akurat dan kontekstual dalam mendukung kebijakan PFB.

Selain itu, keterbatasan dari studi ini adalah estimasi kerugian yang dihasilkan hanya berupa kerugian langsung (*direct loss*), yaitu kerugian fisik saat jalan dan jembatan mengalami kerusakan akibat gempa bumi. Nilai *annual loss* yang dihasilkan dapat digunakan sebagai acuan dasar untuk analisis lebih lanjut dalam penentuan premi asuransi. Nilai kerugian tak langsung (*indirect loss)* berupa dampak ekonomi akibat tidak berfungsinya suatu ruas jalan dan jembatan, tidak ditinjau pada studi ini.

Untuk mengisi keterbatasan studi ini, penelitian selanjutnya dapat mengembangkan basis data dengan parameter seismik lokal yang lebih komprehensif, mencakup berbagai periode ulang gempa untuk mendukung estimasi AAL kerugian fisik yang lebih akurat. Selain itu, perlu dilakukan kalibrasi kurva fragilitas dan *cost variable* berdasarkan karakteristik infrastruktur Indonesia, baik dari segi desain teknis maupun kondisi geologis. Penelitian kolaboratif lintas institusi dapat mempercepat proses ini, terutama dengan melibatkan Kementerian PUPR, BNPB, dan lembaga akademik. Pengembangan model HAZUS yang terlokalisasi juga dapat membuka peluang integrasi dengan sistem anggaran nasional, sehingga estimasi kerugian tidak hanya bersifat akademik, tetapi juga aplikatif dalam mendukung kebijakan *Pool Funding* Bencana secara berkelanjutan.

KESIMPULAN

Studi ini menunjukkan bahwa metode HAZUS dapat diadaptasi untuk estimasi kerugian gempa bumi pada infrastruktur jalan dan jembatan di Indonesia, khususnya dalam mendukung kebijakan *Pool Funding* Bencana (PFB). Studi kasus *fly over* Jalan Jakarta Kota Bandung menghasilkan estimasi kerugian tahunan (AAL) yang dapat menjadi acuan dalam perencanaan ketahanan finansial pascabencana. Meskipun metode ini dikembangkan di Amerika Serikat, hasil analisis menunjukkan bahwa parameter EDP dan *cost variable* yang digunakan tetap relevan dengan kondisi infrastruktur lokal, terutama karena standar desain nasional masih mengacu pada referensi internasional.

Namun, penelitian ini juga mengungkap beberapa keterbatasan, seperti keterbatasan data parameter seismik lokal dan belum adanya kurva fragilitas serta *cost variable* yang dikembangkan khusus untuk konteks Indonesia. Oleh sebab itu, penelitian selanjutnya dapat berfokus pada pengembangan basis data lokal yang lebih komprehensif dan kalibrasi model HAZUS agar lebih representatif pada karakteristik infrastruktur nasional. Dengan demikian, estimasi kerugian yang dihasilkan akan lebih akurat dan aplikatif dalam mendukung kebijakan publik, khususnya pengalokasian dana PFB secara efektif dan berkelanjutan.

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Roi Milyardi merupakan dosen Program Studi Teknik Sipil, Fakultas Teknologi dan Rekayasa Cerdas, Universitas Kristen Maranatha. Ia menyelesaikan pendidikan Doktor Teknik Sipil dari Institut Teknologi Bandung pada tahun 2025. Ia memiliki minat dan fokus riset pada topik estimasi kerugian gempa bumi pada infrastruktur, manajemen bencana, manajemen konstruksi, dan *Building Information Modelling (BIM).*

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Decarbonizing Infrastructure in Indonesia: Opportunities, Barriers, and Stakeholder Perspectives

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ABSTRACT

Infrastructure development is a major driver of climate change, accounting for ~79% of global greenhouse gas (GHG) emissions and 88% of adaptation costs since 2022. In Indonesia, emissions are led by the energy sector (31%), which remains coal-dependent for power infrastructure operations. Other contributors include transport (17%), wastewater (8%), solid waste (5%), and process emissions from cement (5%) and iron–steel (6%). While the country has rapidly expanded roads, ports, airports, and dams, these gains have coincided with deforestation and reduced carbon sequestration. This study investigates barriers and stakeholder aspirations for decarbonizing Indonesia's infrastructure by applying a 5M business management lens—material and machine, methodology, money, and manpower—aligned with four decarbonization pillars (reduce, reuse, replace, remove), using evidence from focus group discussions, desktop reviews, and inductive analysis. Findings identify four principal barriers: (i) materials and technology—uptake of low-carbon options is constrained by cost perceptions and limited use of recycled inputs; (ii) standards and regulation—fragmented guidance and weak enforcement of green procurement; (iii) cost and funding—high certification expenses and underdeveloped green finance instruments; and (iv) skills and capabilities—insufficient technical expertise in low-carbon practices. Stakeholders call for systematic material mapping, stronger tax incentives, adoption of harmonized standards, and deeper academia–industry collaboration. The study proposes a policy roadmap to coordinate actors and accelerate infrastructure decarbonization.

Keywords: Climate Policy Integration; Greenhouse Gas Emissions; Infrastructure Decarbonization

ABSTRAK

Pembangunan infrastruktur merupakan salah satu kontributor utama perubahan iklim, dengan menyumbang 79% emisi Gas Rumah Kaca (GRK) global dan 88% biaya adaptasi sejak tahun 2022. Di Indonesia, emisi didominasi sektor energi (31%) yang masih bergantung pada batu bara untuk operasional infrastruktur. Kontributor lain meliputi transportasi (17%), air limbah (8%), sampah padat (5%), serta emisi proses dari industri semen (5%) dan besi–baja (6%). Ekspansi pesat jalan, pelabuhan, bandara, dan bendungan berlangsung bersamaan dengan deforestasi dan turunnya penyerapan karbon. Studi ini menelaah hambatan dan aspirasi pemangku kepentingan dalam dekarbonisasi infrastruktur Indonesia. Analisis menggunakan kerangka manajemen "5M"—material dan mesin, metodologi, uang, serta tenaga kerja—yang disejajarkan dengan empat pilar dekarbonisasi (reduce, reuse, replace, remove), berdasarkan diskusi kelompok terarah, telaah pustaka, dan analisis induktif. Temuan mengidentifikasi empat hambatan utama: (i) material dan teknologi—adopsi opsi rendah karbon terbatasi persepsi biaya dan rendahnya pemanfaatan material daur ulang; (ii) standar dan regulasi—panduan yang terfragmentasi serta lemahnya penegakan pengadaan hijau; (iii) biaya dan pendanaan—tingginya biaya sertifikasi dan belum berkembangnya instrumen pembiayaan hijau; dan (iv) keterampilan dan kapasitas—kurangnya keahlian teknis praktik rendah karbon. Para pemangku kepentingan mendorong pemetaan material, penguatan insentif pajak, adopsi standar yang terharmonisasi, dan kolaborasi akademia–industri yang lebih erat. Sebagai kontribusi praktis, studi ini mengajukan peta jalan kebijakan untuk menyinergikan aktor dan mempercepat dekarbonisasi infrastruktur.

Kata Kunci: Dekarbonisasi Infrastruktur; Emisi Gas Rumah Kaca, Integrasi kebijakan iklim

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INTRODUCTION

Infrastructure is one of the largest contributors to global greenhouse gas (GHG) emissions, accounting for approximately 79% of total emissions and 88% of all climate change adaptation costs since 2022 (Owotemu, 2025). Despite increasing global commitments to decarbonization, only 60% of infrastructure assets worldwide currently have GHG reduction targets that align with net-zero goals.

In Indonesia, the role of infrastructure in emissions is particularly significant, with around 80% of non-FOLU (Forestry and Other Land Use) emissions originating from infrastructure-related sectors. The energy sector, primarily dominated by coal-based power generation, contributes the largest share (31%), followed by transport (17%), waste management (13%), and industrial processes, such as cement and steel production (11%) (Hendri et al., 2022). These emissions have already exacerbated environmental vulnerabilities across the country, including sea-level rise, declining rainfall, extreme temperature increases, and land subsidence.

With a real GDP growth of 5.0% (World Bank, 2024) and a 5.12% year-over-year increase in Q2 2025, Indonesia, the largest economy in Southeast Asia, has maintained consistent economic growth in recent years, indicating sustained economic momentum into 2025. These recent macroeconomic conditions highlight Indonesia's dual challenge: maintaining infrastructure-driven growth while coordinating investment and policy decisions with ambitious climate and decarbonization targets. The International Monetary Fund (2025) also expects that these factors will continue to be generally positive.

To prevent the lock-in of high-carbon assets, it is crucial to align procurement, standards, and financing instruments with climate goals as public and private funds flow into infrastructure projects. These macroeconomic developments support the opportunity and urgency of directing infrastructure investment into low-carbon pathways.

To address these pressures, the Indonesian government has submitted its Enhanced Nationally Determined Contribution (ENDC), pledging to reduce emissions by 31.89% through domestic measures or up to 43.20% with international support, by 2030 (Puteri, 2024). The majority of reductions are expected to come from the forestry and energy sectors, while contributions from waste and industry remain comparatively modest. In parallel, Indonesia is preparing its Second NDC (SNDC), scheduled for 2025, which will introduce updated baselines and targets, with the overarching objective of peaking emissions before 2030.

In alignment with its Net Zero Emissions (NZE) aspiration by 2060—or earlier, contingent on enabling conditions—the government launched the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050 (Fitriana et al., 2024). This strategy sets gradual emission reduction pathways for high-emitting industries, e.g., cement and steel, with interventions including the adoption of blended cement, advanced manufacturing technologies, and circular economy practices.

In parallel to policy commitments, Indonesia has experienced unprecedented infrastructure expansion over the past decade, constructing hundreds of thousands of kilometers of roads, multiple new ports and airports, and large-scale water facilities (McCawley, 2015). While these investments have been vital for economic development and connectivity, they have also caused considerable environmental costs. For example, emissions from precast building materials can reach up to 283 $kgCO_2e$ per square meter (Atmo et al., 2017). These trade-offs highlight the need to integrate environmental safeguards and decarbonization strategies directly into infrastructure planning and implementation.

Recent institutional initiatives indicate a shift toward mainstreaming sustainability. The Ministry of Finance, supported by KIAT, launched the ESG Framework and Manual in 2022 (updated in 2024), designed to strengthen project preparation, enhance environmental and social co-benefits, and improve governance mechanisms (Pambudi et al., 2023; Setyowati, 2023). The framework aims to expand access to green financing and blended finance opportunities by aligning projects with global Environmental, Social, and Governance (ESG) standards.

Although Indonesia has yet to establish explicit regulatory targets for infrastructure decarbonization, the Ministry of Public Works has introduced a Roadmap for Implementing Sustainable Construction (2025–2030). The plan is guided by three main principles: boosting the economy, safeguarding the environment, and promoting social equity. By placing decarbonization firmly within the environmental pillar, the roadmap guarantees that reducing carbon emissions is an automatic and integrated consideration throughout infrastructure development (Owojori & Erasmus, 2025)

Within such a context, this study elaborates on how infrastructure decarbonization is developing in Indonesia. Our specific aim is to identify the main challenges to implementation and gather input from key stakeholders. This approach will help craft practical and shared solutions. Pushing decarbonization forward in infrastructure is critical not only for achieving Indonesia's national emission reduction goals but also for maintaining its nation's role in the global fight against climate change.

LITERATURE REVIEW

An increasing body of research suggests that decarbonizing infrastructure extends beyond the adoption of new technologies. It primarily requires driving systemic change by integrating governance, financing mechanisms, and regulatory frameworks (Geels, 2002; Geels et al., 2017; Jordan & Huitema, 2014). Recent studies evaluating emerging economies, which rely heavily on public infrastructure spending, emphasize that institutional resistance, lack of governance coordination, and conflicting policies are significant obstacles to low-carbon transitions (Anguelov, 2024; Owojori & Erasmus, 2025).

Cutting Carbon in Infrastructure: A Look at Global and Indonesian Strategies

The infrastructure sector plays a significant role in economic development; yet, it is also a main source of environmental degradation. Given that it contributes nearly 79% of global GHG emissions and requires 88% of climate adaptation spending, its actions are very critical in determining the world's climate future. The urgency to decarbonize this sector is grounded in climate mitigation theory, which argues that early interventions yield long-term economic and ecological dividends by reducing the costs of delayed action (Stern & Taylor, 2007). Within this framework, decarbonization transcends beyond technological or financial efforts; it is a matter of strategic foresight.

In Indonesia, the tension between infrastructure-driven growth and emission reduction targets is particularly pronounced. Infrastructure-related sectors, including energy, transportation, waste, and industry, are responsible for roughly 80% of national non-FOLU emissions. The dominance of coal-fired power plants places the energy sector at the core of Indonesia's mitigation challenge, while transport, waste, and industrial processes add significant pressure.

To address the above issues, Indonesia has articulated its Enhanced Nationally Determined Contribution (ENDC), targeting 43.20% reduction in emissions with international support, and has further committed to achieving Net Zero Emissions by 2060 or earlier. These institutional commitments reflect climate governance theory, which highlights the need for coordination across multiple levels of government, sectors, and stakeholders to address complex, cross-sectoral environmental challenges (Jordan & Huitema, 2014). Together, the NDCs and the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR 2050) embody Indonesia's efforts to balance developmental priorities with climate responsibility.

Analytical Framing: Integrating the 5M Framework as a Diagnostic Business Lens and the Four Decarbonization Principles

The 5M framework (Manpower, Materials, Machines, Methods, Measurement) serves as an effective managerial tool for locating operational bottlenecks in infrastructure projects. This paradigm links operational issues at the micro level with policies at the macro level when mapped against the four decarbonization pillars: reduce, reuse, replace, and eliminate. The framework employs specific terms like "replace" (substituting carbon-intensive materials), "decrease" (improving efficiency), "reuse" (circular processes), and "remove" (carbon capture or offsets). Combining these with the decarbonization pillars allows for a complete evaluation of technological, institutional, and behavioral barriers. Studies confirm that construction and Public-Private Partnership (PPP) projects often fail due to interconnected challenges in these non-technical areas, rather than technological deficiencies (Atmo et al., 2017; Roshdi et al., 2023).

Although global agreements set the goals, the implementation of decarbonization requires specialized diagnostic tools to pinpoint specific roadblocks at the project level. To meet this need, the present study employs the 5M Framework, which encompasses Material & Machine, Method, Money, and Manpower. This framework is borrowed from classic literature on operations and quality management which is traditionally used to systematically identify sources of inefficiency and error in industrial processes (Roshdi et al., 2023). In the context of sustainable infrastructure, the framework is adapted to

reveal the interplay between organizational, technical, and financial factors that hinder decarbonization efforts.

For example, constraints related to “Material & Method” may manifest through outdated contract specifications that continue to mandate the use of high-carbon materials, or through entrenched cost perceptions that regard low-carbon alternatives as prohibitively expensive. Meanwhile, “Manpower” constraints arise from insufficient technical expertise and the absence of certification systems that validate low-carbon competencies. “Money,” as a category, captures the persistent financing gaps that discourage investment in green infrastructure, while “Machine” refers to technological obsolescence and the limited dissemination of advanced, low-emission construction technologies.

By categorizing barriers in this manner, the 5M framework not only systematically diagnoses problems but also suggests tailored solutions. For example, it might identify the need for capacity-building efforts under “Manpower” or recommend specific procurement reforms under the “Method” category.

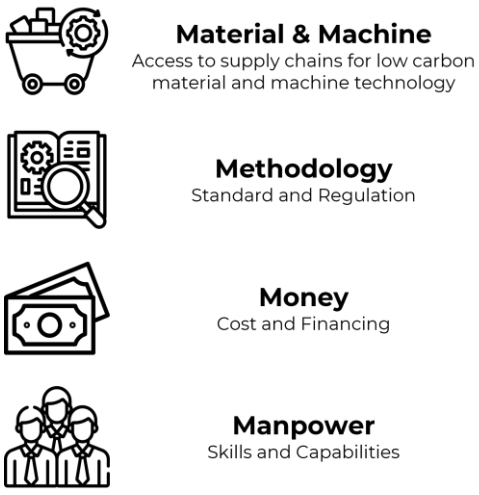

Figure 1. 5M’s Project Management Framework for Barrier Classification

Circular Economy and the 4Rs of Decarbonization

The 5M framework is complemented by the circular economy, which serves as a theoretical lens offering a systems-level view of resource efficiency. At its heart, the circular economy rejects the traditional, wasteful "take-make-dispose" approach. Instead, it promotes closed-loop processes designed to cut down on waste and retain the maximum value from materials. To put this into practice for decarbonization, this study adopts the “4Rs” as its guiding principles: Reduce, Reuse, Replace, and Remove (Geissdoerfer et al., 2017). Each of these strategies offers a method to lower the carbon intensity of infrastructure. Specifically, “Reduce” emphasizes minimizing the consumption of raw materials and energy; “Reuse” focuses on extending the lifespan of materials like steel and concrete; “Replace” encourages substituting carbon-heavy inputs with sustainable alternatives (such as blended cements); and “Remove” highlights the need to phase out dependence on fossil fuels.

Circular economy practices in Indonesia are still in the very early stages. Currently, regulatory systems do not offer sufficient incentives for the recycling of construction materials, and technological limitations restrict the use of innovative replacement materials. Despite these hurdles, examples from other places prove that progress is achievable. For instance, Thailand’s zero-OPC cement policy sets a regional standard for effective regulatory action, while the European Union’s Circular Economy Action Plan shows how harmonized policies can successfully guide transitions across entire sector (Korhonen et al., 2018; Kurniawan et al., 2024). Taken together, these examples demonstrate that the 4Rs can function as both a theoretical basis and a practical roadmap for Indonesia’s efforts to achieve decarbonization.

Recent trends underscore the vital role of circular economy concepts in infrastructure planning. The circular economy, as defined by researchers like Geissdoerfer et al. (2017) and Korhonen et al. (2018), is a systemic model aimed at boosting resource efficiency and drastically cutting waste throughout a project's life cycle. By incorporating these ideas into the 5M method, we can connect project-level management with sustainability policies, thereby strengthening the analytical capacity of decarbonization frameworks.

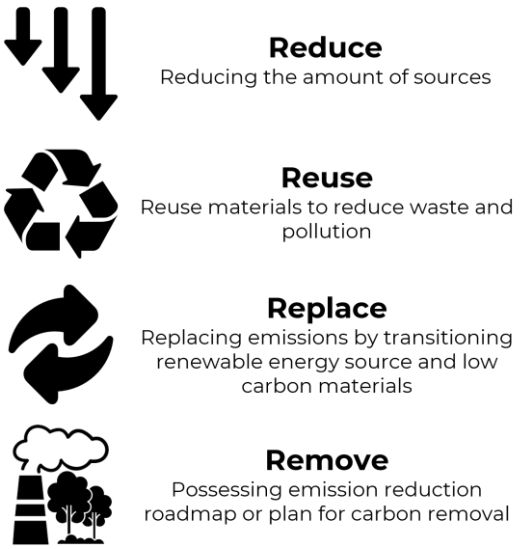

Figure 2. 4R' Decarbonization Strategies for Initial Approach

Public-Private Partnership (PPP) and Institutional Economics

In Indonesia, Public-Private Partnerships (PPPs) are becoming an increasingly prevalent mechanism to fund and deliver infrastructure projects. These arrangements are heavily influenced by institutional economics, which emphasizes that transaction costs, incentive structure design, and clear regulations ultimately determine a project's success (Chou & Leatemia, 2016). When it comes to green infrastructure, PPPs encounter unique obstacles. The need for complicated certification and fragmented approval processes leads to high transaction costs. At the same time, vague financing mechanisms create uncertainty for investors. These inefficiencies stem from weak institutional arrangements and unequal access to information (information asymmetries), which are key concerns in New Institutional Economics.

Despite the challenges, PPPs create opportunities to integrate decarbonization goals directly into the project contracts. For example, by linking emission reduction metrics to performance indicators, these agreements can better align incentives, lower agency costs, and boost accountability (Akomea-Frimpong et al., 2022). Furthermore, using risk-sharing tools—such as government guarantees or viability gap funding—could reduce the perceived risks for private investors, ultimately unlocking more green capital. Thus, institutional economics is valuable because it both explains current weaknesses and provides a guideline for designing more effective PPPs that are better aligned with climate goals.

Skills Gap and Human Capital Theory

A lack of skilled human resources is a significant barrier to developing low-carbon infrastructure, alongside financial and institutional challenges. According to human capital theory, investing in people, through education and training, leads directly to innovation and productivity. For the infrastructure sector, this means we urgently need to embed sustainability skills across all levels of professional development, from engineering schools to vocational programs, to create a competent green workforce.

However, in Indonesia, this integration of skills is still limited. Major professional organizations like BNSP and LPJK have not fully incorporated climate-related competencies into their official certification standards. Consequently, many engineers and

contractors lack the necessary training to adopt advanced materials, energy-efficient design, and digital tools needed for low-carbon construction (Gui et al., 2024). Bridging this skills gap requires coordinated efforts among educators, industry groups, and government bodies. Furthermore, the human capital perspective suggests that such investments will deliver more than just environmental benefits; a better-skilled workforce will also boost innovation, cut project costs, and enhance Indonesia's competitiveness in both regional and global markets.

Climate Finance and Risk Mitigation Frameworks

Ultimately, securing financing is the determining factor in how rapidly infrastructure can decarbonize. Climate finance theory emphasize the need to find ways to mobilize both public and private capital, typically through instruments, such as bonds, blended finance, and various guarantees (Stoll et al., 2021). Despite their potential, these instruments are underutilized in Indonesia due to market issues, including information gaps, high risk perception, and missing eligibility standards. The risk-return framework clarifies the situation: investors pull back when private partners are forced to take on disproportionate risk without adequate safeguards in place.

Developments such as PT PII's initiative to launch a green guarantee prove that offering de-risking mechanisms successfully boosts project bankability and increases participation from the private sector (Anguelov, 2024). Such instruments can accelerate the flow of investment into low-carbon infrastructure by decreasing uncertainty, enhancing creditworthiness, and lowering capital costs. Achieving Indonesia's decarbonization targets will require a concerted effort to both expand these mechanisms and simultaneously strengthen the regulatory clarity and investors' confidence.

Policy Tools: Focusing on Green Procurement and De-Risking Finance

Green Public Procurement (GPP) is one of the most pivotal demand-side policies for boosting the use of low-carbon products and technologies. Although Indonesia has regulations to support GPP, evidence shows that there are still challenges in setting technological standards, ensuring sufficient institutional capacity, and effectively enforcing compliance (International Institute for Sustainable Development, 2024). The government's purchasing authority cannot successfully direct the market toward sustainable infrastructure solutions in the absence of well-organized procurement procedures. Procurement reform is also essential to institutionalizing low-carbon transitions, according to research conducted in other ASEAN countries (Gui et al., 2024).

Significant financial barriers remain on the supply side. Low-carbon initiatives are sometimes viewed as risky by private investors because of their lengthy payback periods and unpredictable revenue streams. Research on de-risking tactics suggests that first-loss facilities, blended finance, and guarantee systems can mitigate perceived risks and raise private capital (Anguelov, 2024; OECD, 2024). The *Green Infrastructure Investment Opportunities (GIIO) Indonesia Report* illustrates how fiscal incentives and catalytic capital can stimulate private sector engagement in green infrastructure (Climate Bonds Initiative, 2022). The "Methods" and "Measurement" parts of the 5M framework, which focus on the institutional design and performance monitoring, completely align with these processes.

Capacity Building and Measurement Systems

While funding and regulations are vital, the success of infrastructure decarbonization fundamentally depends on human capital and green skills. Research in Southeast Asia indicates persistent deficits in the ability to conduct environmental audits, apply life-cycle assessment (LCA) methods, and effectively manage Measurement, Reporting, and Verification (MRV) systems (Cook et al., 2025; Gui et al., 2024). Without adequate technological capability, policies like GPP and other sustainable procurement rules risk being merely symbolic. To prevent this problem, we need to coordinate investments that close these gaps, specifically in technical training, certification programs, and institutional development for both the people doing the work and the regulators.

Successful decarbonization requires reliable measurement and data transparency. Research confirms this view: Chen et al. (2023) proposed a flow-based carbon accounting system for power grids, showing how detailed emission tracking can lead to better infrastructure planning. In the same vein, Royapoor et al. (2023) illustrated that using digital MRV tools in infrastructure projects boosts accountability and helps meet national climate targets. This evidence confirms the central importance of "Measurement" within the 5M framework.

Recent Technological and Policy Developments (2023–2025)

Recent evaluations have led to a better understanding of decarbonization technologies and how they interact with policy tools. Wang et al. (2025) offer a strategic reference for infrastructure project design by categorizing global decarbonization technologies, such as hydrogen, CCUS, and renewable energy, into discrete routes that align with sectoral settings. In order to achieve substantial decarbonization across the U.S. energy sector, the Annual Review of Environment and Resources (2024) highlights the interdependence of governance reform and technology innovation. This is a useful insight for rising economies such as Indonesia. In the meantime, Soares et al. (2025) emphasize the significance of city-scale decarbonization plans in areas like digital infrastructure, transportation, and building, which reiterate the necessity of cross-sectoral collaboration.

The social aspect of infrastructure changes is further emphasized by Smith et al. (2025), who contend that fair and inclusive methods improve legitimacy and long-term success. To resolve transition impediments, these new insights support adopting frameworks that explicitly connect technological, financial, institutional, and social factors, such as the integrated 5M and decarbonization pillars.

Synthesis and Research Gap

An analytical framework that integrates technical, institutional, financial, and human-capacity viewpoints is necessary for the transition to low-carbon and climate-resilient infrastructure systems. Few studies empirically investigate how operational bottlenecks interact with institutional and policy barriers in actual infrastructure projects, especially in the Indonesian context, regardless the fact that global and regional scholarship offers strong insights into decarbonization technologies, finance, and governance. These issues are often treated separately in existing studies.

This study closes that gap by identifying interconnected impediments across material, institutional, financial, and human-capacity dimensions using an integrated 5M–Decarbonization Pillar framework. This study combines focus groups, in-depth

interviews, and document analysis to provide a multifaceted, grounded understanding of Indonesia's infrastructure decarbonization landscape. Building on the previously discussed concepts and frameworks, this qualitative study investigates the systemic obstacles to decarbonizing Indonesia's infrastructure sector.

METHODOLOGY

The theoretical viewpoints examined in the previous part served as a guide for the research design. The assessment of barriers to decarbonizing infrastructure in Indonesia is structured around a combination of the "5M" business management approach and four interrelated pillars of decarbonization. Using the 5M framework combined with four decarbonization pillars, we assessed barriers across the infrastructure value chain.

The team applied a mixed qualitative design: FGD with the Ministry of Public Works and Housing (MPWH); twelve in-depth interviews over three months (academia, R&D, government, construction/inspection firms, finance/guarantee institutions, and industry associations); and a validation seminar/workshop with >200 participants – from the same respondent categories. The data were transcribed, clustered, coded, and thematically linked and triangulated with policy documents, recent literature, and the validation workshop.

Research Framework

The framework used in this study is structured around four dimensions.

1. The availability of supply chain technology

Our investigation within this pillar addresses two connected challenges. First, we identify barriers to low-carbon technology adoption and propose strategies for boosting energy efficiency, integrating renewables, conserving water, and cutting emissions. Second, we analyze the infrastructure material supply chain—both its current status and areas showing advanced practices. We combine these elements because the supply chain profoundly influences how infrastructure materials are manufactured and used.

2. Standards and regulations

Because the regulatory environment dictates the pace of decarbonization, this part of the analysis focuses on reviewing existing policies and regulations in Indonesia. The goal is to identify enabling conditions required to accelerate the transition to low-carbon infrastructure (Adityawarman et al., 2025). Special consideration is given to harmonizing the technical standards, procurement requirements, and sustainability criteria that apply across the board.

3. Cost and financing

Since economic concerns often decide whether low-carbon practices are viable, this part of the analysis examines funding opportunities for decarbonization. We specifically look at the role of incentive and penalty mechanisms and assess the broader economic impacts of using green materials in infrastructure systems (Madadizadeh et al., 2024). A further goal of the analysis is to determine how well innovative financial mechanisms can overcome the barriers posed by significant initial costs and investor risk perceptions.

4. Skills and capabilities

Decarbonization heavily relies on human resources. This section evaluates the Indonesian workforce's capacity to implement and scale green technologies and materials, while specifically identifying the gaps in training, certification, and technical

know-how. In doing so, the study clarifies the current professional abilities and helps prioritize investments in skill development.

The study applied a mixed qualitative methodology, involving in-depth interviews, Focus Group Discussions (FGDs), desktop reviews, and inductive reasoning, to make the framework operational. Interviews targeted four key stakeholder groups: government bodies, industry professionals and associations, academic and research organizations, and financial institutions and investors. We selected these participants for their specialized knowledge across key domains: workforce capacity, technological access, supply chain viability for low-carbon materials, and financial feasibility.

FGDs were employed to gather collective perspectives, explore stakeholders' views on the issues, and identify both new problems and the priorities of various actors in the infrastructure sector. To supplement the primary data, desktop reviews were conducted to synthesize existing academic literature, policy documents, and case studies concerning decarbonization in Indonesia and similar countries. The entire dataset was then analyzed using inductive reasoning, which allowed us to identify recurring patterns, connections, and core themes systematically. The method aligns with established qualitative research practices, which allowed us to draw conclusions grounded in empirical evidence while remaining open to discoveries.

To fully detail the data gathering process, we employed a qualitative, exploratory methodology, including focus group discussions, in-depth interviews, and a desktop review, to investigate the hurdles involved in decarbonizing Indonesia's infrastructure. The study team conducted stakeholder engagement in 2025 through series of Focus Group Discussions (FGDs) and in-depth interviews. These sessions were designed to identify cross-cutting issues and practical barriers hindering infrastructure decarbonization in Indonesia.

The discussions involved a wide array of participants, including government representatives, industry groups, academia, research institutions, and financial actors. The 90 to 120-minute discussions were systematically structured using the 5M analytical framework (Manpower, Machine, Method, Money) to ensure comprehensive coverage of technological, regulatory, financial, and human-capacity challenges.

The stakeholder engagement sessions generated practical insights that support and deepen our qualitative review of policy and literature. The following points summarize the key findings from the FGDs and interviews, which reflect the direct experiences of relevant institutional and industrial actors.

1. Availability of skills (manpower)

The participants called for the government to financially support the growth of green skills by providing subsidies, establishing publicly financed national training programs, and improving collaboration with training institutions. A major concern raised was the failure to integrate emission benchmarks and technical standards into professional certification systems, underscoring the immediate requirement to mainstream GHG-related competencies for engineers and project managers.

2. Availability of technology (machine)

To accelerate the use of low-carbon construction technology, participants highlighted the importance of implementing incentives, improving international collaboration, and achieving inter-sectoral

policy consistency. They agreed that standardization efforts (like SNI for green materials) and robust digital emission tracking systems are essential to enable national-scale deployment.

3. *Access to supply chains for low-carbon construction (material)*

Stakeholders called for mandatory procurement policies that prioritize low-carbon materials, supported by financial incentives aimed at mitigating risk for sustainable production innovations. To boost local supply chains, they also suggested improving the promotion of low-carbon construction products and creating stronger collaborative networks across government, industry, and academia.

4. *Cost and financing (money)*

The primary deterrent is the steep upfront cost of decarbonization. To address this, respondents suggested creating subsidy schemes for alternative fuels and implementing tax incentives for low-carbon sectors. They also recommended simplifying green product certification and using financial instruments like guarantees and concessional financing more broadly to attract greater private participation in these projects.

5. *Standard and regulation (method)*

The participants called for integrated policy formulation across ministerial lines and the immediate adoption of mandatory emission reduction standards in construction. They also stressed the need for broad awareness campaigns targeting the industry. Finally, a national monitoring dashboard was recommended to track implementation progress and ensure all parties are accountable for achieving decarbonization goals.

6. *Other findings*

The general recommendations included launching national awareness campaigns for low-carbon infrastructure, developing clear carbon trading mechanisms, and creating a multi-stakeholder roadmap to foster cooperation across ministries, academia, and industry groups. It was also recommended that a formal coordination forum be established to align public–private initiatives and facilitate the sharing of best practices and strategies.

Collectively, these findings highlight how infrastructure decarbonization relies mainly on the interdependence of institutional reform, financial incentives, and capacity building. The multi-stakeholder format of the engagement was crucial as it enables diverse actors to successfully exchange perspectives, agree on shared priorities, and co-develop feasible entry points for both policy and project interventions.

Data Collection and Analysis

In addition to gathering stakeholder perspectives on future decarbonization strategies, the FGDs examined four elements drawn from the 5M framework: materials and technology, standards and regulations, cost and financing, and skills and capacities. With participant consent, all conversations were audio recorded, verbatim transcribed, and cross-referenced with secondary data from technical reports, policy documents, and pertinent literature. Furthermore, to validate and enhance the ideas gleaned from the group talks, many informants from the same institutional categories participated in in-depth interviews to supplement the FGDs. To synthesize previous research, national policy frameworks, and comparative case analyses, a desktop review was also conducted.

Inductive theme analysis was used to analyze the data, and conventional qualitative coding techniques were adopted from Braun & Clarke (2006). To guarantee alignment among institutional impediments, stakeholder perceptions, and the conceptual structure of the 5M framework, themes and subthemes were identified iteratively. Triangulation of focus group discussions, interviews, and document reviews improved the validity of the results and enabled a more comprehensive understanding of the behavioral and structural elements affecting Indonesia's infrastructure decarbonization.

RESULTS

This section presents empirical findings derived from FGD notes, in-depth interviews, and validation-seminar feedback, which were then linked thematically and triangulated to strengthen the evidence. Reporting follows the 5M lens, with "Material & Machine" combined due to the close linkage between low-carbon material availability/properties and process/technology readiness in the decarbonization context.

In line with this section's purpose, findings are presented as factual outputs—recurring patterns, convergent statements, and paraphrased illustrative quotations—without interpretation or recommendations; further interpretation is provided in the Discussion. Institutional affiliations are disclosed in general terms to preserve credibility and confidentiality.

Mismatch Supply and Demand on Low Carbon Material and Technology Use in the Material Manufacturing

The adoption of low-carbon materials within Indonesia's construction sector remains at a nascent stage (Chan et al., 2022). Although the Ministry of Public Works has issued directives encouraging the use of non-Ordinary Portland Cement (non-OPC), actual implementation has been limited, primarily due to outdated technical specifications embedded in contract documents, which continue to favor conventional materials. In parallel, the adoption of technology in construction logistics also lags. For instance, Electric Vehicles (EVs) have yet to be deployed for transporting construction materials, with contractors instead relying on equipment with short operational lifespans as interim measures to reduce emissions.

The procurement system remains primarily price-oriented, and participants noted that contractors often face disincentives to adopt environmentally preferable but higher-cost materials. According to stakeholder feedback, PPP schemes provide greater contractual flexibility, though sustainability clauses are not yet systematically included in project terms. Participants reported that concrete recycling is considered a more feasible pathway than direct material reuse, which continues to face technical and operational constraints.

Stakeholders also noted persistent dependence on fossil fuels for material transport. According to FGD discussions, industries such as iron, steel, and cement are in the early stages of exploring low-carbon alternatives. Yet, they currently rely on limited green energy sources and lack clear economic incentives for large-scale adoption.

Lack of Harmonization of Standard and Regulation in Supporting Industry Sectors

Participants identified regulatory misalignment as a key obstacle to sector-wide decarbonization. The absence of harmonized standards was frequently cited in FGDs as a barrier to scaling low-carbon practices. Large contractors, such as PT Waskita Karya (Persero) Tbk, expressed concerns that decarbonization measures increase

operational costs and reduce competitiveness under current public tender regulations that prioritize the lowest bidder.

Participants noted increasing pressure to adopt emission calculation methodologies, particularly in response to the growing requirements of sustainable financing instruments. They highlighted the lack of a standardized and cost-effective roadmap adapted to local conditions. Respondents also reported that, although Minister of Public Works and Housing Regulation No. 9 of 2021 prioritizes local materials, the implementation remains inconsistent across projects.

Limited Availability of Green Financing Instrument to De-Risk Decarbonization Cost

Participants widely acknowledged that access to finance remains the main factor influencing the pace of decarbonization. Several green financing instruments have been introduced through banks and state-owned financial entities, including Special Mission Vehicles (SMVs), but their utilization in infrastructure projects remains limited. Stakeholders stated that while fiscal incentives exist, information on eligibility criteria and application procedures is not clearly communicated to potential project developers.

PT Penjaminan Infrastruktur Indonesia (Persero) is currently developing a green guarantee mechanism designed to enhance the bankability of sustainable projects. According to stakeholders, this initiative remains in the early stages of development and has not yet been fully implemented.

Gap in Skills and Capability on Infrastructure-based Emission Management and Technology

Human capital limitations further constrain Indonesia's decarbonization trajectory. A skills gap persists in both emission management and the application of low-carbon technologies within infrastructure development (Gui et al., 2024). Findings from a recent validation workshop revealed that the current engineering certification frameworks do not adequately incorporate competencies related to greenhouse gas (GHG) emissions measurement, monitoring, and mitigation. At present, only seven institutions in Indonesia are accredited to perform GHG verification and validation, reflecting a severe shortage in national capacity.

Participants reported that current capacity-building initiatives are fragmented and not yet aligned with the nine industrial sectors developing decarbonization roadmaps. Respondents noted limited coordination among ministries and training institutions responsible for developing these programs

DISCUSSION

Theoretical Interpretation of Key Barriers

The theoretical and empirical insights previously covered are used to explain these findings in the following discussion, connecting them to practical and policy consequences. The results show a complicated network of interconnected obstacles that work together to prevent Indonesia's infrastructure sector from being carbon neutral.

The challenges spanning material technology, regulatory frameworks, financing mechanisms, and human capital are not isolated problems; instead, they are signs of more profound systemic and institutional weaknesses when analyzed through the integrated 5M framework and the four decarbonization pillars (reduce, reuse, replace, remove). Therefore, the empirical data offer not only a glimpse of the current

implementation issues but also an opportunity to analyze them using more comprehensive theoretical frameworks that clarify the reasons for the obstacles' persistence and provide solutions.

Obstacles to decarbonization function concurrently on the "material and machine," "method," "money," and "manpower" dimensions. Stakeholder talks reveal how material and technological limitations, such as restricted access to low-carbon products and outdated contract specifications, reflect what Roshdi et al. (2023) refer to as structural inefficiencies ingrained in supply chain and procurement procedures. It emphasizes that institutional inertia, not only technical flaws, is the cause of operational-level inefficiencies. The idea that technological adoption depends on market incentives and regulatory clarity is supported by the continued use of high-carbon materials despite increased policy attention (Chan et al., 2022).

Comparative studies show that the lack of standardized sustainability criteria slows down the shift to low-carbon construction. This problem is directly mirrored in Indonesia's procurement system, which still prioritizes selecting the lowest-cost bid over using value-based criteria (Kurniawan et al., 2024). Ultimately, these findings validate the 5M framework's effectiveness in diagnosing how the combined influence of institutional rules, market forces, and operational decisions determines the pace of decarbonization.

Institutional and Regulatory Fragmentation

Fragmented institutional frameworks—evidenced by inconsistent standards and regulations—are slowing down decarbonization. These institutional misalignments, as noted by North (1990) and Chou and Leatemia (2016), increase transaction costs and stifle innovation, particularly where national procurement rules clash with sustainability goals. Enforcement of these goals by ministries remains weak due to conflicting mandates and poor coordination.

From an institutional economics perspective, this fragmentation creates uncertainty, which discourages both public and private investment in green technology. Clear regulatory signals, such as Thailand's successful zero-ordinary Portland cement program, can accelerate the market shift by aligning incentives and lowering perceived risk. Therefore, Indonesia's regulatory environment needs a more cohesive structure that fully integrates sustainability into its technical standards, procurement, and monitoring systems.

Financial Governance and Investment De-Risking

Financial limitations compound these institutional challenges. Although domestic banks and Special Mission Vehicles (SMVs) have introduced green financing mechanisms, their application in infrastructure projects remains limited due to complex administrative procedures and unclear eligibility requirements. It aligns with findings from Stoll et al. (2021) and the OECD, who noted that information asymmetries and high transaction costs often deter private investment in climate infrastructure.

Drawing on climate finance theory, de-risking tools—such as blended finance, guarantees, and concessional loans—are essential for shifting the risk-return balance toward low-carbon projects. The move by PT Penjaminan Infrastruktur Indonesia (Persero) to establish a green assurance mechanism is a significant step in the right direction. However, these tools will not be truly transformative unless they are expanded and backed by clear financial incentives. We can

boost project viability and investor confidence by improving financial governance through streamlined processes, unambiguous eligibility criteria, and structured technical support.

Human Capital and Capacity Constraints

A significant obstacle also arises from limitations in human capital. Specifically, the lack of greenhouse gas (GHG)-related skills in engineering certification and the shortage of accredited GHG verification organizations are slowing down the practical deployment of low-carbon infrastructure. This problem underscores the principles of human capital theory, which holds that investing in training and skills eventually leads to greater productivity and innovation.

According to studies by Cook et al. (2025) and Gui et al. (2024), sustainability activities risk remaining aspirational if climate capabilities are not purposefully incorporated into professional certification and education. Consequently, it is crucial to integrate decarbonization information into professional accreditation, occupational training, and university curricula. To ensure that human resource development directly supports national emission targets, training programs should align with the industry decarbonization roadmaps currently being developed.

Circular Economy and the 4R Approach

Indonesia's infrastructure sector still lacks a firm grasp of circular economy ideas, as seen by the low use of circular processes and the restricted usage of recycled materials. The 4R strategies described by Geissdoerfer et al. (2017) and Korhonen et al. (2018) are in line with this observation. By incorporating these ideas into project design, procurement, and monitoring systems, the gap between the goals of policy and its actual application would be closed.

Policymakers would be better able to pinpoint areas where linear practices continue, especially in the material and machine dimensions, by integrating the 4Rs with the 5M framework. They could then create focused interventions like required material audits, performance-based tendering, and financial incentives for recycled inputs. This integration would transform current infrastructure delivery models into systems that internalize environmental costs and, in turn, promote resource efficiency.

Governance Synthesis and Stage-Based Policy Implications

Indonesia's decarbonization challenges are better viewed as a governance issue rather than just a technological or financial one. A systemic imbalance between macro-level policy aims and micro-level implementation mechanisms is shown in the interaction of fragmented regulation, restricted financing, and inadequate capacity. It is crucial to integrate policies to address these issues.

Government spending would be in line with sustainability results if procurement and regulatory frameworks were harmonized. Additionally, incorporating decarbonization indicators into PPP contracts might strengthen market signals and institutionalize accountability. According to Royapoor et al. (2023), increasing data openness through digital Measurement, Reporting, and Verification (MRV) systems would boost investor confidence and monitoring accuracy. Cross-sectoral cooperation between financial institutions, industry groups, and ministries is essential at the institutional level to ensure that low-carbon goals are integrated throughout project lifecycles.

To facilitate shared learning and minimize effort duplication, public agencies should serve as facilitators of multi-stakeholder collaboration. Financially, increasing tax

breaks, guarantee systems, and green bond frameworks will be essential to growing private investment.

These financial and institutional ties highlight the need to view Indonesia's decarbonization initiatives as a continuum of activities integrated across the infrastructure project cycle rather than as a collection of disjointed measures. Therefore, a more stage-based approach can help define the starting point for reform initiatives and the best way to order them.

Three strategic directions are crucial from a policy standpoint. To provide consistent incentives for low-carbon behaviors, it is first necessary to increase institutional coherence by harmonizing technical standards and procurement mechanisms. Then, to encourage private investment and improve project bankability, new financial tools, including guarantees, fiscal incentives, and blended finance, should be made available. Last, to integrate decarbonization competencies into professional training, certification, and education systems, a thorough framework for capacity-building is required. To better align Indonesia's infrastructure development with its long-term emission reduction goals under the LTS-LCCR 2050 and Enhanced NDC frameworks, these three dimensions should be strengthened.

To draw private investment into low-carbon projects, the financing stage must be reorganized to prioritize de-risking measures and incentive-based tools like guarantees, concessional loans, and blended finance plans. Consistent use of performance-based contracts and green procurement standards will be essential during implementation to uphold accountability and guarantee that decarbonization goals are met locally. Last but not least, maintaining progress throughout all stages requires institutional coordination and capacity building to make sure that contractors, funders, and project planners all grasp the same low-carbon goals.

Thus, our research leads to three strategic imperatives. *First*, all infrastructure planning should be guided by institutional coherence, which can be achieved through integrated project screening tools and standardized procurement regulations. *Second,* to maintain long-term investment flows and encourage private participation, financial innovation must increase risk-sharing and fiscal incentives. *Third,* all phases of implementation should be supported by the acquisition of capacity through national certification and training systems. The study advances academic knowledge and practical avenues for infrastructure decarbonization in Indonesia by linking empirical findings to theoretical perspectives and transforming them into feasible policy strategies.

CONCLUSION

This study identified four main barriers hindering Indonesia's infrastructure sector's decarbonization: (i) a lack of technology and materials; (ii) fragmented regulations; (iii) financial constraints; and (iv) insufficient technical skill capability. Instead of being discrete operational problems, these difficulties show interrelated structural and institutional flaws, which underscore the necessity of focused reforms at every stage of the infrastructure project cycle.

Three areas of change are suggested to improve the way policies are implemented. *First,* to avoid locking in high-carbon assets, sustainability indicators should be included in feasibility studies, cost-benefit assessments, and design requirements during the project planning phase. *Second,* to attract private investment and reduce the perceived risks of green projects, the government and financial institutions should increase the use of de-

risking instruments at the financing stage, such as blended finance, tax incentives, and green guarantees. *Third,* to enforce adherence to standardized low-carbon requirements and prioritize lifecycle carbon performance, procurement procedures should be updated during implementation. All of these phases should be accompanied by capacity building to ensure that practitioners have the institutional and technical 'know-how' needed to operationalize decarbonization goals.

Although this study offers a fresh empirical understanding of the structural barriers to infrastructure decarbonization, the generalizability of the findings is constrained by its qualitative focus. To measure the impact of each obstacle and assess the long-term efficacy of specific policy tools, future research should use mixed-method approaches. However, policymakers and other stakeholders looking to initiate and advance reforms toward low-carbon, climate-resilient infrastructure development in Indonesia will find this report offers a valuable starting point.

As a practical implementation path of the policy, improvements should be sequenced along the project cycle: (i) planning—mainstream emission targets, a low-carbon material inventory, and a project-level MRV plan in feasibility/early design; (ii) financing—expand green guarantees and clarify eligibility; (iii) implementation—adopt performance-based procurement and contract-bound, measurable green standards; and (iv) M&E—mandate project-level MRV to ensure target–outcome consistency. This staged roadmap clarifies the starting point and short-term priorities.

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Kebijakan Pendaftaran Elektronik: Perspektif Regulasi, Teknologi, dan Aksesibilitas

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ABSTRACT

This study examines the electronic land registration policy as a reform measure in land services in Indonesia. Through Minister of ATR/BPN Regulation Number 3 of 2023, the land administration system has begun to transition from a manual to a digital format to improve efficiency, transparency, and data security. Although this system offers numerous benefits, its implementation in the field still faces several obstacles, including limited internet access, a lack of technological understanding, and the public's reliance on physical documents. This situation demonstrates that the success of an electronic system depends not only on the readiness of technology and regulations but also on how easily the public can access and utilize it. This article presents a more comprehensive approach by promoting synergy among policymakers, technology service providers, and the broader community. If all parties are actively involved, the electronic land registration system will not only be an administrative change but also a tool to strengthen land rights and improve the quality of public services.

Keywords: Electronic Certificates; Electronic Documents; Land Services

ABSTRAK

Artikel ini membahas kebijakan pendaftaran tanah elektronik sebagai langkah pembaruan dalam sistem layanan pertanahan di Indonesia. Melalui Peraturan Menteri ATR/BPN Nomor 3 Tahun 2023, sistem administrasi pertanahan mulai beralih dari bentuk manual ke bentuk digital. Peralihan ini bertujuan untuk meningkatkan efisiensi, transparansi, dan keamanan data. Meskipun sistem ini menawarkan banyak manfaat, penerapannya di lapangan masih menghadapi berbagai kendala, seperti keterbatasan jaringan internet, kurangnya pemahaman teknologi, serta kebiasaan masyarakat yang masih mengandalkan dokumen fisik. Situasi ini menunjukkan bahwa keberhasilan sistem elektronik tidak hanya bergantung pada kesiapan teknologi dan regulasi, tetapi juga pada seberapa mudah masyarakat bisa mengakses dan memanfaatkan teknologi tersebut. Artikel ini menawarkan pendekatan yang lebih menyeluruh dengan mendorong sinergi antara pembuat kebijakan, penyedia layanan teknologi, dan masyarakat luas. Jika semua pihak terlibat secara aktif, maka sistem pendaftaran tanah elektronik tidak hanya menjadi landasan perubahan administratif, tetapi juga menjadi alat untuk memperkuat hak atas tanah dan meningkatkan kualitas pelayanan publik.

Kata Kunci: Dokumen elektronik; Layanan Pertanahan; Sertifikat Elektronik

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PENDAHULUAN

Transformasi digital di sektor publik kini menjadi kebutuhan global, termasuk dalam sistem administrasi pertanahan. Seiring perkembangan Teknologi Informasi dan Komunikasi (TIK), metode tradisional berbasis dokumen fisik mulai ditinggalkan. Sebagai gantinya, sistem pendaftaran tanah elektronik hadir untuk mewujudkan layanan yang efisien, transparan, dan terintegrasi. Sistem ini tidak hanya mempercepat pelayanan publik, tetapi juga memperkuat kepastian hukum atas kepemilikan tanah. Menurut Kaczorowska (2019), inti digitalisasi pertanahan terletak pada keterbukaan akses data secara daring yang ditopang oleh kerangka hukum, infrastruktur digital, dan tata kelola data yang kuat sebagai fondasi pelayanan publik modern.

Berbagai negara telah menerapkan sistem pendaftaran tanah elektronik dengan pendekatan yang berbeda. Kanada melalui provinsi Ontario, misalnya, mengembangkan Polaris (*Province of Ontario Land Registration Information System*) dengan model kemitraan publik-swasta (Gainer, 2017). Australia mengadopsi *National Electronic Conveyancing System* (NECS) untuk menyederhanakan transaksi lintas negara bagian (Clark, 2010). Inggris dan Wales menggunakan *E-conveyancing* untuk mempercepat registrasi dan menghindari duplikasi dokumen (Bogusz, 2002). Kolombia menerapkan *Electronic Filing System* (EFS). Selandia Baru menggunakan *Landonline*, sementara Singapura melalui *STARS E-lodgment* menghadirkan layanan pelaporan tanah elektronik yang efisien dan terintegrasi (Low, 2005).

Penerapan sistem elektronik membawa berbagai keunggulan dibandingkan metode manual. *Pertama,* efisiensi dan keamanan meningkat karena data tersimpan secara digital dan terlindungi dari risiko fisik seperti kebakaran atau bencana. *Kedua,* proses administrasi menjadi lebih cepat dan minim kesalahan tanpa perlu kehadiran langsung. *Ketiga,* digitalisasi mempersempit ruang praktik mafia tanah melalui transparansi dan pencatatan otomatis. *Keempat,* keberadaan sertifikat elektronik mempercepat transaksi, meningkatkan kepercayaan investasi, serta mendukung pertumbuhan ekonomi. Dengan demikian, sistem ini menjadi instrumen penting dalam reformasi birokrasi dan tata kelola pertanahan yang lebih akuntabel dan modern.

Dalam konteks dokumen elektronik, sistem ini dirancang untuk mencegah pemalsuan, klaim ganda, dan manipulasi data yang sering menjadi sumber sengketa tanah. Teknologi digital memungkinkan proses enkripsi dan validasi otomatis dan memberikan perlindungan hukum yang lebih kuat bagi

pemilik tanah (Rosmidah *et al.*, 2024). Sertifikat elektronik kini diakui secara sah sebagai alat bukti dalam transaksi maupun sengketa hukum. Penerapan ini menegaskan bahwa keamanan digital menjadi pilar utama keandalan sistem pertanahan modern. Penguatan regulasi dan teknologi enkripsi menjadi penting agar keabsahan dokumen elektronik diakui secara universal oleh lembaga peradilan dan publik.

Kajian kebijakan pendaftaran tanah elektronik terus berkembang seiring meningkatnya digitalisasi layanan publik. Dari sisi regulasi, Tetama (2023) menilai bahwa implementasi pasca Undang-Undang Cipta Kerja masih menghadapi tumpang tindih norma hukum. Andari dan Mujiburohman (2023) juga mencatat adanya kebingungan di tingkat pelaksana akibat perbedaan antara regulasi lama yang berbasis analog dengan sistem baru berbasis digital. Sementara itu, Azzahra dan Alfiany (2025) menegaskan pentingnya kejelasan regulasi dan dukungan kelembagaan untuk menjamin keberhasilan implementasi sistem pendaftaran elektronik, khususnya di wilayah 3T (Tertinggal, Terdepan, dan Terluar).

Dari sisi teknologi, tantangan utama terletak pada keamanan dan keandalan sistem digital. Wiratmaja dan Rokhim (2025) memfokuskan ancaman peretasan serta penyalahgunaan data pertanahan. Untuk mengatasinya, Afdilah *et al.* (2024) dan Nugraha *et al.* (2024) mengusulkan pemanfaatan teknologi *blockchain* guna meningkatkan keamanan sistem dan mencegah pemalsuan data elektronik, terutama dalam konteks pendaftaran tanah. Teknologi ini dinilai mampu menyediakan enkripsi kuat serta menjamin transparansi data yang lebih baik.

Dari sisi aksesibilitas, penerimaan masyarakat terhadap sistem digital masih terbatas. Syarief (2021) menemukan bahwa rendahnya literasi digital dan kebiasaan masyarakat menggunakan dokumen fisik menjadi kendala utama. Ketimpangan infrastruktur digital juga memperburuk kesenjangan layanan di daerah terpencil. Azzahra dan Alfiany (2025) menegaskan bahwa pemerataan akses teknologi dan edukasi publik sangat penting agar sistem dapat digunakan secara inklusif. Upaya pemerintah dalam memperluas jaringan internet, menyediakan pelatihan digital, dan membangun pusat layanan berbasis komunitas menjadi langkah strategis untuk memastikan keadilan akses layanan pertanahan elektronik di seluruh wilayah Indonesia.

Berdasarkan pemikiran di atas, penelitian ini diarahkan untuk mengulas kebijakan pendaftarah tanah elektronik dari tiga perspektif utama, yaitu regulasi, teknologi, dan aksesibilitas, untuk memahami keterkaitan dan tantangan di antara ketiganya. Pendekatan integratif ini menghasilkan model konseptual yang menggambarkan hubungan dinamis antara dimensi hukum, teknis, dan sosial dalam kebijakan digitalisasi pertanahan. Secara akademik, penelitian ini memperluas pemahaman tentang sinergi lintas dimensi, sedangkan secara praktis memberikan rekomendasi berbasis bukti untuk memperkuat efektivitas, keamanan, dan inklusivitas sistem pertanahan elektronik di Indonesia yang berorientasi pada keadilan sosial dan efisiensi layanan publik.

TINJAUAN PUSTAKA

Regulasi Sistem Pendaftaran Elektronik

Transformasi digital di bidang pertanahan sangat bergantung pada regulasi yang menjadi dasar hukumnya. Undang-Undang Nomor 11 Tahun 2008 tentang Informasi dan Transaksi Elektronik (UU ITE) menjadi pijakan utama bagi pelaksanaan layanan daring pemerintah. Namun, tumpang tindih

aturan antarinstansi masih sering terjadi (Anggraini *et al.*, 2024). Ketidakharmonisan regulasi ini membuat implementasi sistem elektronik tidak berjalan seragam di seluruh lembaga. Menurut Rajagukguk (2022), adanya benturan antara regulasi baru tentang pendaftaran badan usaha secara daring dengan hukum lama menunjukkan perlunya harmonisasi peraturan agar proses digitalisasi administrasi pertanahan dapat berjalan konsisten dan efektif di berbagai level pemerintahan.

Peraturan Presiden Nomor 95 Tahun 2018 tentang Sistem Pemerintahan Berbasis Elektronik (SPBE) sebenarnya telah memberikan kerangka kerja nasional bagi digitalisasi birokrasi. Namun, penerapannya di tingkat daerah masih menghadapi kendala. Gumati (2024) menemukan bahwa banyak pemerintah daerah belum memiliki kapasitas sumber daya manusia, infrastruktur, dan pendanaan yang memadai untuk memenuhi standar SPBE. Pendekatan regulatif yang terlalu *"top-down"* justru berpotensi mengabaikan kondisi lokal dan memperlebar kesenjangan digital antarwilayah. Oleh karena itu, kebijakan yang lebih adaptif dan kontekstual perlu dirumuskan agar regulasi nasional dapat diimplementasikan secara merata sesuai kemampuan daerah.

Banyak pihak mengkhawatirkan sejauh mana perlindungan data pribadi dan keamanan sistem dapat mengamankan data pengguna layanan daring. Misalnya, walaupun sistem pendaftaran jaminan secara *online* sudah diatur oleh Permenkumham Nomor 25 Tahun 2021, belum banyak pihak mengetahui bagaimana aturan ini dapat melindungi hak pemohon (Alfedo, 2021). Selain itu, status hukum sertifikat elektronik masih memunculkan pertanyaan mengenai kekuatan pembuktiannya di pengadilan. Krismantoro (2023) menegaskan bahwa kejelasan hukum mengenai validitas dokumen digital perlu diperkuat melalui pengaturan eksplisit dalam Undang-Undang agar keabsahan hukum digital diakui secara nasional.

Teknologi Informasi Pertanahan

Sistem Komputerisasi Kegiatan Pertanahan (KKP) merupakan fondasi utama digitalisasi layanan pertanahan di Indonesia. Sistem ini memungkinkan seluruh proses administrasi, seperti pendaftaran tanah, pembaruan data, dan pencatatan hak, dilakukan secara elektronik dan terintegrasi. Melalui KKP, data yuridis dan spasial diolah menggunakan basis data digital yang terstandar, sehingga meningkatkan akurasi dan efisiensi pelayanan publik. Kelebihan utama sistem ini adalah kemampuannya untuk menekan duplikasi data dan mempercepat validasi kepemilikan tanah melalui verifikasi otomatis. Namun, efektivitasnya bergantung pada infrastruktur jaringan, kebijakan interoperabilitas antarinstansi, serta kapasitas sumber daya manusia pengelola (Mujiburohman, 2021; Mustofa, 2020).

Perkembangan KKP menunjukkan adanya kemajuan teknologi yang signifikan dari sistem lokal menjadi berbasis web nasional. Dimulai dari LOC pada 1997 hingga KKP-Web saat ini, sistem mengalami perbaikan pada sisi performa, penyimpanan data spasial, dan kecepatan akses. Versi terbaru, KKP-Web, didesain menggunakan arsitektur *cloud* untuk memungkinkan sinkronisasi data lintas wilayah secara *real time*. Interoperabilitasnya kini diarahkan agar terhubung dengan sistem data kependudukan (Dukcapil), pajak (DJP), dan tata ruang (Kementerian ATR), guna memastikan konsistensi informasi dan mencegah konflik administratif. Integrasi ini mencerminkan upaya menuju tata kelola pertanahan yang kolaboratif dan berbasis data tunggal nasional.

Implementasi KKP berbasis sistem elektronik melibatkan proses digitalisasi dokumen hukum dan spasial dengan tingkat keamanan tinggi. Dokumen digital yang diterbitkan sistem disahkan melalui tanda tangan elektronik dan segel digital yang diatur oleh Permen ATR/BPN Nomor 3 Tahun 2023. Selain itu, sistem ini mendukung enkripsi data dua lapis untuk mencegah perubahan atau akses ilegal. Teknologi *blockchain* mulai dipertimbangkan sebagai solusi tambahan guna menjaga transparansi dan jejak audit transaksi pertanahan. Kelebihan *blockchain* adalah kemampuannya mencatat setiap perubahan secara permanen meskipun tantangan utamanya terletak pada biaya infrastruktur dan kesiapan teknis lembaga pelaksana.

Kunci keberhasilan KKP bukan hanya terletak pada kecanggihan teknologi, tetapi juga pada tingkat integrasi antarlembaga. Saat ini, sistem KKP masih menghadapi keterbatasan dalam pertukaran data dengan instansi lain karena perbedaan format, protokol, dan tingkat keamanan sistem. Integrasi dengan Dukcapil penting untuk validasi identitas pemilik tanah, sementara koneksi dengan sistem perpajakan membantu penilaian kewajiban fiskal. Di sisi lain, sinkronisasi dengan sistem tata ruang memastikan pemanfaatan lahan sesuai regulasi. Agar interoperabilitas berjalan efektif, dibutuhkan standar pertukaran data nasional, mekanisme otorisasi, dan audit keamanan siber yang terkoordinasi.

Dari sisi teknis, KKP dan *blockchain* menawarkan keunggulan dalam hal efisiensi, validitas data, serta kemampuan pelacakan transaksi secara *real time*. Namun, keterbatasan muncul pada aspek skalabilitas dan adaptasi terhadap kondisi infrastruktur di daerah. Sistem berbasis *cloud* membutuhkan konektivitas tinggi, sedangkan banyak wilayah Indonesia masih menghadapi keterbatasan jaringan internet. Selain itu, kesadaran keamanan digital di kalangan masyarakat dan pejabat publik masih rendah. Oleh sebab itu, keberhasilan implementasi sistem pertanahan digital tidak hanya bergantung pada teknologi, tetapi juga pada kesiapan sosial, ekonomi, dan kebijakan yang menyertai (Pamungkas & Purwadi, 2023).

Kemudahan Akses untuk Semua Warga

Kemudahan akses terhadap layanan elektronik sangat bergantung pada kemampuan masyarakat dalam memahami dan menggunakan teknologi digital. Masih banyak warga belum memiliki literasi digital yang memadai. Meskipun jumlah penduduk cukup besar, kualitas sumber daya manusia masih rendah karena minimnya pendidikan dan dominasi budaya tutur dibanding budaya baca. Padahal, kemampuan menggunakan perangkat digital sangat dibutuhkan untuk menunjang kehidupan sehari-hari, baik dalam bidang pendidikan, pekerjaan, maupun layanan publik seperti administrasi pertanahan.

Literasi digital bukan hanya sekadar bisa menyalakan komputer atau membuka internet. Menurut Eshet (2004) dan Spires *et al.* (2018), literasi digital adalah cara berpikir yang mencakup kemampuan memahami informasi dari berbagai sumber, mengevaluasinya secara kritis, dan menyusunnya menjadi pengetahuan yang berguna. Bahkan, menurut Warschauer (2009), literasi digital adalah gabungan dari kemampuan komputer, informasi, visual, media, dan komunikasi. Artinya, masyarakat harus bisa menilai informasi yang diterima, berkomunikasi secara tepat, serta sadar terhadap keamanan data dan norma sosial yang berlaku di dunia digital.

Agar semua warga bisa memanfaatkan layanan digital, seperti pendaftaran tanah elektronik, peningkatan literasi digital perlu

dilakukan secara merata. Pelatihan atau penyuluhan harus diberikan di berbagai tempat, termasuk desa, sekolah, dan komunitas lokal. Jika tidak, layanan digital hanya akan dinikmati oleh kelompok yang sudah terbiasa dengan teknologi, dan ketimpangan sosial bisa semakin melebar. Literasi digital yang baik memungkinkan warga untuk berpartisipasi aktif dalam masyarakat digital, membangun kreativitas, berkolaborasi, serta menjangkau layanan publik secara mandiri dan adil.

Sintesis dan Kerangka Konseptual

Secara konseptual, ketiga dimensi utama dalam digitalisasi sistem pendaftaran tanah (yaitu regulasi, teknologi, dan aksesibilitas) tidak dapat dipisahkan satu sama lain. Regulasi berperan sebagai fondasi hukum yang menentukan legitimasi dan arah implementasi sistem. Sementara itu, teknologi menjadi instrumen utama yang mengubah proses administratif menjadi lebih efisien dan transparan. Di sisi lain, aksesibilitas menentukan sejauh mana masyarakat dapat berpartisipasi secara adil dalam layanan digital tersebut.

Sintesis kepustakaan menunjukkan bahwa kesenjangan implementasi digitalisasi pertanahan di Indonesia bukan hanya bersumber dari lemahnya regulasi atau keterbatasan teknologi, tetapi dari ketidaksinkronan antara ketiga dimensi digitalisasi. Regulasi yang belum adaptif terhadap kemajuan teknologi berpotensi menimbulkan ketidakpastian hukum, sementara inovasi teknologi tanpa memperhatikan tingkat literasi digital masyarakat dapat memperlebar kesenjangan layanan publik.

Berdasarkan pemahaman tersebut, penelitian ini hendak membangun kerangka konseptual integratif yang menghubungkan tiga dimensi di atas. Dalam kerangka ini, regulasi berfungsi sebagai pengatur legitimasi dan keamanan data, teknologi sebagai penggerak efisiensi dan inovasi layanan, serta aksesibilitas sebagai jaminan inklusivitas sosial. Keterpaduan ketiga dimensi ini menjadi dasar analisis penelitian dalam menilai efektivitas dan keadilan kebijakan pendaftaran tanah elektronik di Indonesia.

PEMBAHASAN

Aspek Yuridis Pendaftaran Tanah Elektronik

Pendaftaran tanah memiliki peran dalam menjamin kepastian dan perlindungan hukum terhadap hak-hak atas tanah. Selain berfungsi memberikan perlindungan bagi pemilik tanah, ia juga berfungsi sebagai sarana untuk memperoleh informasi mengenai status hukum suatu bidang tanah, siapa pemegang haknya, jenis hak yang dimiliki, luas tanah, serta tujuan penggunaannya (Mujiburohman, 2018). Tujuan utama dari pendaftaran tanah adalah menciptakan kepastian hukum yang mencakup kejelasan atas status hak, subjek yang memiliki hak, dan objek tanah yang menjadi hak tersebut. Hasil akhir dari proses ini berupa sertifikat tanah yang menjadi alat bukti resmi atas kepemilikan hak.

Pendaftaran tanah elektronik merupakan bagian dari inovasi hukum administrasi pertanahan di Indonesia. Sebagai suatu sistem yang menggantikan prosedur manual, penerapan teknologi dalam proses legalitas pertanahan perlu ditinjau dari perspektif normatif untuk memastikan tidak adanya pertentangan dengan asas-asas hukum yang berlaku. Salah satu isu utama yang mencuat adalah tentang legalitas dan keabsahan dokumen elektronik sebagai alat bukti kepemilikan tanah.

Permen ATR/BPN Nomor 3 Tahun 2023 menjadi dasar pengaturan dokumen elektronik, termasuk sertifikat tanah

elektronik. Pasal 6 menyatakan bahwa dokumen elektronik memiliki kekuatan hukum yang sama dengan dokumen fisik. Pernyataan ini memang memberikan afirmasi administratif, tetapi dalam sistem hukum Indonesia, kekuatan hukum suatu dokumen tidak hanya ditentukan oleh peraturan menteri, tetapi harus bersumber dari peraturan perundang-undangan yang lebih tinggi.

Menurut teori hierarki norma hukum dari Hans Kelsen, aturan hukum yang lebih rendah tidak boleh bertentangan atau membuat aturan baru yang belum diatur oleh peraturan yang lebih tinggi. Permen ini mencoba mengatur hal substantif (legalitas dokumen elektronik) yang belum mendapat landasan eksplisit dalam Undang-Undang Pokok Agraria (UUPA) maupun dalam PP Nomor 24 Tahun 1997 tentang Pendaftaran Tanah. Di dalam kedua regulasi tersebut, alat bukti kepemilikan tanah masih dirumuskan dalam bentuk dokumen fisik, yakni sertifikat tertulis yang dicetak dan dibubuhi tanda tangan basah.

Masalah ini menjadi relevan karena, pada tataran yuridis, keabsahan dokumen berpengaruh langsung terhadap kekuatan pembuktian dalam perkara hukum. Mahkamah Konstitusi di Putusan Nomor 20/PUU-XIV/2016 menegaskan bahwa dokumen elektronik memang diakui sebagai alat bukti hukum berdasarkan Pasal 5 UU ITE, namun tidak bisa berdiri sendiri dalam kasus keperdataan seperti sengketa tanah. Artinya, walau dokumen elektronik diakui, penggunaannya tetap membutuhkan bukti tambahan atau bukti pendukung lainnya (Adinda *et al.*, 2023; Putra & Winanti, 2024).

Permasalahan lain muncul pada aspek autentikasi dokumen digital. Sertifikat tanah elektronik harus memiliki fitur keamanan tinggi, seperti tanda tangan elektronik, segel elektronik, serta QR Code yang berfungsi sebagai alat verifikasi. Namun, keberadaan teknologi ini belum sepenuhnya dipahami oleh seluruh pemangku kepentingan, termasuk hakim, notaris, dan Pejabat Pembuat Akta Tanah (PPAT). Ketidaktahuan ini berpotensi mengurangi nilai pembuktian dokumen elektronik di pengadilan.

Kritik lainnya terhadap Permen ATR/BPN Nomor 3 Tahun 2023 adalah bahwa regulasi ini belum membedakan secara tegas antara dokumen elektronik hasil konversi (alih media) dan dokumen yang secara asli dibuat secara digital. Dalam praktiknya, konversi dokumen dari bentuk fisik ke bentuk digital mengandung potensi penyimpangan atau kesalahan, seperti kelalaian dalam pemindaian, kehilangan halaman, atau kerusakan dokumen sebelum pemindaian. Tanpa pengaturan rinci mengenai standar dan prosedur alih media, validitas dokumen bisa dipertanyakan (Pramesti *et al.*, 2024; Wulan *et al.*, 2022).

keabsahan sertifikat elektronik akan selalu bergantung pada integritas data dan prosedur validasinya. Sistem validasi yang tidak dapat diaudit atau diverifikasi oleh pihak ketiga dapat menurunkan kepercayaan hukum publik. Oleh sebab itu, sistem pembuktian digital harus diatur lebih lanjut dalam peraturan yang memiliki kedudukan hukum lebih tinggi dari peraturan menteri.

Lebih jauh lagi, landasan konstitusional terhadap hak atas tanah tercantum di Pasal 33 UUD 1945 yang menyatakan bahwa bumi, air, dan kekayaan alam yang terkandung di dalamnya dikuasai oleh negara dan digunakan untuk sebesar-besar kemakmuran rakyat. Hal ini menegaskan bahwa negara bertanggung jawab menjamin kepastian hukum dan perlindungan hak atas tanah. Dengan demikian, setiap inovasi kebijakan yang menyangkut kepemilikan tanah harus disertai dengan penguatan perlindungan hukum.

Revisi terhadap PP Nomor 24 Tahun 1997 dan UUPA menjadi kebutuhan mendesak. Regulasi-regulasi tersebut harus diperbarui agar dapat mengakomodasi perkembangan teknologi informasi dan komunikasi, serta mengakui secara jelas keabsahan dokumen elektronik sebagai alat bukti hukum. Tanpa revisi tersebut, konflik antara praktik administratif yang modern dengan sistem hukum yang konservatif akan terus terjadi.

Penguatan ini tidak hanya menyangkut substansi hukum, tetapi juga tata kelola kelembagaan. Lembaga peradilan, lembaga pembuat kebijakan, dan institusi pendidikan hukum harus mulai menyusun kurikulum, pelatihan, dan sosialisasi terkait bukti elektronik. Pengetahuan hukum yang memadai akan mereduksi potensi kesalahan interpretasi hukum atas dokumen digital.

Di sisi lain, tidak bisa dipungkiri bahwa digitalisasi pertanahan menawarkan berbagai kelebihan. Efisiensi birokrasi, penghematan biaya, dan kecepatan layanan menjadi keunggulan utama. Hal ini sejalan dengan pandangan dari Weber (2009), yang menegaskan perlunya sistem administratif yang tertib, terdokumentasi, dan rasional. Namun, efisiensi tidak dapat mengorbankan asas kepastian hukum. Menurut Radbruch (2006), hukum yang baik adalah hukum yang adil, bermanfaat, dan memberikan kepastian. Jika dokumen elektronik tidak memiliki perlindungan hukum yang setara dengan dokumen fisik, maka hal ini dapat mencederai prinsip keadilan dan keamanan hukum bagi pemilik hak atas tanah.

Digitalisasi Pendaftaran Tanah Elektronik

Layanan elektronik pertanahan merupakan bagian dari transformasi digital sektor agraria. Layanan ini dirancang untuk meningkatkan transparansi, efisiensi, dan akuntabilitas dalam pengelolaan data serta proses administrasi pertanahan yang selama ini dikenal rumit dan memakan waktu. Dengan pendekatan digital, ATR/BPN membuka akses masyarakat terhadap berbagai informasi pertanahan serta mempermudah proses pelayanan yang dulunya hanya bisa dilakukan secara manual atau langsung datang ke kantor.

Beberapa layanan utama yang kini tersedia secara elektronik meliputi pengecekan sertifikat tanah, pengecekan Surat Keterangan Pendaftaran Tanah (SKPT), Zona Nilai Tanah (ZNT), dan pendaftaran Hak Tanggungan Elektronik (HT-el). Menurut data resmi ATR/BPN tahun 2025, layanan-layanan ini telah digunakan secara luas oleh masyarakat.

Tabel 1. Layanan Elektronik Pertanahan

Sertifikat HT Elektronik	4.652.567
Pengecekan Elektronik	14.839.835
SKPT Elektronik	704.258
ZNT Elektronik	1.267.539

Sumber: Dashboard Aplikasi KKP (2025)

Layanan elektronik pertanahan dapat mempermudah akses informasi dan pengurusan administrasi tanah secara digital. Melalui fitur pengecekan sertifikat, masyarakat dapat mengetahui keabsahan kepemilikan secara langsung untuk menghindari sengketa. SKPT elektronik memfasilitasi pihak yang berkepentingan, seperti pembeli dan perbankan, dalam mengecek status hukum suatu bidang tanah. ZNT menyediakan data nilai tanah berdasarkan zonasi yang bermanfaat untuk pajak, investasi, dan perencanaan tata ruang. Adapun HT-el membantu mempercepat proses pendaftaran jaminan kredit serta mendukung kelancaran pembiayaan oleh lembaga keuangan.

Penguatan berbagai layanan digital tersebut selaras dengan terbitnya Peraturan Menteri ATR/BPN Nomor 3 Tahun 2023 yang menjadi tonggak penting dalam transformasi sistem administrasi pertanahan dari konvensional ke berbasis elektronik. Regulasi ini memungkinkan seluruh proses pendaftaran tanah, mulai dari pendaftaran awal, pemeliharaan data, hingga perubahan dan alih media dokumen, dilakukan secara digital. Dengan penerapan sistem ini, dokumen penting seperti Buku Tanah Elektronik (BT-el) dan Sertifikat Elektronik (Sertifikat-el) tidak hanya diterbitkan secara sah, tetapi juga dijamin kekuatan hukumnya melalui penggunaan tanda tangan dan segel elektronik yang telah diatur secara resmi.

Seluruh proses ini diatur dalam kerangka sistem elektronik yang diselenggarakan dan dijaga keandalannya oleh Kementerian ATR/BPN (Pasal 3 ayat (1)). Pemilik hak tanah juga diberi akses melalui akun pertanahan tunggal yang diintegrasikan dengan data kependudukan atau identitas badan hukum (Pasal 19 ayat (4)-(5)). Sertifikat-el dapat diakses secara daring atau dicetak secara resmi dalam kertas berspesifikasi khusus (Pasal 20). Dalam keadaan darurat saat sistem terganggu, pelaksanaan pendaftaran masih dimungkinkan secara manual sesuai ketentuan peralihan (Pasal 44). Inovasi ini menciptakan sistem yang tidak hanya efisien, tetapi juga memperkuat keamanan data, kepastian hukum, serta memberikan kemudahan akses informasi bagi masyarakat.

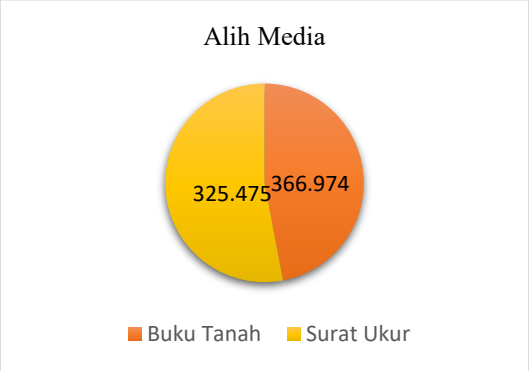
Salah satu aspek strategis dalam transformasi ini adalah proses digitalisasi atau alih media. Namun, peralihan dari sistem manual ke sistem elektronik bukanlah hal yang mudah dilakukan. Hal ini disebabkan oleh banyaknya komponen yang harus disiapkan dan disatukan agar bisa berjalan secara integratif. Secara umum, proses alih media ke bentuk digital memerlukan kesiapan infrastruktur, kegiatan pemindaian *(scanning)* dokumen, *editing* data, serta proses penyimpanan dan penyajian informasi secara digital (Laksono, 2018). Proses penggabungan berbagai sistem dan infrastruktur memiliki tantangan tersendiri, terutama karena informasi pertanahan yang dihasilkan harus akurat baik dari sisi lokasi (spasial) maupun dari sisi hukum (yuridis).

Tantangan-tantangan tersebut menjelaskan mengapa proses digitalisasi membutuhkan perhatian khusus dalam pelaksanaannya. Setelah infrastruktur dan sistem pendukung dipersiapkan, langkah penting berikutnya dalam transformasi ini adalah pelaksanaan teknis untuk alih media itu sendiri. Alih media mengacu pada proses konversi dokumen cetak (surat ukur dan Buku Tanah) menjadi bentuk elektronik. Kegiatan ini dilakukan dengan verifikasi dan validasi atas *data fisik* (letak, luas, batas, status bidang tanah) dan *data yuridis* (pemegang hak, jenis hak, dasar perolehan hak, dan riwayat kepemilikan). Dokumen hasil alih media kemudian disahkan oleh pejabat melalui tanda tangan elektronik dan segel elektronik untuk memastikan keaslian dan integritas data yang telah ditransformasi. Selanjutnya, seluruh perubahan administrasi dilakukan langsung melalui sistem elektronik.

Hasil dari proses verifikasi dan validasi ini dituangkan dalam bentuk Blok Data, lalu disahkan oleh pejabat pertanahan melalui tanda tangan elektronik. Setelah disahkan, dokumen asli diberi catatan bahwa telah dilakukan validasi dan pencatatan lanjutan yang dilakukan melalui sistem elektronik. Dokumen yang telah dialihmediakan lalu dipindai ulang dan dibubuhi segel elektronik untuk menjamin keasliannya, serta disimpan dalam pangkalan data nasional sebagai bagian dari warkah elektronik pertanahan. Dengan sistem ini, seluruh riwayat perubahan

administrasi tanah dilakukan sepenuhnya secara digital sehingga efisiensi tata kelola pertanahan terus meningkat dan kepastian hukum atas hak atas tanah semakin menguat.

Hasil nyata dari proses digitalisasi ini terlihat dari jumlah dokumen yang telah dialihmediakan hingga tahun 2024.



Gambar 1. Alih Media

Sumber: Dashboard Aplikasi KKP (2025)

Untuk memahami sejauh mana implementasi digitalisasi pertanahan telah berjalan, capaian konkret dalam bentuk data perlu dilihat. Salah satu indikator keberhasilan tersebut dapat dilihat dari jumlah dokumen pertanahan yang telah berhasil dialihmediakan dari bentuk fisik ke elektronik. Data rekapitulasi berikut memberi gambaran menyeluruh mengenai volume Buku Tanah dan Sertifikat Elektronik yang telah diterbitkan hingga Juli tahun 2025.

Tabel 2.Rekapitulasi Sertifikat Elektronik

HAT	Buku Tanah-el	Sertifikat-el
HM	4.705.394	4.359.478
HGU	1.786	1.761
HGB	821.813	749.983
HP	179.886	172.373
HPL	574	496
HMSRS	78.376	71.557
Wakaf	21.037	20.495
Total	5.808.874	5.376.144

Sumber: Dashboard Aplikasi KKP (2025)

Perspektif Aksesibilitas

Digitalisasi pendaftaran tanah merupakan langkah strategis pemerintah untuk meningkatkan efisiensi, transparansi, dan akurasi pelayanan publik. Namun, kesiapan masyarakat dalam menerima sistem baru ini masih beragam. Warga di daerah pedesaan lebih nyaman menggunakan sertifikat fisik yang bisa dipegang dan disimpan secara langsung karena dianggap lebih aman dan nyata. Kekhawatiran kehilangan data, kesulitan mengakses dokumen elektronik, serta potensi kebocoran informasi menjadi hambatan utama dalam adopsi sistem digital. Dengan demikian, keberhasilan digitalisasi tidak hanya ditentukan oleh kesiapan teknologi, tetapi juga kesiapan sosial dan psikologis masyarakat dalam beradaptasi dengan perubahan.

Tantangan terbesar dalam penerapan layanan digital di bidang pertanahan adalah rendahnya tingkat literasi digital. Survei Indeks Literasi Digital Nasional 2022 menunjukkan bahwa skor literasi digital Indonesia baru mencapai 3,54 dari skala 5, dengan kesenjangan signifikan antarwilayah. Papua, Nusa Tenggara Timur, dan Maluku mencatat skor di bawah rata-rata, sedangkan Yogyakarta menjadi yang tertinggi dengan skor 3,64 (Kementerian Kominfo & Katadata Insight Center, 2022) Kondisi ini menunjukkan bahwa sebagian masyarakat masih kesulitan memahami dan menggunakan teknologi digital secara efektif, terutama di wilayah 3T yang memiliki akses terbatas terhadap infrastruktur dan pendidikan teknologi.

Walaupun teknologi digital menawarkan kemudahan dan efisiensi, penerimaan masyarakat terhadap inovasi ini sangat dipengaruhi oleh faktor psikologis dan sosial. Banyak warga ragu terhadap keandalan sistem digital pemerintah karena khawatir kehilangan hak kepemilikan jika terjadi

gangguan sistem atau peretasan. Sertifikat elektronik juga membutuhkan perangkat tertentu serta kemampuan teknis untuk diakses, yang tidak semua orang miliki. Lansia dan masyarakat berpendidikan rendah menjadi kelompok paling rentan terhadap ketertinggalan digital. Oleh sebab itu, peningkatan literasi dan kepercayaan publik menjadi syarat utama dalam mendorong keberhasilan digitalisasi pertanahan.

Selain aspek teknis, faktor sosial dan budaya turut memengaruhi resistensi terhadap digitalisasi. Bagi masyarakat adat, sertifikat tanah bukan sekadar dokumen hukum, tetapi juga simbol warisan leluhur dan identitas komunal. Transformasi dari format konvensional ke bentuk digital menimbulkan kekhawatiran akan hilangnya nilai simbolik tersebut. Demikian pula, bagi lansia dan penyandang disabilitas, keterbatasan perangkat dan desain sistem yang kurang inklusif menjadi hambatan signifikan. Oleh karena itu, digitalisasi pertanahan perlu dirancang dengan mempertimbangkan keragaman sosial, budaya, dan kebutuhan kelompok rentan agar tidak menimbulkan ketimpangan baru dalam pelayanan publik.

Keterbatasan infrastruktur digital juga menjadi tantangan nyata. Di berbagai wilayah Indonesia, sinyal internet masih lemah dan koneksi tidak stabil, sementara perangkat seperti ponsel pintar atau komputer belum dimiliki secara luas. Bahkan jika perangkat tersedia, banyak warga belum memahami cara mengoperasikan aplikasi pertanahan digital dengan benar. Hambatan ini tidak hanya dialami masyarakat, tetapi juga petugas pertanahan dan notaris yang terlibat langsung dalam pelayanan. Kesenjangan infrastruktur dan kemampuan teknis ini memperlihatkan bahwa pemerataan akses digital harus menjadi prioritas utama sebelum kebijakan digitalisasi diterapkan secara menyeluruh dan efektif.

Pemerintah memiliki peran penting sebagai fasilitator dalam menjembatani kesenjangan digital masyarakat. Langkah strategis yang dapat dilakukan antara lain memperluas jaringan internet melalui kerja sama dengan penyedia layanan telekomunikasi, menyelenggarakan pelatihan literasi digital, serta memperkuat regulasi keamanan data. Selain itu, pelibatan masyarakat sejak tahap perancangan sistem akan meningkatkan rasa memiliki dan kepercayaan terhadap teknologi baru (Singh, 2014). Dengan menerapkan prinsip inklusivitas dan partisipasi publik, digitalisasi pertanahan dapat menjadi kebijakan yang tidak hanya efisien secara teknis, tetapi juga diterima secara sosial.

Isu keamanan data menjadi salah satu sumber kekhawatiran masyarakat terhadap pendaftaran tanah elektronik. Untuk itu, sistem harus menjamin perlindungan data melalui tanda tangan elektronik, enkripsi, serta mekanisme kontrol akses berbasis izin. Beberapa negara bahkan telah menerapkan teknologi *blockchain* untuk menjamin integritas data dan mencegah manipulasi informasi (Merukar *et al.*, 2022). Penggunaan teknologi ini dapat meningkatkan transparansi dan memperkuat kepercayaan publik terhadap layanan pemerintah. Jika diterapkan secara tepat, *blockchain* dapat menjadi solusi efektif untuk menjaga keamanan dan akuntabilitas data pertanahan.

Budaya menyimpan dokumen fisik juga menjadi faktor yang memperlambat adopsi sistem digital. Banyak masyarakat merasa lebih tenang jika sertifikat tanah dapat dipegang dan disimpan secara pribadi. File digital dianggap tidak stabil karena bergantung pada perangkat dan koneksi internet. Kekhawatiran akan lupa kata sandi, perangkat rusak, atau akun terblokir semakin memperkuat resistensi terhadap digitalisasi. Untuk mengatasi hal ini, pemerintah perlu menyediakan layanan bantuan teknis yang

mudah diakses serta sistem pemulihan data yang sederhana agar masyarakat merasa aman dan percaya pada penggunaan dokumen digital.

Dari sisi legalitas, masyarakat juga perlu diyakinkan bahwa sertipikat digital memiliki kekuatan hukum yang sama dengan versi cetaknya. Hal ini bisa dilakukan dengan menjelaskan adanya tanda tangan dan segel elektronik yang sah secara hukum. Penjelasan ini harus dilakukan dengan bahasa yang sederhana, bukan istilah teknis yang sulit dimengerti. Selain itu, penting juga untuk memastikan bahwa data digital benar-benar aman, tidak bisa diubah sembarangan, dan hanya bisa diakses oleh pemilik atau pihak berwenang. Jika sistem ini dirancang dengan prinsip transparansi dan keamanan, kepercayaan masyarakat terhadap layanan digital akan meningkat secara perlahan.

Digitalisasi pendaftaran tanah memiliki potensi besar dalam mempercepat layanan publik, mengurangi konflik agraria, serta memperluas akses ekonomi melalui kemudahan verifikasi aset. Namun, manfaat tersebut hanya dapat tercapai jika seluruh lapisan masyarakat mampu mengakses dan memanfaatkannya secara setara. Oleh karena itu, kebijakan digitalisasi harus diiringi pemerataan infrastruktur, pendampingan masyarakat, serta edukasi berkelanjutan. Dengan pendekatan kolaboratif antara pemerintah, swasta, dan masyarakat, digitalisasi pertanahan dapat menjadi inovasi yang inklusif, aman, dan berkeadilan bagi seluruh warga negara Indonesia.

Integrasi Tiga Perspektif: Regulasi, Teknologi, dan Aksesibilitas

Regulasi berfungsi sebagai kerangka penentu yang mendasari validitas sistem pendaftaran tanah elektronik. Tanpa landasan hukum yang kuat, inovasi teknologi dapat kehilangan legitimasi dan rentan digugat. Misalnya, studi *Legal Dynamics of Land Digitalization* menunjukkan bahwa meskipun telah ada kebijakan elektronik, aturan pelaksana terkait layanan *online* belum konsisten di beberapa Kantor Pertanahan (Leonard & Simarmata, 2023). Di sinilah regulasi perlu diperluas dari sekadar pengakuan administratif ke perlindungan hak dan batas tanggung jawab, agar sistem digital bukan sekadar formalitas, tetapi instrumen penguatan kepastian hukum.

Regulasi menjadi kerangka utama yang menentukan keabsahan sertifikat elektronik sebagai alat bukti hukum. Saat ini, Permen ATR/BPN Nomor 3 Tahun 2023 telah mengatur mekanisme pendaftaran tanah elektronik, namun dasar konstitutifnya belum kuat karena tidak terintegrasi secara menyeluruh dengan UUPA dan PP Nomor 24 Tahun 1997. Sinkronisasi dengan UU ITE, UU Keterbukaan Informasi Publik, dan UU Pelindungan Data Pribadi juga penting untuk menghindari konflik hukum antarperaturan. Harmonisasi vertikal dan horizontal diperlukan agar sistem digitalisasi tanah memiliki kepastian hukum yang solid dan dapat meningkatkan kepercayaan masyarakat terhadap proses transformasi digital.

Teknologi menjadi instrumen utama dalam meningkatkan efisiensi dan transparansi layanan pertanahan. Sistem KKP-Web telah memungkinkan integrasi data pertanahan di seluruh Indonesia, namun tantangan interoperabilitas antarlembaga seperti Dukcapil, perpajakan, dan tata ruang masih perlu diperkuat. Teknologi *blockchain* direkomendasikan untuk menjamin integritas data pertanahan karena mampu mencatat transaksi tanpa dapat dimanipulasi (Khalid *et al.*, 2022). Keberhasilan penerapan teknologi ini memerlukan kesiapan sumber daya manusia dan tata kelola kelembagaan yang kuat. Pelatihan teknis bagi petugas BPN, PPAT, dan notaris amat penting agar akurasi data dan pemahaman sistem tetap terjaga.

Aspek aksesibilitas menjadi fondasi utama agar sistem digital dapat digunakan oleh seluruh masyarakat tanpa diskriminasi. Hambatan terbesar masih mencakup keterbatasan infrastruktur, kesenjangan literasi digital, serta resistensi sosial terhadap layanan elektronik. Di wilayah 3T, lemahnya jaringan dan keterbatasan perangkat digital menjadi penghalang utama bagi masyarakat untuk mengakses sistem pertanahan digital. Oleh karena itu, pendekatan berbasis komunitas perlu dikembangkan melalui pelatihan literasi digital, penyediaan sarana publik berbasis teknologi, dan pendampingan masyarakat. Pemerintah perlu bekerja sama dengan lembaga pendidikan dan sektor swasta untuk memperluas akses dan membangun kepercayaan publik.

Agar sistem digital benar-benar inklusif, kebijakan literasi digital harus bersifat struktural dan berkelanjutan. Pemerintah dapat membangun pusat edukasi digital di desa, melatih perangkat daerah, serta menyusun modul pembelajaran berbasis praktik untuk meningkatkan kemampuan masyarakat dalam menggunakan layanan elektronik. *Digital empowerment* hanya dapat tercapai jika masyarakat memiliki kesempatan untuk belajar dan mencoba langsung untuk menggunakan sistem. Selain itu, kolaborasi multipihak seperti akademisi, sektor swasta, dan Lembaga Swadaya Masyarakat (LSM) perlu terus diperkuat untuk mewujudkan tata kelola digital yang partisipatif, akuntabel, dan berorientasi pada pelayanan publik yang prima (M. Zein & Twinomurinzi, 2023).

Keamanan data merupakan unsur penting dalam pendaftaran tanah elektronik. Dokumen digital memuat informasi sensitif seperti identitas pemilik, lokasi, dan riwayat transaksi tanah yang wajib dilindungi dengan enkripsi serta tanda tangan elektronik. Teknologi kriptografi modern, seperti *zero-knowledge proof*, direkomendasikan untuk menjamin privasi data tanpa mengorbankan transparansi sistem (Zhou *et al.*, 2020). Namun, keamanan teknis harus diimbangi dengan edukasi publik agar masyarakat memahami cara melindungi data pribadi. Tanpa kesadaran digital, persepsi risiko akan tetap tinggi, meskipun sistem sudah aman secara teknologi.

Integrasi antara regulasi, teknologi, dan aksesibilitas menuntut pembentukan sistem kelembagaan yang kuat dan koordinatif. Kementerian ATR/BPN, Kominfo, dan Dukcapil perlu mengembangkan sistem interoperabel yang menghubungkan data kependudukan, kepemilikan aset, dan tata ruang secara real-time. Kolaborasi lintas sektor juga harus dilengkapi dengan mekanisme audit data dan evaluasi berkala untuk menjamin transparansi. Dengan sistem yang terintegrasi, sertifikat elektronik dapat berfungsi tidak hanya sebagai bukti hukum, tetapi juga sebagai instrumen penguatan kepercayaan publik terhadap layanan pertanahan digital nasional.

Diperlukan peta jalan *(roadmap)* nasional yang menjelaskan tahapan transformasi digital secara bertahap dan berbasis indikator kinerja yang terukur. Tahapan tersebut mencakup penyelarasan regulasi, peningkatan kapasitas sumber daya manusia, penguatan infrastruktur, serta sistem monitoring dan evaluasi berbasis data. Indikator seperti tingkat adopsi layanan digital, peningkatan literasi, dan jumlah sengketa yang diselesaikan secara elektronik perlu dijadikan ukuran keberhasilan. Dengan integrasi kebijakan hukum, teknologi, dan sosial yang kuat, digitalisasi pertanahan dapat menjadi salah satu fondasi utama bagi reformasi agraria modern yang efisien, inklusif, dan berkeadilan bagi seluruh warga Indonesia.

SIMPULAN

Transformasi pendaftaran tanah menuju sistem elektronik merupakan langkah penting dalam reformasi administrasi pertanahan nasional. Keberhasilan kebijakan ini bergantung pada sinergi tiga pilar utama, yaitu regulasi yang kuat, teknologi yang andal, dan aksesibilitas yang merata. Saat ini, legitimasi sertifikat elektronik masih memerlukan penguatan melalui harmonisasi regulasi antarlembaga seperti ATR/BPN, Kominfo, dan BSSN. Di sisi teknologi, inovasi seperti KKP-Web dan *blockchain* menjanjikan efisiensi, namun terkendala keterbatasan SDM dan interoperabilitas. Sementara itu, dari sisi sosial, masyarakat di wilayah 3T dan kelompok rentan menghadapi kendala infrastruktur, literasi digital, serta kepercayaan terhadap sistem pertanahan elektronik.

Untuk menjawab tantangan tersebut, pemerintah perlu merancang kebijakan yang lebih spesifik dan operasional. ATR/BPN dapat menyusun *roadmap* digitalisasi pertanahan dengan empat tahap utama, yaitu: harmonisasi regulasi, pembangunan infrastruktur digital, peningkatan literasi dan kapasitas SDM, serta pengawasan berkelanjutan. Kominfo dan BSSN harus memperkuat keamanan data melalui enkripsi, tanda tangan elektronik, dan audit sistem. Pemerintah daerah dapat membentuk Pusat Layanan Bantuan Digital Pertanahan (PLBDP) untuk pendampingan masyarakat. Indikator keberhasilan meliputi peningkatan sertifikat elektronik, perluasan layanan di daerah 3T, serta peningkatan literasi digital. Evaluasi rutin lintas lembaga diperlukan untuk menjamin transparansi dan keberlanjutan program.

TENTANG PENULIS

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Embedding Ethical AI in Digital Public Infrastructure: Strategic Governance Pathways for Indonesia

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ABSTRACT

Indonesia's accelerating digital transformation, driven by programs such as Digital ID and INA Digital, has introduced both significant opportunities and complex governance challenges as Artificial Intelligence (AI) becomes integrated into public-sector decision-making. This conceptual paper proposes a strategic governance framework for ethical AI that aligns international standards such as the OECD AI Principles, the EU AI Act, and the NIST AI Risk Management Framework with Indonesia's institutional and regulatory environment. The study contributes to the literature by articulating a policy-oriented model operationalizing ethics, transparency, and accountability within the national digital ecosystem. It further demonstrates how anticipatory governance, multistakeholder collaboration, and adaptive regulation can be embedded through ongoing programs led by the Ministry of Communication and Digital (Komdigi), BSSN, and BRIN. By linking global frameworks with local implementation pathways, this research provides conceptual advancement and policy relevance for emerging economies seeking to institutionalize trustworthy AI governance.

Keywords: AI Governance; Digital Public Infrastructure; Ethical AI; Policy Relevance

ABSTRAK

Transformasi digital yang berkembang pesat di Indonesia melalui berbagai program seperti Digital ID dan INA Digital menghadirkan peluang besar sekaligus tantangan tata kelola yang kompleks ketika Kecerdasan Buatan (*Artificial Intelligence,* AI) mulai digunakan dalam pengambilan keputusan sektor publik. Kajian konseptual ini mengusulkan kerangka tata kelola strategis terhadap AI yang beretika dengan menyesuaikan standar dan kerangka kerja internasional seperti *OECD AI Principles*, *EU AI Act*, dan *NIST AI Risk Management Framework* ke dalam konteks kelembagaan dan regulasi di Indonesia. Penelitian ini memberikan kontribusi konseptual dengan merumuskan model kebijakan yang berorientasi pada implementasi untuk menanamkan nilai etika, transparansi, dan akuntabilitas dalam ekosistem digital nasional. Selain itu, penelitian ini menunjukkan bagaimana tata kelola antisipatif, kolaborasi berbagai pemangku kepentingan, dan regulasi adaptif dapat dijalankan melalui program yang dikelola oleh Kementerian Komunikasi dan Digital (Komdigi)**,** Badan Siber dan Sandi Negara (BSSN)**,** serta Badan Riset dan Inovasi Nasional (BRIN)**.** Dengan menghubungkan kerangka global dengan jalur implementasi nasional, penelitian ini memberikan kemajuan konseptual sekaligus relevansi kebijakan yang nyata bagi negara berkembang yang berupaya melembagakan tata kelola AI yang tepercaya.

Kata Kunci: Etika AI; Infrastruktur Digital; Relevansi Kebijakan; Tata kelola AI

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INTRODUCTION

Indonesia is undergoing a rapid transformation in digital governance, marked by the deployment of national digital identity systems, e-government platforms, and integrated smart infrastructure. As part of this acceleration, Artificial Intelligence (AI) is increasingly being integrated into public infrastructure projects to enhance service delivery, optimize resource allocation, and strengthen institutional responsiveness. However, this integration is not without risk. As AI systems begin to influence high-stakes decisions in public health, social welfare distribution, surveillance, and law enforcement, new ethical concerns emerge, ranging from algorithmic bias and opaque decision-making to the erosion of public trust in digital services.

Recent scholarship has emphasized that the ethical deployment of AI in the public sector must balance innovation with institutional accountability (Busuioc, 2021; Roberts, 2024; Taeihagh, 2021). Comparative studies indicate that governance capacity, rather than mere technical readiness, determines long-term trust and citizen adoption (Zaidan et al., 2024).

Despite the growing attention to digital transformation, academic and policy literature in Indonesia has primarily focused on technical implementation, infrastructure financing, or regulatory compliance. There is limited conceptual exploration of how AI ethics can be embedded upstream into digital public infrastructure governance structures. Most studies treat AI ethics as a reactive or external mechanism, through audits or regulatory catchups, rather than a proactive, embedded practice in design, implementation, and institutional learning. The country's readiness to adopt AI in its national digital public infrastructure framework has been assessed through various global benchmarking initiatives, revealing both opportunities and gaps in governance (UNESCO, 2024).

This gap is further amplified by the absence of a unified governance framework that bridges ethical AI principles with the operational realities of public infrastructure in Indonesia. While global frameworks such as the OECD AI Principles, the EU AI Act, and the NIST AI RMF offer foundational guidance, their adaptation to the Indonesian context remains underdeveloped.

Recent systematic reviews underscore that translating global AI ethics frameworks into national contexts requires multi-level governance and value alignment mechanisms (Alhusban & Rahman, 2025; Mišić et al., 2025; Morley & Floridi, 2023). These studies collectively show that effective adaptation depends on public-sector ethics institutionalization, rather than isolated policy statements.

Existing local regulations, including the SPBE Presidential Decree and the Personal Data Protection Law (UU PDP), provide legal scaffolding but fail to address ethical implementation challenges across sectors and institutions.

In response to this gap, this paper offers a conceptual framework that integrates global best practices in ethical AI with Indonesia's unique institutional, cultural, and regulatory dynamics. The paper aims to expand the discourse beyond compliance, towards anticipatory governance, inclusive stakeholder engagement, and the institutionalization of ethics as a core design principle. To this end, this paper introduces a strategic governance pathway tailored for AI-driven public infrastructure.

This study seeks to address the following research question: How can ethical AI principles be systematically embedded within the governance of digital public infrastructure in Indonesia? The paper aims to propose a strategic governance model that aligns AI deployment in the public sector with ethical, transparent, and accountable practices.

METHODOLOGY

This study adopts a conceptual and normative research design aimed at developing a strategic governance framework for embedding ethical AI within Indonesia's digital public infrastructure.

The research proceeds through three main stages:

1. *Literature synthesis,* i.e., a comprehensive review of global AI governance frameworks (OECD AI Principles, EU AI Act, NIST AI RMF) and Southeast Asian policy literature between 2019 and 2025. The methodological approach aligns with prior conceptual reviews on AI governance frameworks that integrate normative analysis with institutional adaptation (Batool et al., 2025; de Almeida, 2025).

2. *Comparative policy analysis,* i.e., examination of Indonesia's institutional and regulatory landscape, including the SPBE Presidential Regulation, the Personal Data Protection Law (UU PDP No. 27/2022), and sectoral initiatives such as Digital ID (IKD) and the National Data Center (PDN).

3. *Analytical integration,* i.e., synthesis of findings into a conceptual governance model tailored to Indonesia's multistakeholder ecosystem.

Secondary data were obtained from peer-reviewed publications, official government documents, and professional insights gathered from practitioner networks, including Cloud Security Alliance (CSA) working groups and discussions, as well as AI CERTs community events focusing on AI security and compliance. These practitioner exchanges contextualized the ethical implementation challenges in cloud and AI-driven infrastructures.

However, this study acknowledges several methodological limitations. As a conceptual and normative inquiry, it does not collect primary data or empirically validate the proposed framework. While including expert perspectives enhances analytical richness, future research should complement this work with case-based evaluations or pilot implementations to test the framework's practical applicability.

LITERATURE REVIEW

Integrating AI into public infrastructure has stimulated a global body of research focused on its transformative potential and the ethical

implications it generates. Scholars agree that AI can enhance public service delivery, predict policy outcomes, and improve resource allocation (Daly et al., 2019). However, using AI in state-driven infrastructure systems also introduces ethical concerns, including algorithmic bias, lack of transparency, and unequal access, particularly in developing economies like Indonesia (Firdaus, 2024; Nilgiriwala et al., 2024).

Global Ethical AI Frameworks and Their Implications

Globally, frameworks such as the OECD AI Principles (OECD, 2019) advocate for human-centered and trustworthy AI, emphasizing values such as transparency, robustness, and accountability. These principles form a widely accepted normative foundation that has influenced various national and institutional guidelines. The European Union's AI Act further expands this discourse by introducing a risk-based taxonomy, classifying AI systems into four levels: unacceptable, high, limited, and minimal risk (Wadipalapa et al., 2024). High-risk systems, such as those used in public services, surveillance, or national infrastructure, are subject to stringent requirements including impact assessments, documentation, and human oversight.

The NIST AI Risk Management Framework (AI RMF), developed in the United States, emphasizes an iterative and adaptive lifecycle approach to AI governance (Choung et al., 2023). Unlike the EU's compliance-heavy model, NIST offers a more flexible structure centered on organizational learning and contextual risk mapping. This model is particularly applicable to nations that exhibit institutional variability. In countries such as Indonesia, regulatory and ethical capacities differ significantly across agencies and regions.

Ethical Gaps in Southeast Asian AI Governance

In the Southeast Asian context, AI governance remains fragmented. According to Nilgiriwala et al. (2024), while nations like Singapore and Malaysia have launched formal AI ethics guidelines, Indonesia remains in the early stages of development. Although legal structures such as the Personal Data Protection Law (UU PDP No. 27/2022) and Presidential Regulation on SPBE are in place, a comprehensive, ethics-first AI governance model is still absent. Firdaus (2024) notes that many Indonesian government initiatives treat ethics as an afterthought, addressing it mainly through audit functions or reactive compliance rather than a proactive design and deployment component.

There is also limited integration between ethical AI frameworks and infrastructure-specific governance literature. While urban planning and innovative city models address issues such as citizen engagement and sustainability, they often omit AI-related concerns or treat them as a mere technical issue rather than normative challenges (Tjondronegoro, 2024). Likewise, policy papers on e-government frequently assume AI deployment to be value-neutral, which ignores the socio-political implications of automation in public systems (Maria & Riswadi, 2024).

Similar gaps have been identified across other developing economies, where ethical frameworks often remain aspirational until supported by enforceable accountability systems (Ahmed & Leung, 2024; Papagiannidis et al., 2025). The alignment between public trust mechanisms and regulatory design is thus critical for sustainable governance.

These gaps highlight the need for a contextualized governance model that incorporates ethical principles and aligns them with Indonesia's unique regulatory, institutional, and cultural landscape. Existing literature has not yet offered a conceptual synthesis that bridges global AI ethics with Indonesia's operational realities in public infrastructure governance. This paper seeks to fill that gap by providing a strategic framework for embedding ethical AI into Indonesia's digital public infrastructure ecosystem, using global best practices as scaffolding but rooted in local policy dynamics.

Building upon the above synthesis, this paper employs a theoretical lens of anticipatory governance**,** integrating responsible innovation theory and ethical design principles to structure the analysis. This theoretical foundation links the global ethical AI discourse with Indonesia's institutional realities, guiding the development of the proposed governance framework.

DISCUSSION

This section discusses the strategic positioning of ethical AI within Indonesia's evolving digital infrastructure landscape. Drawing from global frameworks and the Indonesian policy context, the analysis highlights a critical shift from compliance-oriented digital transformation toward ethically embedded governance models. This shift reflects the global trend where trust, transparency, and accountability have become integral components of responsible innovation, particularly in public sector digital services (Daly et al., 2019; OECD, 2019).

AI deployment in public digital infrastructure, such as e-government systems and citizen databases, has often been framed as a matter of technical efficiency. However, this conceptual paper reframes the discourse by positioning ethics as a core component of infrastructural governance, not a peripheral concern. While many Southeast Asian governments have released high-level ethical guidelines, Indonesia's approach remains fragmented, lacking a unified framework that can navigate cross-sectoral implementation. By juxtaposing Indonesia's existing digital policies with international standards such as the EU AI Act and the NIST AI RMF, this study argues for a middle-ground model that is both contextually grounded and globally informed.

Scholars increasingly advocate for a governance approach that balances flexibility with institutional coherence by integrating anticipatory and adaptive regulation (de Almeida, 2025; Mišić et al., 2025). Evidence suggests that proactive policy experimentation fosters public-sector innovation without eroding ethical safeguards (Batool et al., 2025; Zaidan et al., 2024).

While the OECD and EU frameworks emphasize formalized regulatory oversight, Indonesia's decentralized administrative structure necessitates adaptive governance. The political economy of digital governance, characterized by fragmented bureaucratic authority and varying local capacities, requires a polycentric model that blends central coordination with regional autonomy.

Culturally, Indonesia's emphasis on *gotong royong* (mutual cooperation) and participatory deliberation can be a normative anchor for AI ethics localization. Embedding public trust mechanisms aligning with these values ensures that ethical AI governance is technically sound and socially legitimate.

A significant insight in this analysis is the necessity of anticipatory governance. This approach is proactive rather than reactive, allowing institutions to anticipate risks and

align AI applications with public values from the outset (Choung et al., 2023). Unlike static regulation, anticipatory governance encourages adaptive learning loops, where ethical considerations evolve alongside technological innovation. Such a model is particularly relevant for Indonesia, where state capacity and regulatory enforcement vary widely across regions.

Empirically, Indonesia's digital public infrastructure ecosystem encompasses initiatives such as the Digital Identity (IKD), the SPBE, and the PDN. They provide rich case material for diagnosing governance gaps. In 2024, the government launched the INA Digital platform, consolidating public service applications and digital identity issuance under one national portal. Concurrently, agencies such as the Komdigi and the Ministry of Home Affairs have accelerated the rollout of IKD to over 60 million citizens as part of the country's push toward a unified digital identity ecosystem.

The World Bank's US$250 million project, approved in 2023 to strengthen Indonesia's civil registration and digital ID infrastructure, reflects the global significance of these reforms. The PDN program, now in its second phase after a 2024 system outage, has sparked national discussions on cloud sovereignty, resilience, and data localization, underscoring the governance tensions between innovation speed and institutional readiness.

Several AI-related policy pilots are also emerging domestically. In early 2025, Komdigi began drafting a National AI Policy Blueprint to complement the Personal Data Protection Law, incorporating ethical AI principles into e-government services. Meanwhile, Indonesia's Financial Services Authority (OJK) and Indonesian Central Bank (Bank Indonesia) have launched regulatory sandboxes to test AI-based credit-scoring and fraud-detection models, revealing both regulatory agility and the need for stronger oversight mechanisms.

A 2025 empirical study on digital-ID acceptance found that trust deficits, uneven broadband infrastructure, and limited digital literacy remain persistent barriers in rural and eastern provinces. Combined with fragmented institutional accountability, these factors highlight the challenge of embedding ethical governance within Indonesia's complex multi-level administrative system.

Regionally, Singapore provides a mature comparative lens. Its Model AI Governance Framework (Version 3.0, 2024) expanded to cover Generative AI, emphasizing risk classification, content provenance, and accountability mechanisms. The framework and the Infocomm Media Development Authority's (IMDA) regulatory sandboxes exemplify anticipatory governance to balance innovation incentives with ethical safeguards.

Malaysia, by contrast, has focused on institutionalizing ethics through formal structures. In 2024, the government issued its National Guidelines on AI Governance and Ethics (AIGE), codifying seven core principles: fairness, safety, privacy, inclusiveness, transparency, accountability, and human-centricity, and establishing the National Blockchain and Artificial Intelligence Committee (NBAIC) under the Ministry of Science, Technology and Innovation. Later that year, the National AI Office (NAIO) under *MyDIGITAL* was created to coordinate nationwide AI initiatives. By 2025, Bank Negara Malaysia (BNM) had opened public consultations on AI use in financial services, reporting that over 70 per cent of financial institutions had deployed at least one AI-driven application by the end of 2024. These initiatives

demonstrate Malaysia's pragmatic, policy-driven approach that offers complementary lessons for Indonesia's evolving AI governance framework.

Another emerging theme is multistakeholder engagement. Ethical governance of AI in public infrastructure cannot rest solely on government agencies. Instead, it requires collaborative ecosystems involving technologists, legal experts, civil society, and citizens. This inclusive governance model supports accountability, builds public trust, and ensures ethical standards are socially legitimate. Drawing from the OECD's emphasis on stakeholder participation, this paper proposes a governance framework that includes consultative mechanisms at both national and sub-national levels.

Furthermore, this study highlights the role of local context. While global frameworks provide valuable blueprints, direct adoption without local calibration may result in ineffective or counterproductive outcomes. For example, algorithmic audits and bias testing methodologies from high-income countries may not reflect the socio-technical realities of Indonesia's public service infrastructure. Therefore, this paper underscores the importance of indigenizing global ethical principles through policy sandboxing, experimental regulation, and public deliberation mechanisms.

In the Indonesian context, civil society actors such as ICT Watch and EngageMedia have actively participated in drafting AI/Internet Governance recommendations and capacity building for community engagement. On the academic front, institutions like Indonesia AI Institute**,** IAIS**,** and researcher groups behind projects such as NusaCrowd or the 2025 national language technology survey are contributing context-sensitive insight. Meanwhile, technology communities, e.g., the startup Nodeflux or industrial-academic collaborations in local LLM projects (such as *Sahabat-AI* by Indosat & GoTo), bring technical implementation perspectives and feedback loops. These actors collectively strengthen oversight, democratize standards, and provide grounded case knowledge beyond theoretical assumptions.

In summary, the discussion demonstrates that ethical AI governance in Indonesia's public digital infrastructure is not merely a normative ideal but a strategic imperative. By embedding ethics into the design, deployment, and oversight of AI systems, the country can not only mitigate risk but also unlock the transformative potential of AI in delivering inclusive, transparent, and responsive public services.

Proposed Strategic Governance Framework

In relation to the Ethical AI in Indonesia, the proposed framework ideally shall consist of four interlinked phases:

1. *Strategic alignment:* Embedding ethical AI principles into national digital strategies, ensuring alignment with SPBE and PDP Law.

2. *Institutional coordination:* Establishing an inter-agency council involving Komdigi, BSSN, BRIN, OJK, and the Ministry of Administrative Reform to oversee AI governance coherence.

3. *Operational integration:* Developing standardized protocols for algorithmic auditing, bias testing, and public transparency dashboards across government platforms.

4. *Ethical assurance and learning:* Institutionalizing continuous monitoring, public participation, and cross-sector

capacity building through civic–academic–industry partnerships.

The framework is iterative, allowing policy feedback loops and adaptive regulation. A schematic illustration (Figure 1) can visualize these components and their interdependencies.

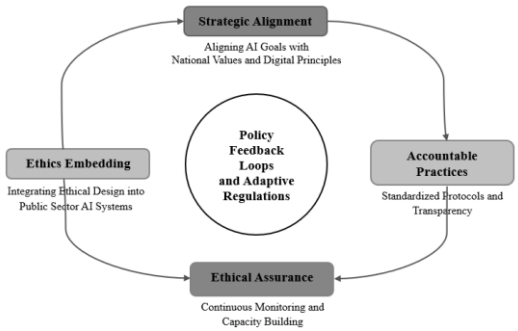

Figure 1. Iterative Framework for Ethical AI Governance in Digital Public Infrastructure

Source: Author's Own Elaboration (2025)

RECOMMENDATIONS

Building upon the proposed strategic governance framework, this section seeks to translate the conceptual foundations into actionable and relevant recommendations that reflect Indonesia's digital-policy landscape in late 2025.

Institutional Implementation

The coordination of ethical AI governance should be anchored in an inter-ministerial structure led by Komdigi, supported by BSSN for cybersecurity assurance, BRIN for AI research and validation, OJK and BI for financial-sector supervision, and the Ministry of Administrative and Bureaucratic Reform (KemenPANRB) for embedding AI governance into *Sistem Pemerintahan Berbasis Elektronik (SPBE)*. At the strategic level, Bappenas plays a pivotal role in aligning AI-ethics policy with the *Digital Indonesia Roadmap 2025–2030* and the Sustainable Development Goals.

Pilot Projects and Regulatory Sandboxes

As of 2025, several pilot initiatives have emerged under Komdigi's INA Digital and IKD programs. The initiatives offer practical entry points for testing algorithmic fairness, transparency, and accountability mechanisms. The government could further establish a National AI Sandbox, jointly facilitated by Komdigi and BRIN, to simulate ethical AI use cases in domains such as e-procurement, social-aid targeting, and citizen-service analytics. While not yet formally launched, this sandbox aligns with the forthcoming National AI Roadmap (2025–2027) currently under policy consultation.

Public and Multistakeholder Participation

Stakeholder engagement should be institutionalized through regular AI Governance Consultative Forums convened by Komdigi and BSSN, integrating perspectives from civil-society organizations (e.g., ICT Watch, EngageMedia), academic networks (e.g., Indonesia AI Institute, IAIS), and industry leaders (e.g., Nodeflux, Telkom, Indosat, GoTo's Sahabat-AI project). These forums can co-design ethical standards, share datasets for algorithmic-bias testing, and document local lessons for ASEAN digital-governance harmonization.

Capacity Building and Human-Resource Development

Sustaining ethical AI governance requires skilled digital professionals. The Digital Talent Scholarship (DTS) initiative under Komdigi now targets 100,000 participants, integrating new tracks on cloud computing, data privacy, and AI ethics. Collaborations with Google Cloud Career Launchpad and Telkom's Digital Academy extend these modules nationwide. Parallel efforts by BSSN through its Cyber Academy emphasize resilience, secure-by-design practices, and

ethical data handling. Partnerships with global professional bodies, such as ISACA, ISC2, and the Cloud Security Alliance, can institutionalize advanced certification pathways and continuous upskilling for public officials and technology practitioners.

Future-Oriented Steps

While several initiatives are operational, the others, such as the National AI Sandbox, integrated ethics audit protocols, and cross-sector certification frameworks, remain prospective and could be prioritized in the National AI Roadmap 2025–2027. These steps would help Indonesia transition from policy formulation to systematic implementation of trustworthy AI governance.

International best practices indicate that embedding ethics into institutional capacity building enhances governance legitimacy and implementation continuity (Busuioc, 2021; Roberts, 2024; Taeihagh, 2021). Establishing cross-sector knowledge networks can translate these principles into measurable performance indicators (Papagiannidis et al., 2025).

Collectively, these actions bridge normative aspirations with practical execution, ensuring that Indonesia's AI governance ecosystem evolves as both ethically grounded and operationally executable within its national digital-transformation agenda.

CONCLUSION

This conceptual paper has examined the intersection between ethical Artificial Intelligence and public digital infrastructure in Indonesia, arguing for a strategic governance framework rooted in ethical principles. By bridging global frameworks such as the OECD Principles, EU AI Act, and NIST AI RMF with the local policy context, the study proposes an anticipatory and multistakeholder model of governance tailored to national needs.

This conclusion resonates with global scholarship emphasizing that ethical AI governance is an iterative learning process rooted in adaptive public institutions (Mišić et al., 2025; Morley & Floridi, 2023). Sustaining this momentum requires embedding evaluation metrics within governance lifecycles, aligning with cross-national studies on responsible innovation and AI accountability (Batool et al., 2025; de Almeida, 2025).

While the framework offers a forward-looking strategy to embed ethics into the lifecycle of AI systems in public services, its implementation may face challenges such as institutional fragmentation, lack of technical expertise, and limited civic participation. These limitations highlight the need for further empirical validation and regulatory experimentation through pilots and sandboxes.

Nonetheless, the insights articulated in this paper provide a conceptual foundation for policymakers and practitioners to reframe AI as an efficient tool and an ethical infrastructure that supports inclusive and trusted digital transformation. Future research may explore cross-sector case studies to refine the proposed framework and assess its real-world applicability.

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