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Emissions–Energy Efficiency Gap and Decarbonization Roadmap Priorities in an Indonesian State-Owned Refinery (PT KPI)

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Abstract

Background: This study evaluates the 2026–2030 energy efficiency and decarbonization roadmap of PT Kilang Pertamina Internasional (PT KPI) to examine the gap between absolute greenhouse gas emission reductions and actual structural energy efficiency improvements.
Objective: This study examined this diagnostic tension at PT Kilang Pertamina Internasional (PT KPI) by evaluating its energy-efficiency and decarbonization roadmap for 2026–2030.
Methods: The study used a single corporate case design combining primary company data (2020–2024 emissions records and 2023 Energy Intensity Index data), document review, and structured judgment from a five-member expert panel, analyzed through a TOWS matrix informed by Dynamic Capability Theory.
Results: PT KPI reduced combined Scope 1 and Scope 2 emissions by approximately 16.3 percent between 2020 and 2024, while its 2023 Energy Intensity Index of 107.8 remained above the company's internal reference value of 100, indicating that the decline could not be confirmed as evidence of structurally embedded efficiency improvement given the limited normalized performance data available. Energy-performance harmonization across refinery units, utility and process-system transformation, and the integration of energy efficiency as a carbon-risk mitigation instrument emerged as the three highest-priority strategies (SPI 5.00, 4.76, and 4.36, respectively), with digital energy-management-system strengthening ranked fourth (SPI 4.24).
Conclusion: These priorities were found to establish necessary governance and measurement foundations but to be insufficient, on their own, to achieve net-zero targets by 2060, positioning the 2026–2030 roadmap as a transition-enabling phase rather than a deep-decarbonization pathway. The findings offer a transferable diagnostic approach for other multi-site, state-owned, energy-intensive enterprises facing comparable data and governance constraints, underscoring the need for normalized performance reporting alongside absolute emissions disclosure.

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INTRODUCTION

Industrial decarbonization is central to global climate strategy, yet heavy, energy-intensive sectors remain among the most difficult to decarbonize because they rely on fossil-based thermal processes, long-lived assets, and capital-intensive infrastructure (Kumar et al., 2024; Rissman et al., 2020). Within this broader challenge, energy and material efficiency are recognized as essential near-term levers that can reduce emissions without requiring wholesale technology replacement (Apata, 2025; Kim et al., 2024). Energy efficiency in particular is often

described as the "first fuel," offering some of the fastest, lowest-cost reductions in energy use, cost, and emissions available to industry (International Energy Agency, 2024). However, translating this technical potential into sustained, verifiable performance requires more than technology adoption; it depends on how firms manage energy internally, including cost accounting practices, organizational routines, and data governance (Dickemann, 2025; Schulze et al., 2016).

A well-documented "energy efficiency gap" persists in heavy industry due to systemic, organizational, and informational barriers that hinder firms from leveraging cost-effective measures (Backlund et al., 2012; Cagno et al., 2013). Closing this gap requires sustained managerial oversight, not just isolated investments (Safarzadeh et al., 2020; Solnørdal & Foss, 2018; Thollander & Palm, 2012; Trianni, Cagno, & Farné, 2016; Trianni, Cagno, Worrell, et al., 2013). Corporate Energy Management Systems (EMS), especially ISO 50001, offer a structure for monitoring, benchmarking, and improvement of energy performance (Al-Qallaf et al., 2017; Arabeyyat & Ragha, 2024; Fuchs et al., 2020; International Organization for Standardization, 2018). Evidence shows that the benefits of ISO 50001 depend more on implementation rigor and maturity than certification alone (Eidt, 2012; Jovanović & Filipović, 2016; Senyonyi et al., 2024). Research indicates that formal procedures, energy audits, and systematic data governance are crucial for translating technical opportunities into ongoing performance gains (Seutche et al., 2021).

Oil refining exemplifies the tension between efficiency and decarbonization: refiners must secure fuel supply and energy security while reducing emissions through waste-heat recovery, process electrification, low-carbon hydrogen, co-processing, and carbon capture (Bergman-Fonte et al., 2023; Griffiths et al., 2022; Yáñez et al., 2022). Sociotechnical reviews show these technological options are well documented, but adoption remains uneven and context-dependent, influenced by asset age, feedstock, and regulations (Bergman-Fonte et al., 2023; Griffiths et al., 2022; Nurdiawati & Urban, 2022; Yáñez et al., 2022). Case studies in Colombia and Latin America indicate that implementation of deep-decarbonization pathways is constrained by infrastructure, investment capacity, and macroeconomic trade-offs, even when pathways are delineated through integrated assessment modeling (Chaichaloempreecha et al., 2024; Timofeeva et al., 2023; Titova et al., 2023). Technical literature shows that near-term abatement potential largely resides in optimizing existing thermal and utility systems, not just deploying new technologies (Jouhara et al., 2018; Pisciotta et al., 2022). Decision-support research emphasizes that integrating these measures into coherent, multi-energy strategies requires careful staging and strategic portfolio design (Fetanat & Tayebib, 2025).

Recent scholarly work considers industrial decarbonization as a socio-technical transition that necessitates coordinated changes across technological, institutional, and user domains, extending beyond mere innovation (Geels, 2002; Sovacool & Geels, 2016). Policy research indicates that relying solely on carbon pricing is insufficient; effective governance mechanisms are essential (Rosenbloom et al., 2020; World Bank, 2022). Governing transitions to net-zero emissions entails strategic planning, policy sequencing, and political considerations, rather than solely technical solutions (Meadowcroft & Rosenbloom, 2023). Corporate roadmaps translate strategic objectives into investment decisions (Phaal et al., 2004); however, research on their development and application remains fragmented. Three primary streams of investigation are identified: technology-pathway assessments that do not evaluate organizational readiness (Yáñez et al., 2022); energy-management studies linking organizational capability to roadmap development Schulze et al. (2016); and governance studies examining the relationship between sustainability performance and firm outcomes, including ESG metrics and market perception (Berg et al., 2022; Du, 2023; Eccles et al., 2014; Friede et al., 2015; Gillan et al., 2021; Xie, 2024). Additional research indicates that environmental commitments such as green bonds impact firms' cost of capital (Bolton & Kacperczyk, 2021; Flammer, 2021; Tang & Zhang, 2020). Nonetheless, there is a conspicuous absence of studies directly assessing whether firms' energy performance indicators and emissions trends are aligned or establishing guidelines for prioritization when discrepancies are evident. Synthesizing these streams comparatively, technology-pathway assessments Yáñez et al. (2022) specify what to deploy but not whether an organization is ready to deploy it; energy-management studies Trianni (2016) establish that organizational capability conditions success but stop short of linking that capability to a staged decarbonization roadmap;

and governance studies Du (2023) connect sustainability performance to firm outcomes without diagnosing the internal efficiency–emissions consistency that underlies those outcomes. The present study sits at the intersection of these streams: its novelty lies in using a normalized-versus-absolute performance discrepancy as the entry point for capability-based roadmap prioritization in a state-owned refinery, an alignment question that none of the three streams addresses directly.

In parallel, Industry 4.0 technologies, notably the Internet of Things (IoT), digital twins, and analytics platforms, are progressively recognized as vital links connecting strategic roadmaps with cross-site operational management. Surveys and systematic reviews demonstrate that digital twins and IoT-based monitoring systems can offer real-time virtual representations of equipment networks, facilitating simulation, predictive maintenance, and data-driven energy optimization (Barricelli et al., 2019; Semeraro et al., 2021; Tao et al., 2019; VanDerHorn & Mahadevan, 2021). Sector-specific analyses within the oil and gas industry reveal that digital twins for production networks and downstream facilities open new avenues for energy monitoring, risk analysis, and operational optimization (Sircar et al., 2023; Wanasinghe et al., 2020). Research on IoT applications in process industries further emphasizes that the efficacy of these technologies is contingent upon their integration with mature energy-management systems and robust data governance frameworks (Aheleroff et al., 2021; Senyonyi et al., 2024). Although this study does not empirically assess digital twins at PT KPI, existing literature underscores that digital capability constitutes a significant component of organizational readiness to implement decarbonization strategies within disciplined frameworks.

Indonesia serves as a vital empirical context for these inquiries. As an emerging economy whose energy infrastructure remains heavily reliant on fossil fuels, the nation must carefully balance emissions reduction with considerations of energy affordability, industrial competitiveness, and energy security (Apriliyanti et al., 2026; Sekaringtias et al., 2023; Yudiartono et al., 2023). Political-economic analyses indicate that Indonesia's energy transition has repeatedly faced constraints due to fragmented authority and misaligned incentives among government institutions and state actors (Sekaringtias et al., 2023). Systems-oriented research describes the transition as a series of interconnected socio-political tensions that necessitate proactive coordination among ministries, state-owned enterprises, and civil society stakeholders, rather than solely relying on top-down technical planning (Sunanda et al., 2026; Upham et al., 2022). Scholarly work on Indonesia's "just transition" commitments further demonstrates that decarbonization pathways must be assessed not only for technical feasibility but also for their distributional and institutional legitimacy (Yuniza et al., 2024). Long-term energy system modeling exercises for Indonesia position the power sector within broader pathways to net-zero emissions, which assume significant early-stage efficiency improvements from state-owned enterprises prior to implementing deeper structural reforms (International Energy Agency, 2022; Sunanda et al., 2026).

Pertamina Group is a central national energy enterprise. PT KPI, a subsidiary in refining and petrochemicals, exemplifies the diagnostic paradox. From 2020-2024, PT KPI's Scope 1 and 2 emissions dropped by 16.3%, from about 11.08 to 9.27 million metric tons CO_2e. Simultaneously, its 2023 Energy Intensity Index (EII) was 107.8, above the reference of 100. The emissions data cover five years, but EII data only one year, making direct comparison challenging (PT Kilang Pertamina Internasional, 2024). The divergence between declining emissions and high EII poses a question: are reduced emissions a sign of genuine efficiency gains or just changes in throughput and operating conditions? Clarifying this distinction is the core contribution of this study. Because the Energy Intensity Index is available for only a single year (2023) whereas the emissions series spans 2020–2024, the two indicators cannot be placed on a common longitudinal axis; this non-comparability is treated here not as a peripheral data limitation but as the central diagnostic gap that motivates the study.

To analyze how staged prioritization can be structured and justified, the study uses Dynamic Capability Theory, which explains how organizations identify performance gaps and opportunities, allocate resources, and change routines to maintain competitive advantage (Eisenhardt & Martin, 2000; Teece, 2007, 2018). This theory extends to product and business-model innovation and reconfiguring routines under environmental pressure (Eisenhardt &

Martin, 2000). The study operationalizes this empirically with the TOWS matrix. This strategic-management tool derives action strategies from internal strengths and weaknesses and external opportunities and threats Weihrich (1982), within a single case-study design that provides context-rich, generalizable insights (Yin, 2018).

This study assesses PT KPI's energy efficiency and decarbonization roadmap for 2026–2030 through an integrated evaluation. It establishes a baseline of energy and emissions, notes limitations of comparing a single-year EII with a five-year emissions series, and uses expert-informed, TOWS-based prioritization rooted in Dynamic Capability Theory to identify key internal and external constraints. The priorities suggest a transition phase from 2026 to 2030, focusing first on standardizing energy data, harmonizing performance metrics, and developing digital infrastructure before deploying advanced decarbonization technologies like electrification, low-carbon hydrogen, renewable integration, and carbon capture.

The approach is transferable to other multi-site, state-owned, energy-intensive firms facing similar data and governance issues, rather than being a universal framework. Accordingly, the study pursues three explicit objectives: (i) empirically, to establish an energy and emissions baseline for PT KPI and to test whether the observed emissions decline can be read as structural efficiency improvement; (ii) theoretically, to extend Dynamic Capability Theory to corporate decarbonization by operationalizing sensing, seizing, and transforming through a TOWS-based prioritization; and (iii) practically and for policy, to derive a staged, transferable set of roadmap priorities and to argue that net-zero governance for state-owned enterprises should require normalized, production-adjusted performance disclosure alongside absolute-emissions reporting. The contribution therefore extends beyond the mere application of the TOWS framework to a single firm.

METHOD

This study adopted an embedded single-case strategic assessment design that combines descriptive quantitative performance data with structured expert judgment and document analysis, rather than a formal mixed-methods design with convergent or sequential strands (Yin, 2018). Quantitative energy and emissions data serve as the empirical baseline against which expert-informed strategic factors are systematically weighted and prioritized within a single organizational case. The single-case format is appropriate because the objective is to generate analytically generalizable, context-rich insight into how one state-owned refining enterprise diagnoses and prioritizes decarbonization action, rather than to produce statistically generalizable findings across a population of firms. Here, "embedded" denotes that the single corporate case (PT KPI) contains multiple embedded sub-units—its individual refinery units—which are examined as contextual sources of within-case variation (in asset age, configuration, and baseline EII) rather than as independent cases; the unit of analysis therefore remains PT KPI at the corporate level (Yin, 2018).

This study examines PT Kilang Pertamina Internasional (PT KPI) at the corporate level, treating all refinery units as a single unified system for roadmap-level strategic assessment. Differences among individual refinery units such as asset age, configuration, and baseline energy efficiency are treated as contextual factors that influence prioritization and readiness rather than as independent units of analysis. The scope covers three domains: (i) energy and emissions performance, represented by the Energy Intensity Index (EII) and Scope 1 and Scope 2 greenhouse gas emissions; (ii) strategic and organizational factors, including EMS maturity, digitalization, policy exposure, and investment constraints; and (iii) roadmap effectiveness for 2026–2030, assessed through relevance, feasibility, and strategic priority. Consistent with the original scope, the analysis excludes detailed techno-economic indicators such as net present value and Scope 3 emissions, and does not claim to establish a causal, production-normalized link between efficiency and emissions performance.

Primary data consist of internal corporate documents related to PT KPI's 2026–2030 energy-efficiency and decarbonization roadmap, including energy-performance records, EII data, Scope 1 and Scope 2 emissions figures for 2020–2024, and internal sustainability reports (PT Kilang Pertamina Internasional, 2024). These internal data were provided by PT Kilang Pertamina Internasional under a formal data-access approval; the raw, disaggregated records are

confidential and are used here only in aggregated form. Secondary data are drawn from peer-reviewed literature and policy documents, including Indonesia's national energy-transition framework Yudiartono et al. (2023), ISO 50001 and related EMS standards International Organization for Standardization (2021), and international net-zero roadmaps (International Energy Agency, 2022; World Bank, 2022).

Document review followed a structured coding procedure in which internal documents and secondary sources were read to extract candidate strategic factors related to energy performance, governance, technology, and external context. An initial list of 47 candidate factors was generated, then reduced through duplicate removal and thematic consolidation to 28 preliminary strategic factors, and finally refined through expert-panel validation to the 20 strategic factors reported in the Results section. This audit trail 47 initial codes → 28 preliminary factors → expert validation → 20 final strategic factors is reported explicitly to make the factor-identification process transparent and replicable.

The expert panel comprises five members: four internal practitioners with direct operational or managerial responsibility for energy performance and decarbonization initiatives at PT KPI, and one external analyst with independent experience in energy-transition policy. The internal panelists include a refinery general manager, a manager of innovation and ISO 50001 implementation, a vice president of operational risk management, and a project partnership manager responsible for integrating ESG considerations with corporate sustainability objectives; the external panelist is an energy activist affiliated with the Indonesian Student Energy Council, providing a macro-level perspective on national transition policy and net-zero dynamics.

Panelists were purposively selected based on: (i) at least five years of relevant professional experience in refinery operations, energy management, or corporate strategy; (ii) direct involvement in, or oversight of, at least one component of the 2026–2030 roadmap; and (iii) availability to complete the full scoring exercise independently. Each panelist completed the scoring instrument independently and without access to other panelists' scores to reduce anchoring and social-desirability effects; no group discussion or score-revision round was conducted, and all panelists provided informed consent for the use of their individual and aggregated scores for research purposes. The internal-majority panel composition introduces a potential risk of institutional confirmation bias, which is mitigated through independent scoring and dispersion analysis but acknowledged explicitly as a limitation.

Each of the 20 strategic factors was scored independently by all five panelists on a five-point ordinal scale (1 = minimal importance to 5 = critical importance), based on three explicit assessment dimensions: (i) expected contribution to reducing the Energy Intensity Index by 2030; (ii) expected contribution to reducing Scope 1 and Scope 2 emissions; and (iii) expected contribution to successful roadmap implementation. These scores capture each panelist's expected strategic contribution of a factor, not a measured causal effect on the Energy Intensity Index or on Scope 1–2 emissions. For each factor \(i\), the average score across panelists was calculated as:

$$S_i = \frac{1}{n}\sum_{j=1}^{n} x_{ij}$$

where (x_{ij})does panelist assign the score (j) to factor (i), and $(n = 5)$ is the number of panelists. Average scores were then normalized into relative factor weights:

$$W_i = \frac{S_i}{\sum_{i=1}^{m} S_i}$$

where $(m = 20)$ is the total number of strategic factors, such that $(\sum_{i=1}^{m} W_i = 1)$.

Following factor weighting, strategic factors were classified into strengths, weaknesses, opportunities, and threats and combined using the TOWS matrix to generate four categories of candidate strategies: SO (strength–opportunity), ST (strength–threat), WO (weakness–opportunity), and WT (weakness–threat) (Weihrich, 1982). Each resulting strategy (k) was then scored by the same expert panel across six explicit dimensions: impact on EII, impact on Scope 1–2 emissions, feasibility, implementation urgency, strategic alignment, and replicability across refinery units. The Strategic Priority Index (SPI) for strategy (k) was calculated as a weighted sum

across these dimensions:

$$SPI_k = \sum_{d=1}^{D} \alpha_d \, \bar{x}_{kd}$$

where $(D = 6)$ is the number of scoring dimensions, $\bar{x}_{kd}$ is the panel-averaged score for strategy (k) on dimension (d) (each on a 1–5 scale), and (α_d) is the normalized weight assigned to dimension (d), with $(\sum_{d=1}^{D} \alpha_d = 1)$. Under this specification, the theoretical range of SPI is 1 to 5, and all SPI values reported in Table 3 fall within this defined 1–5 range. Equal weighting $(\alpha_d = 1/6)$ for all (d)) was applied as the baseline specification, and results were checked for sensitivity to alternative weighting schemes that emphasized emissions impact over feasibility. Under this alternative scheme (higher weight on the EII-impact and Scope 1–2-impact dimensions and correspondingly lower weight on feasibility), the ordering of the three highest-priority strategies remained unchanged, indicating that the ranking is robust to the weighting choice.

To assess agreement among panelists, the standard deviation and range of raw scores were calculated for each strategic factor and strategy dimension. Given the small panel size (n = 5), Kendall's coefficient of concordance was also used to summarize rank-order agreement across the 20 strategic factors. The resulting Kendall's W of approximately 0.70 indicates a relatively strong level of concordance among the five panelists. This agreement measure complements the descriptive dispersion statistics and should be interpreted in conjunction with the purposive composition of the panel. Panel competence was supported by the predefined selection criteria, including a minimum of five years of relevant professional experience and direct involvement in the 2026–2030 roadmap, while the internal-majority composition remains acknowledged as a potential source of institutional bias.

Several measures were taken to support validity and reliability. In this design, "reliability" refers specifically to inter-rater agreement (concordance) among panelists, quantified by Kendall's coefficient of concordance, rather than to the internal-consistency reliability of a measurement scale. Source triangulation was used to cross-check strategic factors and performance data across internal documents, sustainability reporting, and external literature (International Energy Agency, 2022; Schulze et al., 2016). Temporal consistency of energy and emissions data was verified for the 2020–2024 period against the original corporate records (PT Kilang Pertamina Internasional, 2024). Definitions of EII, Scope 1 and Scope 2 emissions, and EMS maturity were aligned with established standards and protocols, including ISO 50001, ISO 50005, and the Greenhouse Gas Protocol, rather than defined ad hoc (International Organization for Standardization, 2018, 2021).

RESULTS AND DISCUSSION

Results

The emissions-efficiency paradox

PT KPI's combined Scope 1 and Scope 2 emissions declined from approximately 11.08 to 9.27 million metric tons of CO_2 equivalent between 2020 and 2024, a reduction of about 16.3 percent (PT Kilang Pertamina Internasional, 2024). Over roughly the same period, the company's corporate Energy Intensity Index (EII) was recorded at 107.8 in 2023, above the internal reference value of 100 used in its performance-monitoring framework (PT Kilang Pertamina Internasional, 2024). These indicators are not directly comparable as a continuous time series EII is available for only one year. At the same time, emissions data span five years, and they capture different dimensions of performance: absolute emissions reflect total operational output in a reporting period, whereas EII compares actual energy consumption against the consumption expected for a refinery's configuration and operating conditions.

Table 1 summarizes PT KPI's corporate Scope 1–2 emissions for 2020–2024 and its 2023 Energy Intensity Index baseline.

Table 1

Baseline energy and emissions performance of PT KPI

Indicator	Year	Value	Strategic interpretation

Corporate EII	2023	107.8	Indicates that refinery energy performance remains above the benchmark level and requires systematic efficiency improvement
Total Scope 1 + Scope 2 emissions	2020	11,083,502.50 tCO_2e	Official baseline for evaluating operational decarbonization performance
Total Scope 1 + Scope 2 emissions	2021	12,022,938.93 tCO_2e	Indicates an increase from baseline and underscores the need for stronger emissions control
Total Scope 1 + Scope 2 emissions	2022	10,966,507.50 tCO_2e	Shows a partial reduction compared with 2020 and 2021 levels
Total Scope 1 + Scope 2 emissions	2023	11,281,789.08 tCO_2e	Shows a renewed increase, indicating a fluctuation in emissions trajectory
Total Scope 1 + Scope 2 emissions	2024	9,272,695.77 tCO_2e	Shows a significant reduction, approximately 16.3% below the 2020 baseline
Scope 1 emissions	2024	9,112,229.13 tCO_2e	Indicates that direct operational emissions are the primary driver of the decarbonization challenge
Scope 2 emissions	2024	160,466.64 tCO_2e	Indicates that purchased electricity contributes relatively few emissions compared with direct refinery operations

Several operational factors could plausibly explain the co-occurrence of falling emissions and an above-reference EII, including changes in throughput, capacity utilization, feedstock and product mix, outage duration, fuel characteristics, and utility-system operating conditions. Such factors can reduce total energy consumption and emissions without producing a durable improvement in the efficiency with which energy is converted into output. In this study, structural energy-performance improvement is defined as a sustained reduction in normalized energy consumption that remains evident after adjusting for production, configuration, and operating conditions. Given the fluctuating emissions trajectory an increase in 2021, partial declines in 2022, a renewed increase in 2023, and a marked decline in 2024 together with a single EII observation, this persistence cannot yet be established empirically. Because unit-level production, throughput, and feedstock data were not available to this study, these operational factors are presented strictly as plausible explanations to be tested against normalized baselines, not as established causes of the observed emissions trajectory. Figure 1 illustrates the non-monotonic trajectory of PT KPI's Scope 1–2 emissions over 2020–2024.

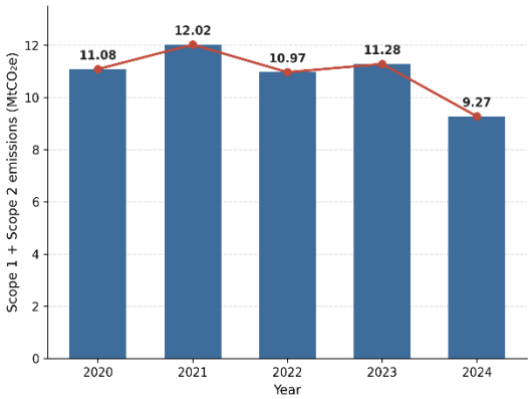


Figure 1. Annual combined Scope 1 and Scope 2 greenhouse-gas emissions of PT KPI, 2020–2024 (million tonnes CO_2-equivalent). Emissions rose to a peak of 12.02 $MtCO_2e$ in 2021, declined in 2022, increased again in 2023, and fell to 9.27 $MtCO_2e$ in 2024—a net reduction of 16.3% relative to the 2020 baseline of 11.08 $MtCO_2e$.

Technical interventions such as heat integration, combustion optimization, steam-system enhancement, advanced process control, and systematic maintenance are well documented as effective levers for reducing energy consumption in refineries Pisciotta et al. (2022), but their contribution to PT KPI's specific trajectory should be validated against consistent energy baselines and normalized indicators rather than inferred solely from changes in absolute emissions **Error! Reference source not found.**.

Organizational capabilities and cross-refinery heterogeneity

The synthesis of strategic factors indicates that PT KPI's decarbonization challenge is not driven primarily by the availability of efficiency technologies. The company already possesses an EII roadmap, internal benchmarking practices, emissions-governance mechanisms, and performance metrics, which together constitute a basic platform for efficiency and decarbonization initiatives (Griffiths et al., 2022). However, wide disparities in EII performance across refinery units, inconsistent energy-management practices, and cross-year data comparability issues constrain the replication and consolidation of improvements across the portfolio. Organizational capability is defined here as the capacity to coordinate governance, personnel, data, operational routines, and investment decisions so that technically available opportunities translate into measurable and sustained outcomes, an interpretation consistent with evidence that industrial energy performance depends on organizational competence and reliable information alongside technology (Dickemann, 2025). The final 20 strategic factors and their normalized weights are reported in Table 2.

Table 2
Strategic factors affecting PT KPI's energy efficiency and decarbonization roadmap

Code	Strategic factor	Implication for roadmap refinement
S1	Proof of execution in emissions reduction	Demonstrates existing execution capability
S2	Internal efficiency benchmark across refinery units	Enables cross-unit learning and replication
S3	Structured EII roadmap and portfolio of initiatives	Provides an initial platform for prioritization
S4	Strengthening emissions governance	Supports monitoring and accountability
S5	Availability of energy and emissions metrics	Enables evidence-based decision-making
W1	Wide disparity in EII performance across refinery units	Requires cross-refinery synchronization
W2	Corporate EII remains above the benchmark	Shows a strategic need for efficiency improvement
W3	Dominance of Scope 1 emissions	Requires focus on direct energy use and on combustion
W4	Very low renewable-energy share	Limits near-term renewable contribution
W5	Cross-year data comparability challenges	Requires stronger data governance
O1	Net-zero and energy-transition policy alignment	Strengthens roadmap legitimacy
O2	Scalable modular efficiency portfolio	Enables near-term efficiency gains
O3	Scope 3 accounting and ESG value-chain expansion	Opens broader ESG accountability
O4	Measurable ESG program performance	Strengthens stakeholder confidence
O5	Green refinery and co-processing pathways	Positions refinery assets for low-carbon fuels
T1	Short-term emissions-reduction pressure	Requires high-impact, executable measures
T2	Technology transformation gap toward NZE	Requires staged readiness and investment gates
T3	Investment constraints	Necessitates prioritizing efficient capital allocation
T4	Aging asset conditions	Requires risk-based implementation

T5	Regulatory and market uncertainty	Requires adaptive roadmap governance

The TOWS-based prioritization reinforces this view. Harmonization of energy performance across refinery units emerged as the highest-priority strategy, followed by utility and process-system transformation, with the integration of energy efficiency as a carbon-risk mitigation instrument ranked third and strengthening of digital EMS ranked fourth, consistent with the SPI scores in Table 3. This ordering suggests that the expert panel treats corporate-level standardization, cross-unit coordination, and data integration as prerequisites for scaling technical improvements; at the same time, because SPI scores reflect structured expert judgment rather than measured outcomes, they should be interpreted as indicators of perceived strategic importance rather than as quantified causal effects (Yin, 2018).

Dynamic Capability Theory offers a useful lens: PT KPI's EII monitoring, emissions inventory, and internal benchmarking correspond to sensing; the TOWS-based prioritization represents seizing; and the translation of priorities into standardized procedures, accountability structures, digital monitoring, and cross-refinery learning routines embodies transforming (Teece, 2018). The evidence suggests that sensing and seizing capabilities are present, while organization-wide institutionalization of transforming remains incomplete. Concretely, sensing corresponds to factors S5 (availability of energy and emissions metrics), S4 (emissions governance), and W5 (cross-year data comparability); seizing corresponds to the TOWS-derived priorities WO-1 and WO-2 together with factors S3 and O2; and transforming corresponds to WO-3 (digital EMS) together with factors W1 and S2, whose institutionalization across units remains only partial. The SPI ranking thus carries a theoretical implication: the highest-scoring strategies cluster in seizing and transforming, indicating that PT KPI's binding constraint is the conversion of existing sensing capability into embedded routines rather than a shortage of diagnostic information.

The transition-enabling roadmap framework

The evaluation concerning PT KPI's 2060 net-zero objective indicates that the three highest-ranked TOWS strategies energy-performance harmonization, utility and process-system transformation, and positioning energy efficiency as a carbon-risk mitigation instrument are feasible and pertinent priorities for 2026–2030. The Strategic Priority Index scores for all TOWS-derived strategies are presented in Table 3.

Table 3

TOWS-based strategic priority ranking for PT KPI's roadmap refinement

Rank	Code	Strategy	SPI Score	Strategic Meaning
1	WO-1	Harmonization of energy performance across refinery units	5.00	Strengthens corporate-wide energy governance, EMS standardization, digital monitoring, benchmarking, and the replication of best practices
2	WO-2	Transformation of utility and process systems	4.76	Targets direct energy consumption and Scope 1 emissions through process optimization, utility improvements, heat integration, and improved combustion efficiency
3	ST-1	Integration of energy efficiency as a carbon risk mitigation instrument	4.36	Positions energy efficiency as a strategic response to carbon pricing, emissions regulation, and transition risk exposure
4	WO-3	Strengthening of digital EMS and data-driven roadmap execution	4.24	Improves data integration, early-warning capability, performance monitoring, and evidence-based decision-making

5	SO-1	Expansion of data-driven efficiency programs through ESG and green-finance initiatives	3.95	Uses existing performance data and ESG commitment to support financing and scaling of efficiency initiatives
6	WT-1	Prioritizing low-cost and quick-win efficiency programs under investment constraints	3.43	Reduces risk from capital constraints by focusing on modular and executable efficiency measures
7	ST-2	Strengthening emissions governance to respond to regulatory pressure	3.25	Enhances carbon accounting, reporting consistency, and accountability amid increasing policy pressure
8	SO-2	Preparation of low-carbon fuel and green refinery pathways	3.02	Supports long-term transformation through co-processing, low-carbon fuels, and repurposing of future refineries
9	WT-2	Staged readiness for capital-intensive decarbonization technologies	2.79	Avoids premature investment in technologies with high costs, long lead times, and uncertain readiness

However, they are not sufficient independently to fulfill the long-term net-zero commitments. This conclusion underscores the primary conceptual contribution: defining PT KPI's 2026–2030 roadmap as a transition-enabling phase that must initially establish reliable baselines, harmonized measurement protocols, and digital infrastructure prior to the deployment of structural technologies at scale (Sunanda et al., 2026). Table 4 summarizes the consistency assessment between the 2026–2030 roadmap strategies and PT KPI's 2060 net-zero pathway.

Table 4
Backcasting validation of PT KPI's 2026- 2030 roadmap priorities

Backcasting Dimension	2026–2030 Roadmap Implication	NZE 2060 Implication	Strategic Interpretation
Energy-performance harmonization	Standardize EMS, benchmarking, digital monitoring, and cross-refinery performance management.	Provides a foundation for corporate-wide transformation	Realistic and necessary as an enabling phase
Utility and process-system transformation	Improve heaters, boilers, turbines, steam systems, flare management, heat integration, and process optimization.	Reduces Scope 1 emissions but does not eliminate residual emissions.	Strong medium-term lever, but insufficient alone to achieve net zero
Digital EMS and data governance	Integrate energy and emissions data, early warning, monitoring, and decision support systems.	Enables future readiness for deeper decarbonization investments.	Foundational capability for long-term transition
ESG-based prioritization	Link efficiency and decarbonization programs to risk, investment, and accountability	Supports green finance, carbon risk management, and stakeholder legitimacy	Important governance bridge between operations and strategy
Low-carbon technology readiness	Begin a feasibility assessment for electrification, hydrogen, co-processing, renewable integration, and CCUS.	Required for structural emissions reduction after 2030	Must be prepared for 2026–2030, even if implementation occurs later

Residual-emissions management	Not yet central in the 2026–2030 phase	Required for NZE 2060 through CCUS, offsets, removals, or systemic changes	Long-term gap that must be explicitly acknowledged

Institutionalizing this phase necessitates differentiating between the existence of management standards and the evidenced organizational maturity. ISO 50001 stipulates requirements concerning energy policy, objectives, data-driven decision-making, measurement, management review, and continual improvement; however, it does not expressly categorize organizations into specific maturity levels (International Organization for Standardization, 2018). Multi-site energy management maturity models integrate quantitative indicators with qualitative evidence of technical and non-technical readiness at both site and corporate levels (Finnerty et al., 2017). Meanwhile, phased implementation guidance provided by ISO 50005 delineates staged progression across essential elements of an EMS (International Organization for Standardization, 2021). Given that this study did not conduct a formal maturity assessment utilizing these instruments, PT KPI should not be attributed to a particular maturity level; instead, these frameworks should be regarded as diagnostic tools for future evaluation. Additionally, residual emissions management through carbon capture, utilization, and storage, offsets, and systemic technological change remains a long-term structural gap that is not yet central to the 2026–2030 phase but must be explicitly acknowledged (Upham et al., 2022). The "validation" originally claimed for the roadmap is more accurately characterized as an assessment of strategic coherence against stated long-term targets, rather than an independent quantitative validation.

Discussion

Implications for state-owned refineries in emerging economies

The experience of PT KPI offers analytically transferable insights into the decarbonization challenges encountered by state-owned refineries in emerging economies at large. These entities are tasked with reducing emissions while safeguarding energy security, managing legacy assets, and operating within the confines of investment and regulatory constraints (Sekaringtias et al., 2023). Consequently, their transition strategies are unlikely to replicate those of developed economies, which are centered on rapid asset divestment or immediate deployment of capital-intensive technologies. Instead, a phased approach, incorporating operational efficiency, organizational capacity building, and staged technology readiness, appears to be a more pragmatic solution (Bataille, 2020; Chaichaloempreecha et al., 2024).

Findings from PT KPI indicate that the availability of technology constitutes merely one aspect of transition readiness. Disparities in unit-level performance, fragmented data, inconsistent management practices, and limited implementation capacity can hinder technically viable measures from achieving sustainable results at the corporate level (Trianni, Cagno, & Farné, 2016). Industrial decarbonization within this framework should be regarded as a socio-technical transformation necessitating coordination across technology, policy, finance, governance, and organizational learning (Geels, 2002; Sovacool & Geels, 2016). For state-owned enterprises, this coordination challenge is further compounded by the need to balance commercial expectations, national energy security priorities, and long-term climate commitments (World Bank, 2022). The priority sequence, derived from the TOWS analysis and harmonizing performance, utility-system enhancement, and digital EMS reinforcement, proposes a pragmatic order for the initial phase of transition that may be adapted to other contexts.

Managerial and policy implications

For PT KPI's management, the results indicate that energy efficiency and decarbonization should be governed as an integrated corporate performance agenda rather than as isolated refinery-level initiatives. The top-priority strategy of energy-performance harmonization requires clear corporate ownership of EII methodology, energy baselines, emissions-accounting conventions, and project-verification procedures, while allowing technical implementation to remain tailored to each refinery's configuration (Jovanović & Filipović, 2016). Near-term implementation can prioritize established efficiency measures such as utility optimization,

combustion enhancement, heat integration, advanced process control, and steam-system upgrades, assessed against standardized criteria including expected EII improvement, emissions reduction, readiness, and replicability (Jouhara et al., 2018; Pisciotta et al., 2022). Table 5 summarizes the principal implementation risks associated with the prioritized strategies and the corresponding mitigation measures.

Table 5
Implementation risks and mitigation measures for PT KPI's roadmap priorities

Priority Strategy	Main Implementation Risk	Potential Impact	Recommended Mitigation
Harmonization of energy performance across refinery units	Differences in refinery configuration, asset age, process complexity, and local operating practices	Best practices may not be directly replicated	Apply refinery-specific adaptation, cross-unit benchmarking, and a structured replication protocol.
Harmonization of energy performance across refinery units	Organizational resistance to standardization	Slow adoption and inconsistent implementation	Strengthen leadership commitment, change management, and performance incentives.
Transformation of utility and process systems	Potential disruption to refinery reliability, maintenance schedules, and process safety	Delayed implementation or operational risk	Integrate efficiency projects with turnaround planning, asset integrity, and process safety management.
Digital EMS and data-driven roadmap execution	Inconsistent data quality, calculation methodology changes, metering gaps, and data restatement	Weak decision quality and reduced monitoring credibility	Establish corporate data governance standards and periodic data validation
Digital EMS and data-driven roadmap execution	Limited analytical capability and digital-energy competency	Underutilization of digital tools	Develop energy analytics capability and train energy managers
Energy efficiency as carbon-risk mitigation	Uncertainty in carbon pricing and emissions regulation	Difficulty in justifying investment decisions	Use scenario-based carbon risk assessment and internal carbon price sensitivity.
ESG-based prioritization and green-finance readiness	Weak linkage between ESG indicators and investment decision-making	ESG remains a reporting function	Integrate EII, Scope 1–2 emissions, and carbon risk into project-screening criteria.
Low-carbon technology readiness	High capital cost, technology uncertainty, and long lead time	Premature or delayed investment	Use staged feasibility studies and technology-readiness assessments

Capital-intensive options such as electrification, low-carbon hydrogen, and CCUS should progress through staged feasibility assessment and investment gates rather than compete directly with short-term efficiency initiatives for the same capital pool (Timofeeva et al., 2023). At the policy level, the case indicates that net-zero frameworks for state-owned enterprises should recognize a transition-enabling phase centered on measurement standardization and organizational capability, rather than treating reductions in absolute emissions alone as evidence of structural efficiency improvement. Disclosure of normalized, production-adjusted performance indicators alongside absolute emissions could help address the diagnostic ambiguity identified in this study (World Bank, 2022). Table 6 presents the strategic economic interpretation of the roadmap priorities by summarizing their main economic logic, strategic value, and key cautions.

Because engineering, measurement-and-verification, and net-present-value data were not available, these priorities should be interpreted as strategic options and readiness considerations rather than as investment recommendations with demonstrated economic feasibility.

Table 6
Strategic economic interpretation of roadmap priorities

Roadmap priority	Main economic logic	Strategic value	Key caution
Energy-performance harmonization across refinery units	Replication of internal best practices and reduction of EII disparity	Captures efficiency gains through benchmarking and cross-unit learning.	Requires refinery-specific adaptation
Utility and process-system transformation	Reduction of direct energy use and operational losses	Reduces fuel consumption, utility costs, and Scope 1 emissions	Must be integrated into reliability and process-safety planning
Energy efficiency as carbon-risk mitigation	Lower emissions reduce exposure to future carbon costs	Converts energy efficiency into a tool for transition-risk management	Carbon pricing and regulatory design remain uncertain
Digital EMS and data governance	Better data improves monitoring and informs investment decisions	Reduces hidden inefficiencies and improves roadmap execution	Requires reliable metering and analytical capabilities
ESG-based investment prioritization	Sustainability indicators improve capital allocation and enhance the credibility of financing.	Links performance to risk, governance, and sustainable finance	ESG must influence decision-making
Low-carbon technology readiness	Staged preparation for hydrogen, electrification, co-processing, and CCUS	Builds future optionality for NZE alignment	Premature investment may increase financial risk

Limitations

This study analyzes a single state-owned refinery at the corporate level to derive analytical insights (Yin, 2018). The limitations encompass: emissions data from the years 2020 to 2024, while EII data are exclusively available for 2023, thereby impeding longitudinal comparisons; the Strategic Priority Index, which is predicated on expert judgment from a panel of five members and is susceptible to potential confirmation bias; the absence of engineering, measurement, verification, or economic data, which constrains the ability to make comprehensive financial recommendations; and the qualitative assessment of organizational maturity rather than a structured evaluation (International Organization for Standardization, 2021). Future research should aim to incorporate time-series data, utilize decomposition or regression analysis, and compare multiple refineries to evaluate the broader applicability of the transition framework. Specifically, a future methodological agenda should include: (i) multi-year, time-series EII; (ii) production-normalized efficiency analysis; (iii) index-decomposition and regression analysis to separate structural efficiency change from throughput and product-mix effects; (iv) multi-refinery comparison; (v) engineering-based measurement and verification; and (vi) economic-feasibility assessment (net present value and marginal abatement cost). This agenda strengthens future contributions without implying that the present study has already validated the effectiveness of the roadmap.

CONCLUSION

This study evaluated PT KPI's energy-efficiency and decarbonization roadmap for 2026–2030. Combined Scope 1 and Scope 2 emissions declined by approximately 16.3% between 2020 and 2024, while the 2023 Energy Intensity Index (EII) of 107.8 remained above the company's

internal reference value of 100. Because the emissions series covers five years whereas EII is available for only one year, the observed emissions decline cannot be confirmed as evidence of structural efficiency improvement. The findings therefore demonstrate the importance of interpreting absolute emissions together with consistent normalized performance indicators. The TOWS-based prioritization identifies energy-performance harmonization across refinery units, utility and process-system transformation, integration of energy efficiency as a carbon-risk mitigation instrument, and strengthening of digital energy-management systems as key priorities for the 2026–2030 period. Within the Dynamic Capability Theory framework, these priorities indicate the importance of converting existing sensing and seizing capabilities into more consistently embedded organizational routines.

The findings position PT KPI's 2026–2030 roadmap as a transition-enabling phase rather than a complete deep-decarbonization pathway toward the 2060 net-zero objective. The prioritized measures can strengthen measurement, governance, organizational capability, and readiness for subsequent structural decarbonization options, including electrification, low-carbon hydrogen, co-processing, renewable integration, and carbon capture. However, their technical and economic feasibility cannot be established from the present study because engineering, measurement-and-verification, production-normalized, and economic data were not available. The proposed diagnostic and prioritization approach may therefore provide a useful reference for other multi-site, state-owned, energy-intensive enterprises facing comparable data and governance constraints, but its broader applicability requires confirmation through multi-year EII data, production-normalized analysis, multi-refinery comparison, and engineering and economic verification.

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AUTHOR CONTRIBUTION STATEMENT

Arie Gumilar: conceptualization, data collection, formal analysis, methodology, writing the original draft, and editing. Silviana Silviana: supervision, conceptual review, and methodology validation. Sri Widodo Agung Suedy: supervision, formal analysis review, and review. Hadiyanto Hadiyanto: supervision, analysis review, and manuscript refinement. All authors read and approved the final manuscript.

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Appendix

The corresponding author, Arie Gumilar, holds the position of Senior Manager at PT Pertamina Patra Niaga, a subsidiary of the Pertamina Group, and is distinct from PT KPI, the refining subholding examined in this study. He possesses no direct authority over the roadmap, data, or decisions articulated in this publication. His affiliation is disclosed purely for transparency, given that both entities operate under the Pertamina corporate umbrella. Four of the five expert panelists are employees of PT KPI, which may introduce confirmation bias; however, this is mitigated through independent scoring and consensus analysis, and is acknowledged as a limitation. The fifth panelist is external and offered an independent perspective on policy and transition dynamics. Data were obtained from PT KPI with proper approval, with the latter reviewing the factual accuracy of the data but not influencing the interpretation or conclusions of the study. The authors assert no conflicts of interest, and confirm that no compensation was received from PT KPI or Pertamina Patra Niaga in relation to this research.

The primary quantitative data, including the Energy Intensity Index and Scope 1–2 emissions for 2020–2024, were provided by PT Kilang Pertamina Internasional with approval. These data are shown in Table 1 and Figure 1. Raw, disaggregated records are confidential and not publicly available. Researchers can request access by contacting PT Kilang Pertamina Internasional, subject to company policies. The expert-panel scoring data supporting Tables 2 and 3 are available from the corresponding author upon request.