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Technological Advancements and Implementation Barriers in Clean Coal Utilization: A Systematic Review with Indonesian Case Insights

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ABSTRACT

Coal still plays a major role in Indonesia's energy mix, accounting for approximately 40% of the national primary energy mix in 2024., while low-emission technologies are becoming dominant in the world. In this study, a Systematic Literature Review (SLR) was performed to conduct an evaluation of technological developments and implementation challenges on the clean coal utilization which include gasification, clean combustion systems, activated carbon production and valorization of coal residues (fly ash and bottom ash) from both international view as well as Indonesian perspective. All international and national peer-reviewed articles (published between 2014–2024) were reviewed to analyze trends, gaps, and technical readiness. It is found that coal gasification technology provides the highest energy conversion efficiency of up to nearly 75%, and can cut carbon emissions by 40–60% in comparison to traditional combustion. On the other hand, fly ash and bottom ash utilization of for example 20 million tonnes per year could save up to around Indonesia's coal power waste generation as well as support circular economy goals. There are still barriers to the adoption of this technology such as high investment costs ($1.2–1.5 million/MW), medium moisture in low rank coal (>30%) and small-scale pilot projects at industrial level. Lessons learnt This article reiterates that R&D needs the backing of fiscal incentives, demo plants and regulatory frameworks to hasten the sustainable deployment of CCTs in Indonesia.

Keywords: Clean Coal Technology, Gasification, Implementation Barriers, Indonesia, Systematic Review.

Introduction

Coal remains crucial to Indonesia's energy security, supplying around 50% and contributing around 40% to the national primary energy mix in 2024 [1]. As one of leading exporter of coal in the world, Indonesia is dependent on coal for power generation and industrialization[2]. But such a reliance also presents a dilemma: on one hand, coal adds certainty for the energy sector but on the other, it is simultaneously an enormous contributor to carbon emissions and hence challenges Indonesia's Net Zero Emission (NZE) 2060 targets.

Internationally, the energy transition model has led to significant investments in low-emission and high-efficiency technologies. Several developed countries have initiated the integration of clean coal technologies (CCTs) such as gasification, carbon capture, utilization and storage (CCUS), and ultra-super-critical (USC) combustion systems as shortterm measures for decarbonizing the power sector [3]. These technologies offer higher energy conversion efficiencies and substantial emission reductions, placing coal not only as a source of pollutants but also as an interim fuel for cleaner energy systems.

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In this scenario, technological development of coal gasification has been an area of innovation. The gasification process would utilise low-rank coal, which constitutes the majority Indonesia's coal resources (approximately 60% of Indonesia's total proven coal reserves) and transform it into a high-value synthetic gas, known as syngas that is rich in hydrogen (H2) and carbon monoxide (CO). This conversion will open the possibility to utilize Indonesia's large reserve of low-calorific lignite in an efficient way and develop the downstream industries, such as methanol, fertilizer, and hydrogen fuel [4]. The pathways are also in line with Indonesia's policy direction to contribute to energy diversification and to optimization of industrial value chain according to the National Energy Grand Strategy (RUEN).

However, despite the technological promises, clean coal technologies has seen little application yet in Indonesia. A number of issues exist which still hinder the prospects of CCBT development, including cost competitiveness such as economic viability of high capital investment processes like gasification and CCUS, inconsistences in coal quality feedstock (vis a vis variations in moisture content; calorific value), and lack of supportive environments to drive adoption through policy framework [5]. No large demonstration projects (pilot plants) have been implemented and there is poor transfer of technology within international co-operations which in turn also limits this domestically. Moreover, the financial obligations of CCUS integration can be a deterrent given that carbon capture cost was estimated to be between USD 40 and 70 per ton of CO_2' in the absence of regulatory or fiscal assistance [6].

With these complexities dimensions, a comprehensive overview of the global technological environment versus the local barriers in Indonesia is crucial. Previous research on clean coal in Indonesia tend to be piecemeal that either emphasize technical issues (like gasifier design or catalyst optimization) or policy discourse without incorporating both perspectives. Therefore, a systematic and integrative review is important to fill in the gap between the global innovation development trajectory with Indonesia's practical readiness.

Accordingly, this study seeks to systematically investigate and analyze global advances in clean coal utilization technologies (i.e., gasification, combustion efficiency enhancement, CCUS and residue valorization), as well as implementation constraints particularly applicable to the Indonesian context. Based on a systematic review of international and national papers published over the last decade this paper offers evidence-based guidance for policy-makers, industry partners, research community that are interested in facilitating sustainable CCBT deployment efforts in Indonesia. The results are also anticipated to inform the formulation of strategic frameworks viz pilot project planning, incentive schemes for investment and technological localization strategies in supporting Indonesia's shift toward a low carbon energy system.

Methods

The research Using the systematic literature review (SLR) methodology, the author identifies the global advancements and the barriers of implementation of clean coal utilization technologies in the global and Indonesian contexts. For the SLR methodology, the author used the PRISMA [7] guidelines together with the Tranfield et al. (2003) proposal, to make the review as transparent and replicable as possible. The author describes the review process as consisting of the following six steps: defining research questions, identifying relevant literature, screening and eligibility, data extraction, thematic analysis, and synthesis (See Figure 1).

Using the search terms "clean coal technology," "coal gasification," "CCUS," and "fly ash utilization," the author conducted studies in Scopus, the Web of Science, and Google Scholar. The author limited studies to 2014 to 2024 and included peer reviewed, full text, and relevant studies that led to research to yield studies that satisfied the inclusion criteria of relevant studies. Thematic synthesis [8] was employed to code and extract relevant data to the four themes of gasification, clean combustion, CCUS, and valorization of coal residue.

To understand the technological patterns, efficiencies, and barriers of clean coal technologies, the author integrated findings. Dual review validation and inter-coder reliability (Cohen's $\kappa = 0.84$) were used to support the methodology, make the findings more reliable, and to provide an evidence-based analysis and a more reliable policy recommendation [9],[10].

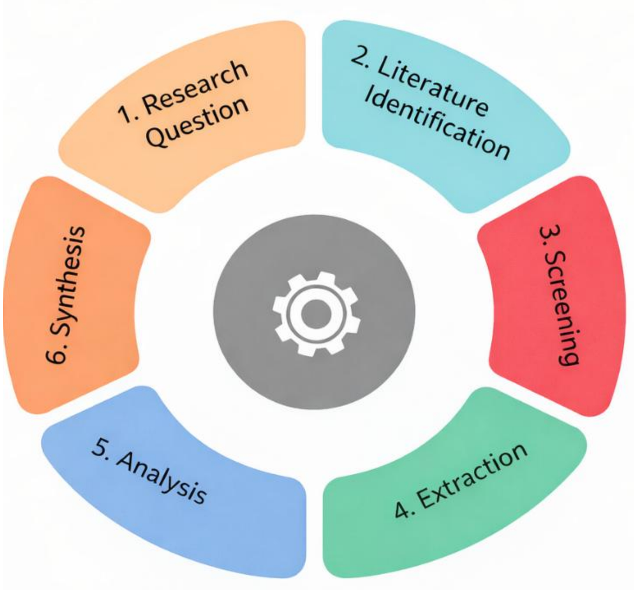


Figure 1. Methodological framework of the Systematic Literature Review (SLR)

Results and Discussion

This part explains the outcomes of the systematic literature review and examines global technology trends and Indonesia's readiness for clean coal implementation. The discussion is divided into three primary components: advancements in the technology of clean coal utilization, implementation impediments, and insights on Indonesia. Each subsection merges global data and contextual reasoning to articulate the comprehensive spectrum of the Indonesia clean coal transition's challenges and opportunities.

A. Technological Advancements in Clean Coal Utilization

In the last 20 years, the rapid reconfiguration of Clean Coal Technologies (CCT) is primarily influenced by the need to constrict the greenhouse gas (GHG) emissions while energy dependability is still maintained for coal reliant economies. The rapid advancements in CCT are primarily seen in the following: (1) gasification and hybrid energy systems, (2) progressive combustion and efficiency enhancement, and (3) the integration of carbon capture, utilization, and storage (CCUS). The above advancements illustrate the move away from conventional coal burning to low-emission and high-efficiency conversion systems [3], [11].

1. Coal Gasification and IGCC Systems

In the realm of innovative clean coal, the cornerstone of modern coal clean technology is the gasification of coal. The gasification process converts coal to gas, in particular, to synthetic gas (syngas) which is predominantly hydrogen (H_2) and carbon monoxide (CO). Gasification efficiency, as cited by Mishra et al. (2018) [12] and Dai et al. (2023) [4], is between 68-75 % which is substantially better than the subcritical combustion systems (33-38 %). Global studies on gasification have focused on the enhancement of catalysts, optimization of reactors, and hybridization to renewable sources of energy to withstand the carbon limitations.The role of the Ni-Fe composite catalysts has been recognized for

the positive shift in the water-gas shift reactions and for generating more hydrogen [13]. The use of plasma-assisted gasifiers and fluidized-bed systems is a major step forward in the continual feeding of gasifiers and in the reduction of tar buildup [14], [15]. In addition, the co-gasification of coal and biomass has been shown to provide a synergistic effect in the use of fossil and renewable resources, with the potential to reduce emissions by 50% of CO2 and 70% of SO2[16],[17].
In terms of practicality, South Korea and China have commercialized Integrated Gasification Combined Cycle (IGCC) systems, exemplified by the Tianjin 250 MW and Taean 300 MW projects, with recorded thermal efficiencies above 70% [11]. The most notable improvement of sustainability in the technology has been the addition of CO2 capture units to the IGCC system, permitting an optimization of the system to accomplish up to 90% reduction in emissions [11], [18].

2. Advancements in Combustion and Efficiency Improvements

Like gasification, advancements in combustion focused on heat transfer improvements, reduction in the formation of pollutants, and the use of low-quality coals, such as Indonesia's lignite. Rybak et al. (2024)[3] and Kuźnia (2025)[19] state that supercritical (SC) and ultra-supercritical (USC) boilers have net thermal efficiencies of 42-47% and operate at temp of 620 and pressures greater than 25MPa. These technologies are now considered state of the art in Japan, Germany, and Poland, and are responsible for 15-25% reduction in CO_2 emissions compared to the average fossil fuel plants.
Moreover, low emissions Circulating Fluidized Bed (CFB) combustion coupled with in-bed limestone desulfurization [20][21] achieves the co-firing of biomass and waste-derived fuels. Additionally, emerging oxy-fuel combustion systems, which use pure oxygen instead of air, produce flue gas with >80% CO_2 and therefore simplify CO_2 capture [15]. These systems have shown great promise in the integration of carbon recycling and are currently being piloted in the EU and China.

3. Integration of Carbon Capture, Utilization, and Storage (CCUS)

According to Samosir et al. (2025)[6] and IEA (2022), CCUS has emerged as a critical addition to both gasification and advanced combustion. Post-combustion amine-based schemes are able to capture close to 90% of CO2 in combustion flue gases; however, this comes at an energy costs (which Samosir estimates to be about 10 to 15 of firm hours). Emerging membrane and cryogenic capture schemes are expected to reduce these costs by 30 to 40 % in the next decade [22].
Currently, there are more than 30 large scale global CCUS initiatives; in terms of numbers these are concentrated in the USA, China and Norway [23]. In terms of volumes, these three nations account for over 45 million tons of CO2 captured annually. Integration of CCUS with gasification-based hydrogen production referred to as Blue Hydrogen has become central to energy transitions; this can be seen in Japan's Osaki CoolGen and China's Yulin CCUS initiatives [24].
In Indonesia, the Gundih CCUS project (Central Java) and the Bukit Asam gasification plant, although full scale integration is still at Technology Readiness Level (TRL) 5–6, both represent preliminary steps to adaptation [25][26]. These initiatives, while building capacities for low carbon innovations, provide useful pathways to decrease the environmental footprint of Indonesia's coal-based industries [27].
The evidence suggests that gasification and integrated gasification combined cycle (IGCC) technologies offer the best prospect for Indonesia's energy transition, especially when combined with CCUS and residue valorization. These technologies improve efficiency and emissions and foster industrial symbiosis through the production of methanol, hydrogen, and DME [28], [29]. However, cost, complexity, and lack of technological maturity remain critical obstacles to full-scale implementation, resulting in a need for focused policy support, international partnerships, and local R&D funding [5], [6].

Table 2. Comparative Performance and Characteristics of Clean Coal Technologies

Technology	Process Description	Efficiency (%)	CO_2 Reduction (%)	TRL Level	Global Example	Key Challenges
Subcritical Boiler	Conventional low-pressure steam combustion	33–38	Baseline	9	Indonesia, India	High CO_2 intensity
Supercritical (SC)	High-pressure (>22 MPa) combustion	40–42	10–15	9	Poland, Japan	Material cost
Ultra-Supercritical (USC)	Advanced >600°C, >25 MPa boiler system	45–47	20–25	8–9	Japan, Germany	Alloy degradation
CFB Combustion	Fluidized bed with limestone for SO_2 reduction	38–44	15–20	8	China, Finland	Bed control
IGCC	Gasification + combined cycle turbine	65–75	40–60	7–8	Korea, China	High CapEx
Gasification + CCUS	Syngas conversion with CO_2 capture	70–75	60–90	6–7	Japan, U.S.	Storage logistics
Oxy-Fuel Combustion	Pure oxygen combustion for CO_2-rich flue gas	38–42	80–90	5–6	EU, China	Energy penalty
Co-Gasification (Coal + Biomass)	Blended feed for cleaner syngas	60–70	50–70	5–7	India, Australia	Feed variability

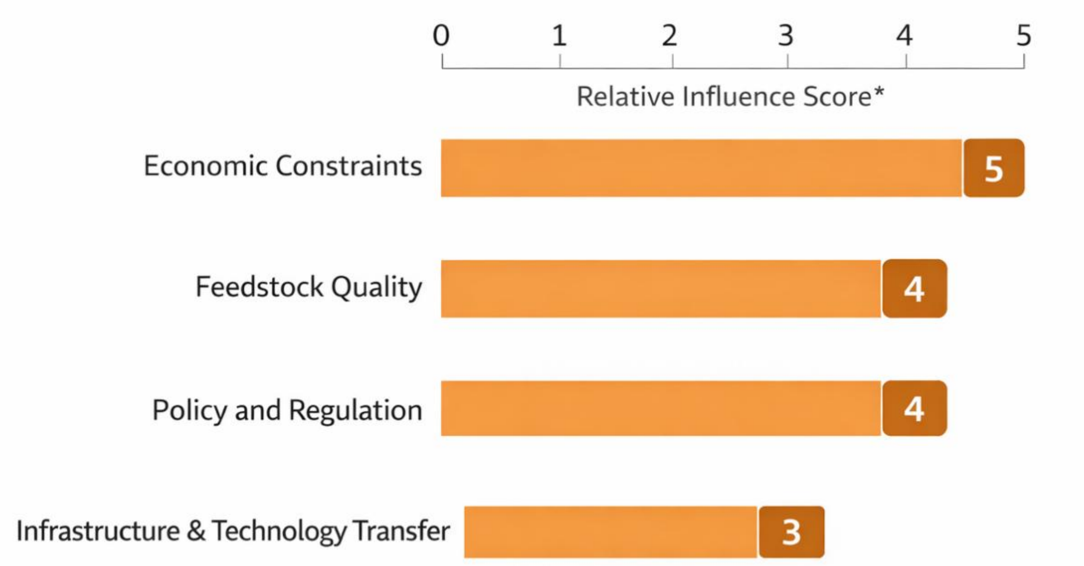
Source: [3], [11], [12], [21], [30]–[33]

B. Implementation Barriers in Clean Coal Technology

Clean coal technologies, including integrated gasification combined cycle (IGCC) systems, currently being developed in Indonesia face technical, financial, and policy barriers, despite technological advances. Undoubtedly, the most pressing issue is financial. The capital investment (CapEx) required for gasification and IGCC projects ranges from USD 1.2–1.5 million per megawatt (MW) [34], nearly double that of traditional coal pulverization. Furthermore, operational costs (OpEx) are higher due to initial drying, oxygen supply, and tar removal in the gasification system [5]. The absence of financial incentives, carbon pricing mechanisms, and electricity purchase tariffs for clean coal-fired power plants further hinders private investment [35].

Raw material quality is another challenge. Approximately 60% of Indonesia's coal reserves are low-rank lignite [36], meaning they contain high moisture (>30%) and have a low calorific value. This increases the amount of CO2 produced for the energy recovered and limits the efficiency with which coal can be converted to gas. Improvements are needed for gasifier systems designed for bituminous coal, which increases costs and technical challenges [37].

Barriers to implementation are also policy and institutional. The absence of a clear national strategy for clean coal, combined with a lack of sufficient synergy between energy and environmental agencies, are factors hampering rapid implementation. Although the Indonesian National Energy Grand Strategy (RUEN) recognizes clean coal in its transitional capacity, for CCUS and IGGC, a specific regulatory framework remains in the background ([38]). Furthermore, limited opportunities for technology transfer and a lack of qualified personnel reduce readiness for industrial-scale adoption [6].



Source: [5], [6],[38]

Figure 2. Barriers to Clean Coal Technology Implementation in Indonesia

C. Indonesian Case Insights: Readiness and Opportunity

Indonesia's energy landscape continues to be shaped by its reliance on coal, which remains the primary source of electricity production (approximately 45% by 2024) [39]. According to the National Energy Policy (KEN) and the Net Zero Emissions by 2060 strategy, clean coal utilization technologies such as gasification, carbon capture, and high-efficiency combustion are considered transitional technologies for achieving energy diversification [40]. Global indicators show that Integrated Gasification Combined Cycle (IGCC) and Carbon Capture Usage and Storage (CCUS) are developing rapidly; however, Indonesia is at an early stage in adapting them. Reliance on low-quality lignite coal, lack of technological development, and high costs are structural barriers to large-scale implementation [41]. However, within the context of the Great National Energy Strategy (RUEN), the government's emphasis on low-emission coal demonstrates increasing alignment with global sustainability goals [11], [42].

The Bukit Asam Gasification Project (South Sumatra) represents a cutting-edge technology. Together with Air Products, the project plans to produce 1.4 million tons of dimethyl ether (DME) annually, replacing imported LPG [43]. The project is also Indonesia's first commercial-scale coal-to-chemical (CTC) plant, which will further serve as a blueprint for the country's downstream industrialization. Similarly, ongoing feasibility studies in East and Central Kalimantan for coal-to-methanol and coal-to-hydrogen pathways further demonstrate the transition to lower-emission, value-added solutions [44], [45]. Despite these efforts, Indonesia's gasification system currently only has a Technology Readiness Level (TRL) of 4–6, considered a pilot to demonstration stage. This contrasts sharply with the TRLs of 8–9 in developed countries, including Japan and Korea [46], which emphasize the need for technology adaptation and localization for Indonesia's high-moisture, low-calorific value lignite [47].

To illustrate Indonesia's decarbonization plan, as one step in the plan, the country is developing Carbon Capture, Utilization, and Storage (CCUS) infrastructure. Pertamina and JOGMEC have launched the Gundih CCUS Pilot Project in Central Java. This will be the first project of its kind in Southeast Asia to integrate CCUS. This will be done in accordance with state regulations to reduce emissions. They have already begun injecting captured CO2 from Jamal (30,000 tons/year) to assess its storage stability [48]. Without fundamental storage regulations, this will provide a fiscally constrained framework, and CCUS will require substantial costs (50-70 USD per ton) for CO2 capture, making commercial operations virtually unattainable [49] [50]. CCUS, under the framework of Presidential Regulation No. 98/2021 concerning the Economic Value of Carbon, will be combined with green financing from the DAB and JETP to deliver greater value [46].

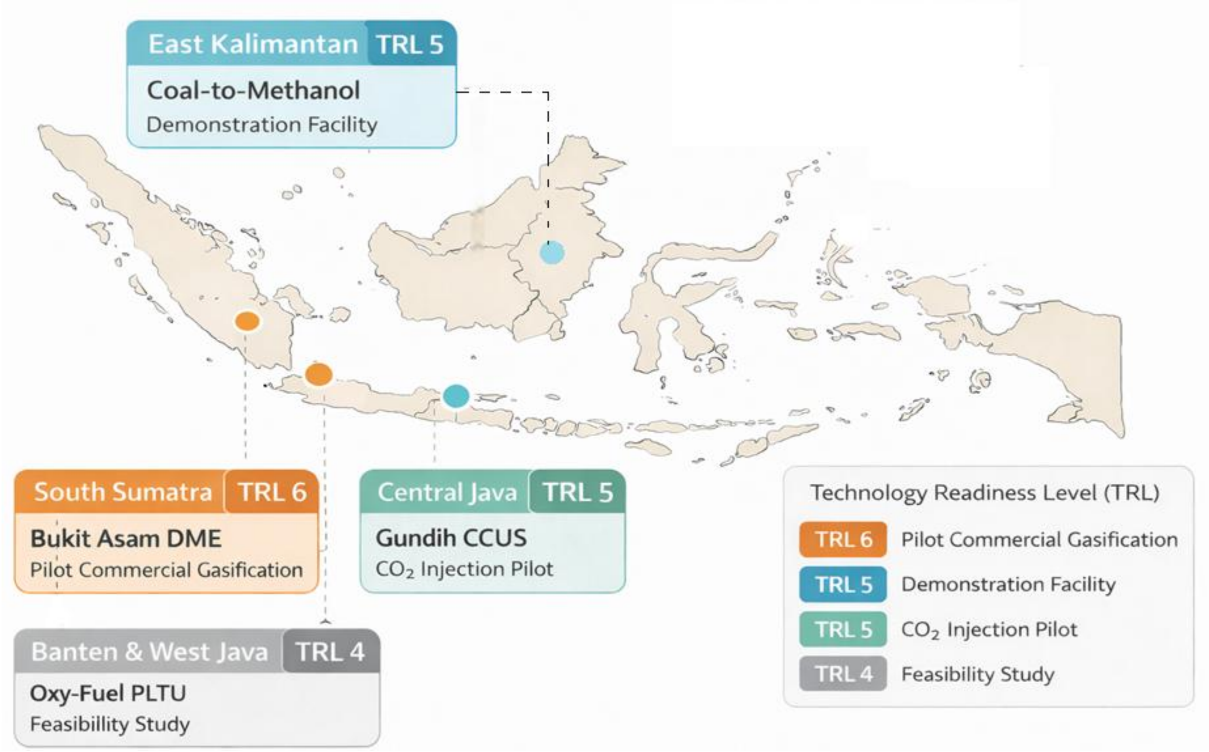


Figure 3. Technological Readiness and Project Distribution in Indonesia

From a systemic perspective, Indonesia's readiness to adopt clean coal technology is institutionally flawed, despite its technical feasibility. According to Susanto et al. (2023) [51], integrated R&D divisions, the lack of coal drying and processing infrastructure, and a shortage of skilled labor hinder the process. Knowledge transfer and industry collaboration are predominantly carried out by state-owned enterprises (SOEs), including PTBA, PLN, and Pertamina, with little involvement from the private sector and universities [52]. In this regard, Indonesia needs to enhance its international cooperation with technology pioneers such as Japan, China, and South Korea, particularly regarding hybrid gasification–CCUS demonstration plants and integrated domestic feedstock [53], [54]. With adequate policy formulation, supported by focused fiscal measures and continuous evaluation of pilot projects, Indonesia's coal industry can be transformed from a carbon burden to a positive driver of low-emission industrial development, in line with the global clean energy transition [11], [40].

Conclusion

This systematic review highlights global breakthroughs in clean coal technologies, emphasizing gasification, Integrated Gasification Combined Cycle (IGCC) systems, and carbon capture, utilization, and storage (CCUS), which deliver energy efficiency and carbon emission reductions of 75% and 40–60%, respectively, compared to subcritical systems. Furthermore, the use of high-efficiency, low-emission (HELE) combustion and oxyfuel systems integrates coal into global decarbonization strategies, as evidenced by the International Energy Agency. Thus, these technologies demonstrate the transformation of coal from a high-emission fuel to a cleaner and more exploitable resource for diversified industrial and chemical feedstocks. Despite Indonesia's efforts to promote national projects such as the Bukit Asam DME gasification and the Gundih CCUS pilot, gasification facilities still face challenges such as consistently high capital costs, low-rank and high-ash coal feedstock, and inadequate regulatory incentives. These challenges illustrate the Indonesian government's commitment to domestic gasification projects, but also the need for substantial progress toward large-scale implementation. To meet the 2060 Net Zero Emissions target, policy consistency, green financing, and international technology transfer from developed democracies need to be strengthened. Increasing domestic R&D and the compatible integration of gasification with CCUS and residue valorization will enable Indonesia to reintegrate coal as a catalyst for low-carbon industries, thus bridging energy security and sustainability within a long-term transition framework.

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