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Firm Low-Carbon Electricity Systems: A France-Germany Comparative Analysis and an Integrated Transition Framework for Indonesia

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ABSTRACT

The global electricity transition presents a persistent challenge: expanding renewable energy does not always lead to lower carbon emissions, stronger electricity-system reliability, or lower total system costs. This study compares the electricity-transition pathways of France and Germany to identify the factors behind their different outcomes and to develop an integrated policy framework for Indonesia's long-term electricity decarbonization. The study compares the long-term performance of nuclear- and renewable-based electricity systems, examines the structural factors that shape transition outcomes, and develops an adaptive framework for reliable, affordable, and low-carbon electricity development. The research uses a descriptive-analytical approach and a comparative longitudinal design covering 1970–2022. The analysis draws on secondary data from international energy databases, government publications, and scientific literature. Comparative historical analysis, techno-economic assessment, geological resource evaluation, and institutional diagnostics based on the DPSIR framework support the analysis. Three findings stand out. First, rapid renewable expansion does not necessarily produce the lowest carbon intensity. Second, lower generation costs for renewable technologies do not automatically translate into lower whole-system electricity costs because high renewable penetration requires additional storage, transmission, reserve generation, and balancing capacity. Third, electricity systems that retain standardized firm low-carbon generation show greater long-term operational stability than systems that rely predominantly on variable renewable resources. Based on these findings, the study proposes the Integrated Firm Low-Carbon Transition Framework (IFLTF), which combines renewable energy, firm low-carbon generation, supporting infrastructure, and institutional capacity within a single transition strategy. The study argues that Indonesia's electricity decarbonization strategy should consider national resource conditions, institutional capacity, and long-term infrastructure requirements alongside renewable deployment.

Keywords: Electricity transition, energy decarbonization, nuclear energy, renewable energy, low-carbon electricity, Indonesia.

ABSTRAK

Transisi ketenagalistrikan global menghadapi persoalan yang tidak sederhana. Peningkatan kapasitas energi terbarukan tidak selalu menghasilkan intensitas karbon yang lebih rendah, keandalan sistem yang lebih baik, atau biaya listrik sistem yang lebih rendah. Penelitian ini membandingkan jalur transisi ketenagalistrikan Prancis dan Jerman untuk mengidentifikasi faktor yang menyebabkan perbedaan hasil serta merumuskan kerangka kebijakan bagi dekarbonisasi ketenagalistrikan Indonesia dalam jangka panjang. Penelitian ini membandingkan kinerja sistem ketenagalistrikan berbasis nuklir dan energi terbarukan, mengkaji faktor struktural yang memengaruhi hasil transisi, serta menyusun kerangka adaptif untuk mendukung penyediaan listrik yang

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andal, terjangkau, dan rendah karbon. Penelitian menggunakan pendekatan deskriptif-analitis dengan desain komparatif longitudinal pada periode 1970–2022. Data sekunder diperoleh dari basis data energi internasional, publikasi pemerintah, dan literatur ilmiah. Analisis mencakup analisis historis komparatif, penilaian tekno-ekonomi, evaluasi sumber daya geologi, dan diagnosis kelembagaan menggunakan kerangka DPSIR. Hasil penelitian menunjukkan tiga temuan utama. Pertama, peningkatan energi terbarukan secara cepat tidak selalu menghasilkan intensitas karbon terendah. Kedua, penurunan biaya pembangkitan energi terbarukan tidak secara otomatis menurunkan biaya listrik pada tingkat sistem karena penetrasi energi terbarukan yang tinggi membutuhkan investasi tambahan pada penyimpanan energi, jaringan transmisi, pembangkit cadangan, dan layanan penyeimbangan. Ketiga, sistem ketenagalistrikan yang mempertahankan pembangkitan rendah karbon yang bersifat firm dan terstandar menunjukkan stabilitas operasional jangka panjang yang lebih baik dibandingkan sistem yang sangat bergantung pada sumber energi terbarukan variabel. Berdasarkan temuan tersebut, penelitian ini mengusulkan Integrated Firm Low-Carbon Transition Framework (IFLTF), yang menggabungkan energi terbarukan, pembangkitan rendah karbon firm, infrastruktur pendukung, dan kapasitas kelembagaan dalam satu strategi transisi. Bagi Indonesia, hasil penelitian menunjukkan bahwa strategi dekarbonisasi perlu mempertimbangkan kondisi sumber daya nasional, kapasitas kelembagaan, dan kebutuhan infrastruktur jangka panjang bersama dengan pengembangan energi terbarukan.

Kata Kunci: Transisi ketenagalistrikan, dekarbonisasi energi, energi nuklir, energi terbarukan, listrik rendah karbon, Indonesia.

1. INTRODUCTION

Electricity decarbonization remains a central challenge in the global energy transition. Renewable electricity capacity has expanded rapidly over the past two decades, yet several countries continue to face high electricity-sector emissions, rising electricity prices, and concerns about system reliability (Nian et al., 2022). France and Germany provide a useful comparison because both countries pursue long-term decarbonization through markedly different electricity strategies. France has maintained one of Europe's lowest electricity-sector carbon intensities through a nuclear-centered system. Germany has invested heavily in wind and solar generation but continues to record substantially higher electricity-sector emissions than France (Marques & Junqueira, 2022). The difference raises a central question: what determines the outcome of an electricity transition when countries pursue the same broad decarbonization objective?

The answer extends beyond the amount of renewable capacity installed. As variable renewable energy becomes a larger part of the generation mix, power systems require additional storage, reserve generation, transmission capacity, and balancing services to maintain system reliability (Nian et al., 2022). The timing of investment also matters. Retiring firm low-carbon generation before replacement capacity and supporting infrastructure become available can alter the emissions and reliability outcomes of an otherwise ambitious transition.

Previous studies have examined several parts of this problem separately. Researchers have assessed nuclear competitiveness, renewable integration, geological resource availability, and institutional readiness, but relatively few studies have examined how these factors interact within a single electricity-transition strategy (Nian et al., 2022; Rahmansyah & Srigutomo, 2022; Sugiharti et al., 2025; Triani & Azy, 2025). This study addresses that gap by connecting the historical experience of France's Messmer Plan with Indonesia's domestic geological potential and institutional conditions

The study asks how lessons from France's Messmer Plan can inform Indonesia's long-term electricity transition while supporting decarbonization, electricity security, and affordability. It therefore pursues three objectives: comparing the long-term performance of nuclear- and renewable-based electricity pathways, evaluating Indonesia's domestic thorium and uranium resources for future electricity development, and developing an integrated policy framework for firm low-carbon electricity within Indonesia's long-term energy planning (Triani & Azy, 2025).

The analysis draws on Energy Trilemma Theory, which treats environmental sustainability, affordability, and security of supply as interconnected objectives of energy policy (Liu et al., 2022). The DPSIR framework provides a structure for examining institutional readiness and policy responses. Carbon Lock-in Theory helps explain why fossil-fuel infrastructure can persist even as renewable generation expands (Unruh, 2000). Socio-Technical Transition Theory adds an institutional perspective by emphasizing coordination and policy continuity during long-term technological change (Triani & Azy, 2025).

Baseload Electricity Theory provides a further basis for examining the role of firm low-carbon generation in maintaining electricity adequacy when renewable output falls. Whole-System Cost Theory shifts the assessment from plant-level generation costs to the wider costs of operating the electricity system. Under high renewable penetration, these costs can include storage, reserve generation, transmission infrastructure, and balancing services (Nian et al., 2022). Research on domestic energy resources also shows that geological potential alone does not guarantee energy security. Governments need coherent institutional and industrial strategies to convert those resources into usable electricity capacity (Rahmansyah & Srigutomo, 2022). Electricity-transition planning therefore needs to connect technological choices with institutional capacity, geological resources, infrastructure, and economic conditions (Chipangamate & Nwaila, 2023).

The main contribution of this study is the Integrated Firm Low-Carbon Transition Framework (IFLTF). The framework brings together comparative historical evidence, techno-economic assessment, geological resource evaluation, and institutional readiness to examine Indonesia's long-term electricity transition. It provides a basis for combining firm low-carbon generation with renewable electricity while addressing decarbonization, electricity security, and affordability within Indonesia's net-zero commitments (Kabeyi & Olanrewaju, 2022).

2. METHODS AND MATERIALS

This study uses a descriptive-analytical approach with a comparative longitudinal design. The analysis examines long-term electricity-transition pathways in France and Germany and evaluates the potential role of nuclear energy in Indonesia's future decarbonization strategy (Kataoka, 2019). The framework considers historical, techno-economic, geological, and

institutional factors to trace changes in electricity-system performance and identify differences between transition pathways (Khoiruddin et al., 2024).

The analysis combines four methods: comparative historical analysis, techno-economic benchmarking, geological resource assessment, and institutional governance diagnostics based on the Drivers–Pressures–State–Impact–Response (DPSIR) framework. These methods allow the study to compare transition pathways while assessing Indonesia's institutional readiness for possible future nuclear deployment.

The study uses secondary data from the International Energy Agency (IEA), Eurostat, Our World in Data (OWID), the BP Statistical Review of World Energy, Indonesia's Ministry of Energy and Mineral Resources (ESDM), BRIN, Bappenas, and Rahmansyah and Srigutomo (2022). The dataset covers approximately 1970–2022 and supports the analysis of long-term electricity-transition dynamics under contrasting policy pathways.

3. RESULTS AND DISCUSSIONS

3.1 Comparative Decarbonization Dynamics Between France and Germany (1990–2022)

The electricity transitions of France and Germany between 1990 and 2022 followed different paths even though both countries sought to reduce electricity-sector carbon emissions. France built its electricity system around nuclear generation following the Messmer Plan, while Germany pursued a renewable-oriented transition through the Energiewende. Carbon intensity measures the amount of carbon dioxide emitted per unit of electricity generated. Electricity-system reliability refers to the system's ability to maintain a secure electricity supply as operating conditions change (Marques & Junqueira, 2022). Examining these indicators together helps reveal how different technology choices affect environmental performance, system operation, and economic conditions.

3.2 Overall Comparative Trends

France maintained a lower electricity-sector carbon intensity than Germany throughout the observation period. Both countries reduced emissions from electricity generation, but they did so through different combinations of technologies and policy measures. France retained a large standardized nuclear fleet, which provided firm low-carbon generation. Germany expanded wind and solar capacity at a much faster rate while reducing its reliance on nuclear generation (Marques & Junqueira, 2022).

Several factors help explain the difference. France's nuclear fleet supplied firm electricity across a wide range of operating conditions. Germany's growing share of variable renewable generation increased the need for storage, reserve generation, transmission capacity, and system balancing (Nian et al., 2022). Germany's decision to accelerate its nuclear phase-out after the Fukushima accident in 2011 also removed dispatchable low-carbon capacity while the renewable system was still expanding. During periods of low renewable output, fossil-fuel generation, including natural gas and lignite, continued to provide part of the required electricity and balancing capacity.

Policy continuity, standardized construction, and long-term institutional commitment also affected system performance (Marques & Junqueira, 2022). These factors matter because electricity infrastructure operates over decades. Decisions about generation capacity,

transmission, financing, and regulation made at one stage of the transition influence the options available at later stages.

Table 3.1 summarizes the estimated long-run relationships between major electricity-generation technologies and carbon emissions using the ARDL model.

Table 1. Long-Run Elasticities of Energy Sources on CO_2 Emissions (ARDL Estimation)

Variable	Dependent Variable	Coefficient	t-statistic	Significance	Interpretation
LNUC(−1)	CO_2 Emissions	−0.105	−3.27	*** (1%)	Nuclear generation is associated with a long-run reduction in emissions.
LCO_2(−1)	Fossil Generation	+2.223	+8.63	* (10%)	Fossil-fuel generation reinforces carbon dependence.
LRES(−1)	Hydroelectricity	+0.423	+3.00	*** (1%)	Renewable deployment is associated with greater demand for hydroelectric balancing capacity.
LRES(−1)	Fossil Generation	−0.130	+1.64	** (5%)	Renewable generation substitutes for fossil generation over the long run.
LNUC(−1)	Renewables	+0.643	+2.09	** (5%)	Nuclear facilitates renewable integration.

Notes: Significance levels: *** p<0.01, ** p<0.05, * p<0.10. Source: Extracted from Marques & Junqueira (2022), Models I & III.

The estimated coefficients show a negative long-run relationship between nuclear generation and carbon emissions, while fossil-fuel generation reinforces carbon dependence. Renewable energy contributes to fossil-fuel substitution over time, but high renewable penetration still requires complementary dispatchable resources to maintain system adequacy (Kabeyi & Olanrewaju, 2022). The positive relationship between nuclear and renewable generation also suggests that the two technologies can operate as complementary components of a low-carbon electricity system.

3.3 Historical Evolution of Electricity Decarbonization

France and Germany followed different trajectories in electricity-sector carbon intensity between 1990 and 2022. Figure 3.1 presents the changes in carbon intensity for both countries over the observation period.

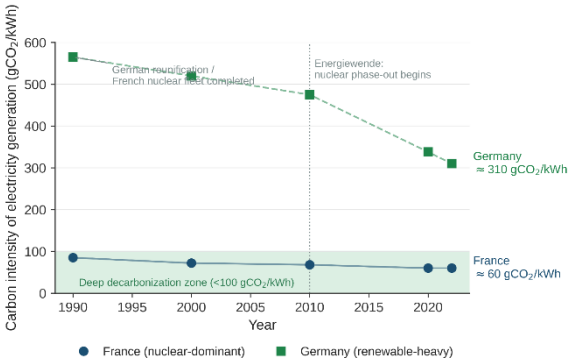

Figure 1. Carbon Intensity Trajectories of France and Germany (1990-2022)

Source: Author's construct based on data from Marques & Junqueira (2022).

France maintained one of the lowest electricity-sector carbon intensities throughout the period. Germany also reduced its carbon intensity, but the decline occurred at a slower pace. The comparison indicates that renewable deployment forms only one part of the decarbonization process. The availability of firm low-carbon generation also affects the emissions profile of the electricity system.

3.4 1990–2011: Diverging Transition Pathways

Between 1990 and 2011, France continued to rely on its standardized nuclear fleet developed under the Messmer Plan. Germany entered the 1990s with substantial coal dependence and later accelerated renewable deployment through the Energiewende.

The Fukushima accident in 2011 changed Germany's electricity strategy. The country accelerated its nuclear phase-out while continuing to expand renewable generation. This decision reduced the amount of dispatchable low-carbon capacity available to the system. During periods when wind and solar output fell, fossil-fuel generation remained important for maintaining electricity supply. As a result, renewable growth did not translate into an equivalent decline in carbon intensity.

3.5 2012–2022: System Integration Challenges

Between 2012 and 2022, Germany faced increasing challenges associated with integrating a larger share of variable renewable generation. Renewable electricity reduced emissions over time, but the system also required greater use of storage, transmission, reserve generation, and fossil-fuel backup during periods of low wind and solar output. These conditions include Dunkelflaute, when low wind and solar generation occur together (Dorileo et al., 2025).

France followed a different trajectory. Nuclear generation continued to provide a large share of firm low-carbon electricity while renewable capacity expanded. This combination reduced the need to rely on fossil generation when renewable output was low.

The comparison shows that renewable deployment works within a wider electricity system. Its effect on emissions and reliability depends partly on the availability of firm generation and the infrastructure used to balance supply and demand.

3.6 Policy Implications and Theoretical Interpretation

The findings point to several considerations for long-term electricity policy. Policymakers need to evaluate generation technologies together with the infrastructure and institutional arrangements required to operate them. Countries that expand variable renewable generation at a rapid pace also need to develop transmission networks, storage, reserve capacity, and operational flexibility (Nian et al., 2022).

Plant-level Levelized Cost of Electricity (LCOE) provides useful information about generation economics, but it does not capture every cost associated with operating a high-renewable electricity system. Storage, reserve generation, transmission reinforcement, and balancing requirements can increase expenditure at the system level.

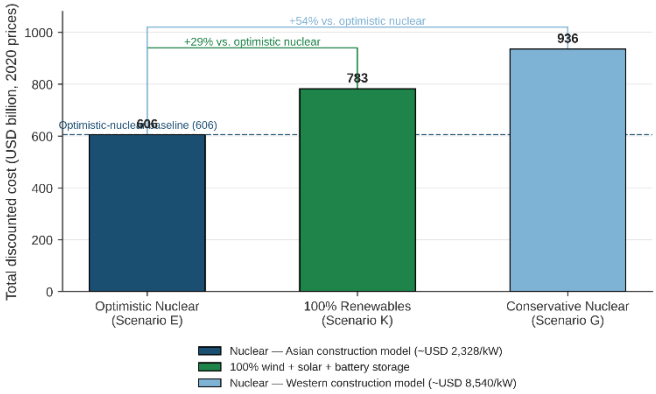

Figure 2. Total Discounted Cost (TDC) Comparison Between Nuclear and 100% Renewable Scenarios
Source: Author's construct based on data from Marques & Junqueira (2022).

Figure 3.2 indicates that nuclear-inclusive pathways achieve lower Total Discounted Cost than fully renewable scenarios in both Indonesia and the Philippines. The difference is associated primarily with lower requirements for storage, reserve generation, and transmission reinforcement rather than with generation costs alone.

The economic performance of nuclear generation also depends on institutional capability. Standardized reactor designs, established supply chains, consistent regulation, and effective project management can reduce construction costs. Under these conditions, overnight construction costs may remain below the approximate competitiveness threshold of US$4,000/kW. Fragmented project delivery and prolonged construction periods can increase total electricity costs.

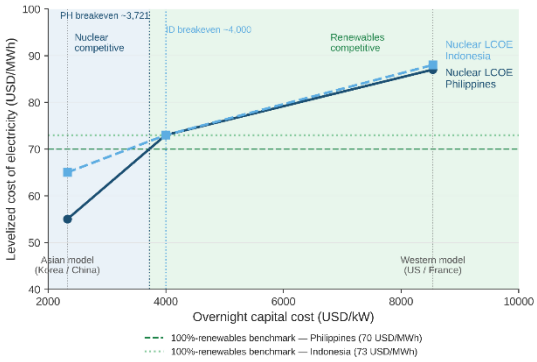

Figure 3. Sensitivity Analysis of Nuclear LCOE Under Alternative Construction Cost Assumptions.
Source: Author's construct based on data from Nian et al. (2022).

The comparative assessment identifies three recurring patterns in electricity decarbonization.

First, rapid renewable expansion does not necessarily produce the lowest carbon intensity. Germany has invested heavily in wind and solar generation, yet its electricity-sector emissions remain substantially higher than those of France, which has relied more heavily on nuclear generation (Marques & Junqueira, 2022). The result points to the role of firm low-carbon generation alongside renewable capacity.

Second, lower renewable generation costs do not automatically translate into lower whole-system electricity costs. As the share of variable renewable generation rises, the system requires additional storage, reserve generation, transmission reinforcement, and balancing services. These requirements affect Total Discounted Cost even when the cost of individual wind and solar projects declines.

Third, electricity systems with standardized firm low-carbon generation can maintain greater operational stability than systems that depend predominantly on variable renewable resources. France's lower carbon intensity compared with Germany illustrates the importance of dispatchable low-carbon capacity in the wider generation portfolio.

Table 2. Comparative Performance Synthesis: France and Germany (2022)

Performance Indicator	France (Nuclear-Centric)	Germany (Renewable-Heavy)	Relative Advantage
Carbon Intensity	~60 gCO_2/kWh	~310 gCO_2/kWh	France: 5× Lower
Price Stability (2021–22)	Moderate Increase (+18%)	High Volatility (+48%)	France: More Stable
Grid Interventions	Low (6 events)	High (34 events)	France: Higher Reliability
Baseload Strategy	Sovereign Firm Capacity	Market-Dependent Backup	France: Structural Sovereignty

Sources: Synthesized from ENTSO-E (2023), Eurostat (2023), and OWID (2023).

The comparison also identifies three structural mismatches that can weaken a transition strategy. The first occurs when renewable capacity grows faster than the flexibility resources needed to integrate it. The second occurs when policymakers retire dispatchable low-carbon generation before equivalent replacement capacity becomes available (Kokubun, 2026). The third concerns institutional capability, including construction standardization, regulatory

consistency, financing mechanisms, and domestic industrial supply chains (Andrews-Speed, 2016). Together, these factors help explain why countries with similar decarbonization objectives can obtain different environmental, economic, and operational results.

This study responds to these challenges through the Integrated Firm Low-Carbon Transition Framework (IFLTF). The framework treats renewable energy and nuclear power as complementary components of an integrated electricity system. Four principles guide the framework:

1. Firm low-carbon generation provides electricity adequacy when renewable output is low.
2. Renewable generation reduces emissions when available resource conditions permit.
3. Storage, transmission expansion, reserve generation, and demand-side flexibility provide balancing capacity.
4. Institutional capability determines whether a technically competitive technology can achieve successful long-term deployment.

The scenario assessment also supports this framework. A business-as-usual pathway can continue to reduce emissions, but system-integration costs may increase as the transition progresses. A renewable-only pathway can accelerate renewable deployment but requires greater investment in storage and balancing infrastructure to maintain reliability. An integrated firm low-carbon pathway combines dispatchable low-carbon generation with renewable expansion and can reduce the need for some balancing investments while supporting stable long-term decarbonization.

Indonesia should not reproduce either the French or German model in its original form. Indonesia has different geographic conditions, resource endowments, institutional structures, and infrastructure needs. The findings instead support an adaptive strategy that combines region-specific renewable deployment, firm low-carbon generation, stronger transmission infrastructure, and continued institutional development.

The econometric evidence, historical comparison, and whole-system economic assessment point to the same planning issue: the composition, timing, and implementation of the electricity portfolio matter alongside the amount of renewable capacity installed (Kabeyi & Olanrewaju, 2022). The IFLTF provides a conceptual basis for incorporating these factors into Indonesia's long-term electricity planning while pursuing environmental sustainability, economic efficiency, and supply reliability.

4. CONCLUSION

The comparison between France and Germany shows that electricity decarbonization outcomes depend on how technologies are combined and implemented across the electricity system. Three factors stand out: the balance between renewable capacity and flexibility resources, the timing of firm low-carbon capacity retirement, and the institutional capacity to deliver long-term electricity infrastructure.

Rapid renewable deployment alone does not guarantee the lowest carbon intensity, the lowest whole-system electricity cost, or the highest level of operational reliability. Germany's experience illustrates the difficulty of integrating large amounts of variable renewable generation while reducing firm low-carbon capacity. France's experience shows how a

standardized nuclear fleet can provide a stable source of low-carbon electricity within a broader generation portfolio.

The Integrated Firm Low-Carbon Transition Framework (IFLTF) addresses these conditions by treating renewable energy and firm low-carbon generation as complementary resources. The framework places equal attention on generation capacity, infrastructure, and institutional capability. Its application should reflect each country's resource availability, electricity demand, infrastructure conditions, and capacity to manage complex energy projects.

For Indonesia, the policy implications are threefold. First, national electricity planning should assess technologies at the whole-system level rather than relying only on plant-level generation costs. Second, the IFLTF can serve as a framework for coordinating renewable deployment, firm low-carbon generation, transmission development, storage, and reserve capacity within long-term energy planning. Third, government institutions need stronger coordination across energy planning, infrastructure development, financing, regulation, and industrial policy.

The experiences of France and Germany therefore provide a basis for comparing transition strategies rather than selecting a single technology for universal application. Indonesia can use these lessons to develop an electricity system that matches its own resources and institutional capacity while maintaining the three objectives of the energy transition: lower emissions, affordable electricity, and reliable supply.

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