



The Role of Green Finance and Technological Innovation in Supporting the Energy Transition: The Case of Germany

دور التمويل الأخضر والابتكار التكنولوجي في دعم التحول الطاقوي: دراسة حالة ألمانيا

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Abstract

This study examines the evolution of green finance in Germany and its link to renewable energy and innovation from 2014 to 2025 using aggregated secondary data. The findings show that Germany's sustainable finance system has matured, shifting from predominantly sovereign issuance to a diversified corporate market. Although green finance strongly supports electricity decarbonisation-reaching a 52% renewable share-progress in primary energy and transport remains limited. Importantly, while capital flows have increased, domestic renewable energy patent activity has declined. The study concludes that green finance accelerates infrastructure deployment but does not automatically sustain innovation, underscoring the need for targeted support in next-generation technologies.

Keywords

Green Finance ;
Renewable Energy;
Energy Transition ;
Innovation ;
Germany ;

JEL Classification Codes : Q42; ; Q43 ; G23 ; O13

الكلمات المفتاحية

الملخص

تبحث هذه الدراسة في تطور التمويل الأخضر في ألمانيا وعلاقته بالطاقة المتجددة والابتكار خلال الفترة 2014-2025، بالاعتماد على بيانات ثانوية مجمعة. وتُظهر النتائج أن منظومة التمويل المستدام في ألمانيا قد نضجت، منتقلةً من إصدار يغلب عليه الطابع السيادي إلى سوق مؤسسية أكثر تنوعاً تقوده الشركات. ورغم أن التمويل الأخضر يدعم بقوة إزالة الكربون في قطاع الكهرباء - حيث بلغت حصة الطاقات المتجددة 52% - فإن التقدم في استهلاك الطاقة الأولية وقطاع النقل لا يزال محدوداً. ومن اللافت أنه رغم زيادة تدفقات رأس المال، فقد تراجعت طلبات براءات الاختراع المحلية في مجال الطاقة المتجددة. وتخلص الدراسة إلى أن التمويل الأخضر يسرّع نشر البنية التحتية، لكنه لا يضمن تلقائياً استدامة الابتكار، مما يؤكد الحاجة إلى دعم موجه للتكنولوجيات من الجيل القادم.

التمويل الأخضر؛ الطاقة
المتجددة؛ التحول الطاقوي؛
الابتكار؛ ألمانيا..

تصنيف JEL: Q42; ; Q43 ; G23 ; O13

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I.INTRODUCTION:

The accelerating climate crisis and the growing urgency of decarbonisation have positioned renewable energy at the centre of global sustainability strategies. Achieving carbon neutrality requires not only technological transformation but also sustained financial mobilisation capable of supporting capital-intensive and long-term energy investments. Renewable energy systems, characterised by high upfront costs, extended payback periods, and regulatory sensitivity, depend fundamentally on stable and innovative financing mechanisms. In this context, green finance has emerged as a strategic instrument for directing capital towards environmentally sustainable activities and facilitating the transition to low-carbon energy systems.

Green finance encompasses a range of financial instruments, including green bonds, sustainable investment funds, green credit schemes, and environmentally oriented capital flows. Empirical research increasingly highlights the relevance of green financial development in promoting renewable energy expansion, particularly in advanced economies with strong institutional frameworks (Hou et al., 2023). Evidence from Germany further suggests that financial innovation and technological diffusion play complementary roles in supporting environmental sustainability (Muhammad & Hoffmann, 2024). These findings indicate that financial and technological dynamics are deeply interconnected within the energy transition process.

Despite the growing literature, important analytical gaps remain. Existing studies often adopt cross-country econometric approaches or focus narrowly on environmental outcomes without providing an integrated national-level examination of how green finance structures evolve and interact with renewable energy deployment mechanisms. In the German context, limited attention has been given to the structural configuration of green financial instruments and their alignment with technological innovation and institutional frameworks over time.

Germany represents a particularly relevant case. As a pioneer of the Energiewende and one of Europe's largest renewable energy markets, Germany has developed an increasingly sophisticated sustainable finance ecosystem supported by both national policies and European Union regulatory initiatives (Kuhn, 2022). However, a comprehensive structural assessment of how green finance dynamics correspond with renewable energy development and innovation indicators remains underexplored.

Accordingly, the central research question guiding this study is: **How has green finance evolved in Germany, and how does its structural development correspond with renewable energy deployment and innovation dynamics?**

The study pursues three main objectives. First, it analyses the evolution and structural composition of green finance instruments in Germany, including green bonds, sustainable investment flows, and promotional funding mechanisms. Second, it examines the temporal relationship between green finance development and renewable energy indicators, with particular attention to innovation outputs. Third, it evaluates the role of institutional and policy frameworks in shaping the configuration of Germany's sustainable finance architecture.

This study contributes to the literature by providing a structured national-level assessment of green finance within a leading renewable energy economy. It integrates financial, technological, and

institutional dimensions into a unified analytical perspective and offers policy-relevant insights into how financial systems can support long-term energy transition strategies. By clarifying the structural interactions between green finance and renewable energy development in Germany, the study advances understanding of the institutional foundations underpinning the transition toward a low-carbon economy.

II. THEORETICAL FRAMEWORK AND PREVIOUS STUDIES:

2.1 Theoretical Foundations

The relationship between green finance and renewable energy development can be understood through several complementary theoretical perspectives that collectively explain how financial systems, sustainability principles, and growth–environment dynamics interact over time. At its core, Financial Intermediation Theory provides the foundational framework for analyzing how financial systems allocate capital efficiently by reducing information asymmetries, transaction costs, and agency problems. Financial intermediaries—such as banks, capital markets, and institutional investors—facilitate the transfer of funds from savers to productive investment projects through screening, monitoring, and signaling mechanisms that enhance market efficiency and macroeconomic stability (Boyd, 2018; Diamond, 1984; Fishman, 2009). In capital-intensive and technologically uncertain sectors such as renewable energy, these intermediation functions become particularly critical, as financing frictions can significantly constrain investment expansion.

Within this theoretical logic, green finance can be conceptualized as a specialized extension of financial intermediation that aligns capital allocation with environmental sustainability objectives. Unlike conventional financial mechanisms, green financial instruments incorporate environmental criteria into funding decisions and explicitly channel resources toward low-carbon and renewable energy projects. Instruments such as green bonds, green loans, and sustainable investment funds reduce financing barriers, improve capital accessibility, and mitigate long-term investment risks (Hou et al., 2023; Rasoulinezhad & Taghizadeh-Hesary, 2022; Taghizadeh-Hesary & Yoshino, 2020). Empirical evidence increasingly supports the argument that green finance promotes renewable energy development through both direct and indirect channels, particularly in countries with developed financial systems and strong environmental governance (Lee et al., 2023; Irfan et al., 2022). Moreover, by alleviating financing constraints and facilitating knowledge spillovers, green financial development stimulates technological innovation and accelerates the diffusion of clean energy technologies, thereby reinforcing structural transformation toward a low-carbon economy (Tan & Huang, 2025; Wang, 2024).

Extending this reasoning, the Sustainable Finance Framework broadens the scope of financial intermediation by systematically integrating Environmental, Social, and Governance (ESG) criteria into financial decision-making processes. Rather than prioritizing short-term profitability alone, sustainable finance embeds environmental externalities into capital allocation strategies in order to enhance long-term value creation and reduce systemic risks associated with unsustainable development pathways (Bandna et al., 2025; Surenthran et al., 2024). This alignment between financial markets and sustainability objectives supports structural energy transformation by mobilizing capital toward renewable infrastructure, green industrial upgrading, and climate-resilient

technologies (Devender et al., 2025; Shafik, 2025). Institutional and regulatory frameworks play a central role in enhancing the effectiveness of sustainable finance by improving transparency, reducing uncertainty, and strengthening investor confidence (Feil et al., 2025; Hossin et al., 2024). Additionally, digital technologies such as artificial intelligence and blockchain improve monitoring efficiency and data reliability, thereby reinforcing the credibility and scalability of green financial mechanisms (Ahmad et al., 2025; Shukla et al., 2025).

A dynamic macroeconomic dimension is provided by the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between economic growth and environmental degradation (Grossman & Krueger, 1995; Stern et al., 1996). According to this framework, environmental degradation initially increases during early stages of development due to industrial expansion and fossil fuel dependence, but declines after income surpasses a certain threshold, driven by structural change, technological progress, and stricter environmental regulation (Kijima et al., 2010; Kaika & Zervas, 2013). Although widely debated (Stern, 2004; Dinda, 2004), the EKC remains central in explaining long-run sustainability transitions.

Recent extensions, particularly the Renewable Environmental Kuznets Curve (RKC), refine this perspective by incorporating renewable energy adoption and green financial development into the growth–environment nexus. The RKC hypothesis suggests that renewable energy expansion may accelerate the turning point at which environmental degradation begins to decline (Yao et al., 2019; Pata et al., 2025). Empirical evidence indicates that renewable energy deployment often precedes reductions in carbon emissions, implying that clean energy investment—supported by green financial mechanisms—can facilitate earlier environmental improvement (Simionescu, 2021; Taher, 2024). Furthermore, governance quality, income heterogeneity, and political stability influence the timing and magnitude of EKC turning points across countries (Sarntisart & Dunyo, 2025; Tachea et al., 2021).

Taken together, these theoretical perspectives converge toward a coherent explanation: green finance functions as a transmission mechanism linking financial development, technological innovation, institutional quality, and renewable energy expansion. By reducing financing frictions, embedding sustainability criteria into capital allocation, and accelerating the structural shift toward renewable energy systems, green finance contributes not only to energy transition but also to advancing the environmental turning point predicted by the EKC framework. In this sense, green finance represents both a micro-level financial innovation and a macro-level catalyst for long-term sustainable development.

2.2 Green Finance and Renewable Energy: Global Evidence

A substantial and rapidly expanding body of empirical research investigates the relationship between green finance and renewable energy development across advanced and emerging economies. While the dominant conclusion in the literature supports a positive association, the magnitude and mechanisms of this relationship appear highly conditional on institutional quality, financial market maturity, and technological capacity. Cross-country evidence indicates that green financial development significantly stimulates renewable energy expansion, particularly in economies characterized by stringent environmental regulations and developed financial systems

(Hou et al., 2023). However, country-specific studies suggest that financial flows alone do not automatically translate into energy transition outcomes. For example, evidence from Germany shows that the interaction between green finance and technological innovation is critical in shaping the pace and depth of the transition process (Muhammad & Hoffmann, 2024). This suggests that green finance operates less as an isolated determinant and more as a complementary catalyst embedded within broader innovation and governance structures.

Empirical findings generally converge around two principal transmission mechanisms: capital deepening and innovation enhancement. Through the first channel, green finance promotes renewable energy deployment by increasing fixed asset investment and improving capital allocation efficiency. By reducing borrowing costs, easing credit constraints, and mitigating risk exposure in capital-intensive sectors, green financial instruments facilitate large-scale renewable energy investment. Empirical studies show that green financial development enhances renewable energy investment efficiency, particularly when banking systems actively channel credit toward environmentally prioritized sectors (He et al., 2019; Rasoulinezhad & Taghizadeh-Hesary, 2022). Yet firm-level analyses reveal important heterogeneity. Green credit policies tend to exert stronger effects on enterprises facing binding financial constraints, especially small and non-state-owned firms, indicating that green finance may correct structural capital misallocation rather than merely expand aggregate investment (Li et al., 2025). Sectoral evidence further demonstrates that regulatory enforcement conditions the magnitude of impact, as illustrated by stronger responses of hydropower investment in regions with credible environmental governance (Hong et al., 2024). These findings imply that capital expansion alone is insufficient; institutional complementarity is necessary to ensure efficient allocation and productive outcomes.

The second mechanism operates through technological innovation. By alleviating financing constraints and lowering the cost of research and development, green finance supports renewable energy technological innovation and improves green total factor productivity (Lee & Lee, 2022; Yu et al., 2021). However, the innovation-enhancing effect appears nonlinear. Threshold analyses indicate that the impact of green finance intensifies once technological development surpasses a critical level (Shi & Shi, 2025), suggesting that absorptive capacity plays a mediating role. In economies with limited innovation infrastructure, financial support may generate limited technological gains, whereas in middle- and lower-income countries-where financing constraints are more binding-the marginal impact of green finance on renewable energy innovation tends to be stronger (Zheng et al., 2023). These findings indicate that green finance functions primarily as an accelerator of existing innovation systems rather than an independent initiator of technological transformation.

Beyond these two central channels, the literature highlights substantial regional heterogeneity and spatial spillover effects. The effectiveness of green finance depends on regulatory coherence, governance quality, and financial market depth (Hou et al., 2023; Zheng et al., 2023). Spatial econometric evidence further suggests that green finance reforms can generate cross-regional diffusion of renewable energy technologies and innovation activities, extending benefits beyond local jurisdictions (Zhao et al., 2026). At the same time, methodological differences across studies-including alternative measurement of green finance indices, renewable energy proxies, and

econometric specifications-contribute to variations in estimated effect sizes. Although the direction of impact remains broadly consistent, the magnitude and transmission pathways are clearly context-specific.

Overall, global empirical evidence supports the argument that green finance contributes positively to renewable energy development, yet its effectiveness is neither automatic nor homogeneous. Its impact is mediated by institutional arrangements, technological capacity, and regulatory frameworks, which jointly determine whether financial resources are efficiently transformed into renewable energy deployment and innovation. Consequently, green finance should be understood not merely as a funding mechanism, but as a systemic coordination instrument that integrates capital allocation, technological upgrading, and governance structures within the broader process of low-carbon structural transformation.

2.3 Sustainable Finance in Germany

Germany provides a critical case for assessing whether sustainable finance can function as a causal driver of renewable energy transition rather than merely a correlated financial development trend. While Germany is frequently portrayed as a European frontrunner in integrating sustainability into financial markets, the analytical challenge lies in distinguishing between three interrelated dynamics: (i) regulatory-induced financial adaptation, (ii) market-driven sustainability preferences, and (iii) policy-led structural transformation under the Energiewende framework.

The evolution of sustainable finance in Germany does not appear to be purely endogenous to financial market maturation. Instead, it reflects policy-induced institutional restructuring shaped by both national climate commitments and supranational European regulation. The EU Action Plan on Sustainable Finance and subsequent taxonomy regulations significantly reduced informational asymmetries and standardized sustainability disclosure, thereby lowering transaction costs associated with green investment screening (Kuhn, 2022). However, regulatory alignment alone does not establish causality between sustainable finance expansion and renewable energy outcomes. A central methodological concern is reverse causality: Germany's already advanced renewable energy sector may have attracted sustainable capital flows, rather than sustainable finance independently driving renewable deployment.

The strength of the German case lies in institutional complementarity across governance layers. Supervisory authorities (e.g., BaFin), development banks (notably KfW), and private financial institutions operate within a coordinated policy environment that internalizes climate risk into credit allocation and long-term investment strategy. Development banking plays a particularly important quasi-public risk-absorbing role, mitigating financing constraints in capital-intensive renewable sectors. This risk-sharing architecture reduces the cost of capital and enhances investment stability, conditions that are critical for infrastructure projects characterized by long amortization horizons. The presence of such institutional scaffolding suggests that sustainable finance in Germany functions less as a market correction mechanism and more as a policy-amplified coordination device.

At the firm level, sustainability integration appears to be driven by a dual mechanism combining regulatory pressure and stakeholder-oriented governance norms (Johnson et al., 2018). Yet, this raises an important causal question: does sustainable finance alter corporate behavior, or do already sustainability-oriented firms self-select into green financial instruments? Without careful identification strategies, the observed association between sustainable finance expansion and renewable energy investment may reflect selection bias rather than treatment effects. System-level analyses suggest that coordinated governance structures reduce transition uncertainty and compress green risk premia (Hussain, 2025), but the magnitude of this effect likely depends on credibility and enforcement capacity, which remain uneven across regulatory layers (Afolabi & Sharma, 2025).

Green bonds represent the most visible operational channel of sustainable finance in Germany, but their causal effectiveness requires careful scrutiny. While evidence of a “greenium” suggests that investors may accept lower yields for certified green instruments (Koziol et al., 2022), it remains debated whether this pricing differential reflects genuine environmental preference or lower perceived default risk. Furthermore, the environmental impact of green bonds depends critically on additionality—whether funded projects would have occurred absent green labeling. Strong legal and verification frameworks enhance credibility and mitigate greenwashing risks (Benlemlih et al., 2026), yet causal attribution remains methodologically complex. Cross-country evidence associating green bond issuance with emission reductions (Li et al., 2023) cannot fully isolate whether emission declines result from financial innovation or from pre-existing environmental policy stringency.

Germany’s comparative leadership among G20 economies in mobilizing sustainable finance (Acharjee et al., 2025) therefore reflects not merely financial sophistication but the interaction between financial innovation, industrial policy, and technological capability. Sustainable finance appears to exert its strongest influence when embedded within a pre-existing renewable innovation ecosystem and supported by coherent climate regulation. In this context, financial instruments amplify structural transformation rather than initiate it. The German case thus supports a conditional causality framework: sustainable finance contributes to renewable energy expansion when institutional stability, regulatory credibility, and technological absorptive capacity are simultaneously present.

Nevertheless, structural vulnerabilities persist. Fragmentation across evolving European sustainability regulations, measurement inconsistencies in ESG metrics, and the ongoing implementation of the Corporate Sustainability Reporting Directive (CSRD) introduce transitional uncertainty (Sharma, 2025). These factors may temporarily increase compliance costs and create short-term capital allocation distortions. The long-term effectiveness of Germany’s sustainable finance ecosystem will therefore depend on its ability to standardize climate risk assessment methodologies and ensure regulatory coherence across federal and EU levels.

Germany’s experience suggests that sustainable finance is neither a sufficient nor an autonomous driver of renewable energy transition. Rather, it operates as an institutional multiplier within a broader policy-technology-finance nexus. Its causal impact emerges when financial instruments are embedded in stable governance structures, reinforced by development banking, and aligned with long-term industrial decarbonization strategies. This conditional interpretation

challenges simplistic narratives of financial determinism and underscores the importance of institutional design in translating sustainable finance into measurable environmental outcomes.

Based on the above theoretical and empirical arguments, this study examines the interaction between sustainable finance development and renewable energy dynamics in Germany.

III.METHOD AND PROCEDURES:

This study adopts a quantitative case study approach focusing on the Federal Republic of Germany to examine the structural evolution of green finance and its relationship with key energy transition indicators. Germany was selected as a single-case analytical framework due to its advanced sustainable finance architecture and its long-standing commitment to the Energiewende.

The population of the study comprises Germany's sustainable financial ecosystem and energy sector. The analysis specifically addresses green bond markets, public promotional funding mechanisms, renewable energy deployment, and innovation indicators. The sample consists of aggregated financial and energy data covering the period from 2001 to 2025, with particular emphasis on the phase of accelerated green finance expansion between 2014 and 2024.

Data collection relied exclusively on secondary data obtained from official institutions and reputable statistical databases. These include the Climate Bonds Initiative (CBI), the Forum Nachhaltige Geldanlagen (FNG), the Working Group on Energy Balances (AGEB), the Federal Ministry for Economic Affairs and Climate Action (BMWK), the German Patent and Trademark Office (DPMA), and Statista. The datasets encompass green bond issuance volumes, KfW promotional funding, renewable energy shares in electricity and primary energy consumption, public R&D allocations, and renewable energy patent applications.

For data processing and analysis, the study employs descriptive statistical techniques to measure key variables, including financial volumes (in EUR and USD), issuance frequency, funding allocations, and percentage shares of renewable energy integration. Chronological aggregation was used to identify long-term growth patterns, structural shifts, and periods of volatility. Particular attention was given to observable transitions, such as the shift from sovereign-led to corporate-led green bond issuance, the stabilising role of development banking, and divergences between electricity decarbonisation and primary energy transformation.

The analytical framework is based on trend analysis and structural interpretation. By juxtaposing financial mobilisation indicators with physical energy outcomes and innovation outputs (e.g., patent activity and research funding), the study evaluates the depth, maturity, and institutional embedding of Germany's sustainable finance system. The approach emphasises temporal correlation and structural dynamics rather than econometric causality, allowing for a comprehensive interpretation of systemic transformation processes.

IV.STUDY RESULTS

4.1 Evolution of Green Finance in Germany

The cumulative value of green bonds issued in Europe between 2014 and 2023 clearly positions Germany as the leading country in the European sustainable finance landscape. With a total issuance

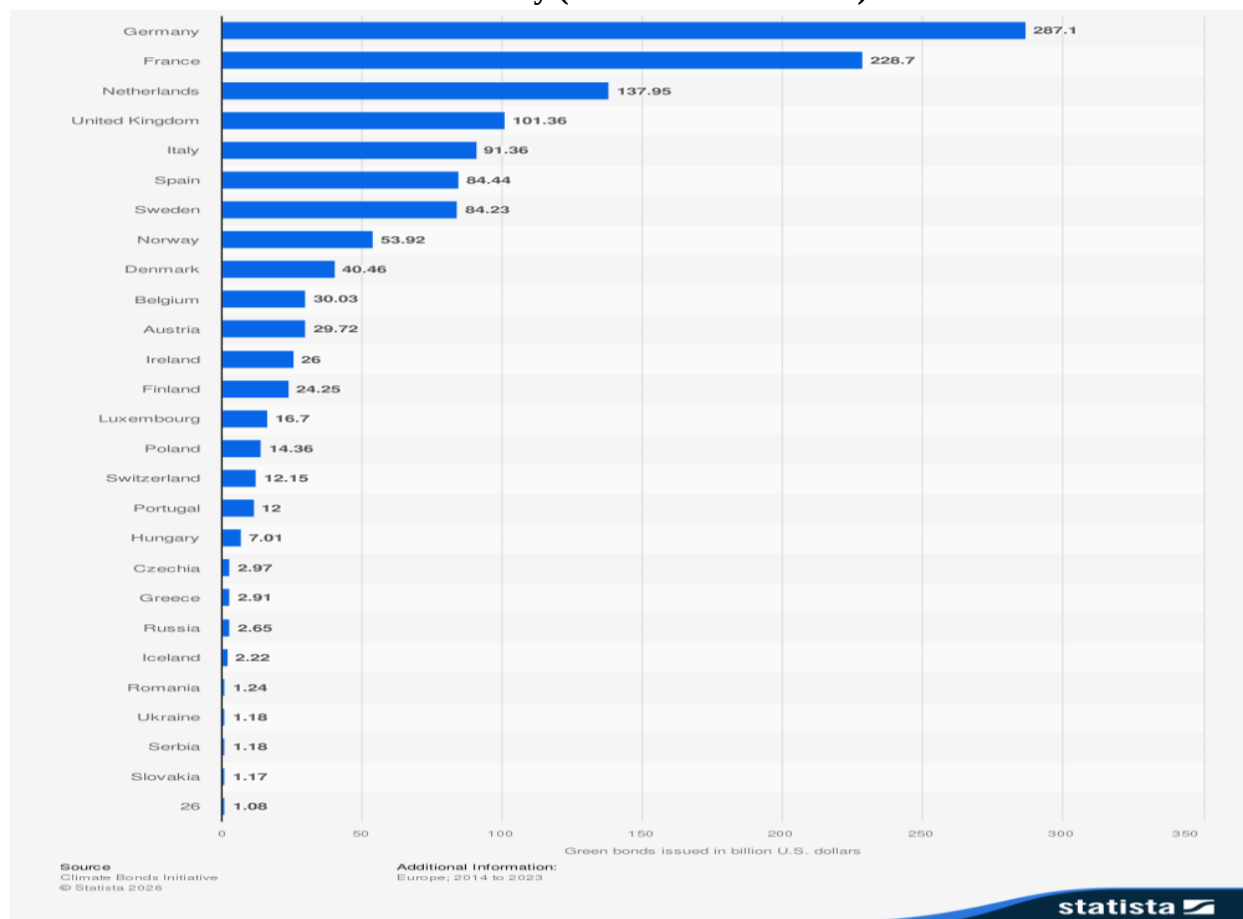
amounting to USD 287.10 billion, Germany ranks first, exceeding France (USD 228.70 billion) and the Netherlands (USD 137.95 billion).

This substantial issuance volume reflects not only market activity but also the structural integration of sustainable finance within Germany's financial system. The notable gap between Germany and other major European economies, including the United Kingdom and Italy, indicates a deeper institutional and financial commitment to green capital mobilization.

The temporal evolution of issuance reveals a marked acceleration after 2016. This upward trajectory coincides with the reinforcement of European sustainable finance regulations and the intensification of Germany's national climate policy commitments. The introduction of regulatory frameworks at both EU and national levels appears to have strengthened investor confidence and stimulated green capital flows.

Public financial institutions-particularly development banks-have played a strategic catalytic role in this expansion. By issuing sovereign and development-backed green bonds and supporting climate-related investment programs, these institutions reduced financing constraints for renewable energy infrastructure and energy efficiency projects.

Figure (1): Cumulative value of green bonds issued Europe between 2014 and 2023, by country (in billion U.S. dollars)



Source: Statista. (2026). European Union: Green debt issued by country from 2014 to 2023.

<https://www.statista.com/statistics/1292729/european-union-green-debt-issued-by-country/>

To assess whether green finance in Germany exhibits a sustained expansion rather than isolated issuance events, a chronological aggregation of major green bond issuances was conducted for the period 2020–2024. The objective is to identify temporal growth patterns and sectoral shifts in capital mobilisation. By calculating the approximate annual issuance volumes and number of transactions, the analysis provides quantitative evidence regarding the depth, continuity, and structural transformation of Germany’s green finance market.

Table (1): T Temporal Evolution of Green Bond Issuances in Germany by Sector (2020–2024)

Year	Dominant Sector	Total Volume (Approx. € bn)	Number of Issuances	Representative Issuers & Thematic Focus
2020	Sovereign	~11.5	2	Federal Republic of Germany – Renewable infrastructure
2021	Sovereign	~12.5	3	Federal Republic of Germany – Climate protection programmes
2022	Sovereign & Transport	~18.5	11	Germany & Volkswagen – EV platforms
2023	Diversified Growth	~25.0	16	Germany, VW, Mercedes, ZF – Supply chain & clean mobility
2024*	Corporate-led Diversification	~15.2	16	VW, ZF, TUI – SLBs & efficiency instruments

Source: Climate Bonds Initiative. (n.d.). *Market Data: Insights from Climate Bonds Data*. Available at: <https://www.climatebonds.net/data-insights/market-data/insights-from-climate-bonds-data?tab=subscribe#> [Accessed 26 Feb. 2026].

As shown in Table 1, the total annual volume of green bond issuances increased from approximately €11.5 billion in 2020 to a peak of €25 billion in 2023. This represents more than a twofold expansion within three years, indicating a clear upward trajectory in Germany’s green capital market.

The period 2020–2021 was dominated exclusively by sovereign issuances, reflecting the state’s central role in initiating and stabilising the domestic green bond market. The limited number of transactions but high volume suggests large-scale public funding directed toward renewable infrastructure and climate-related programmes.

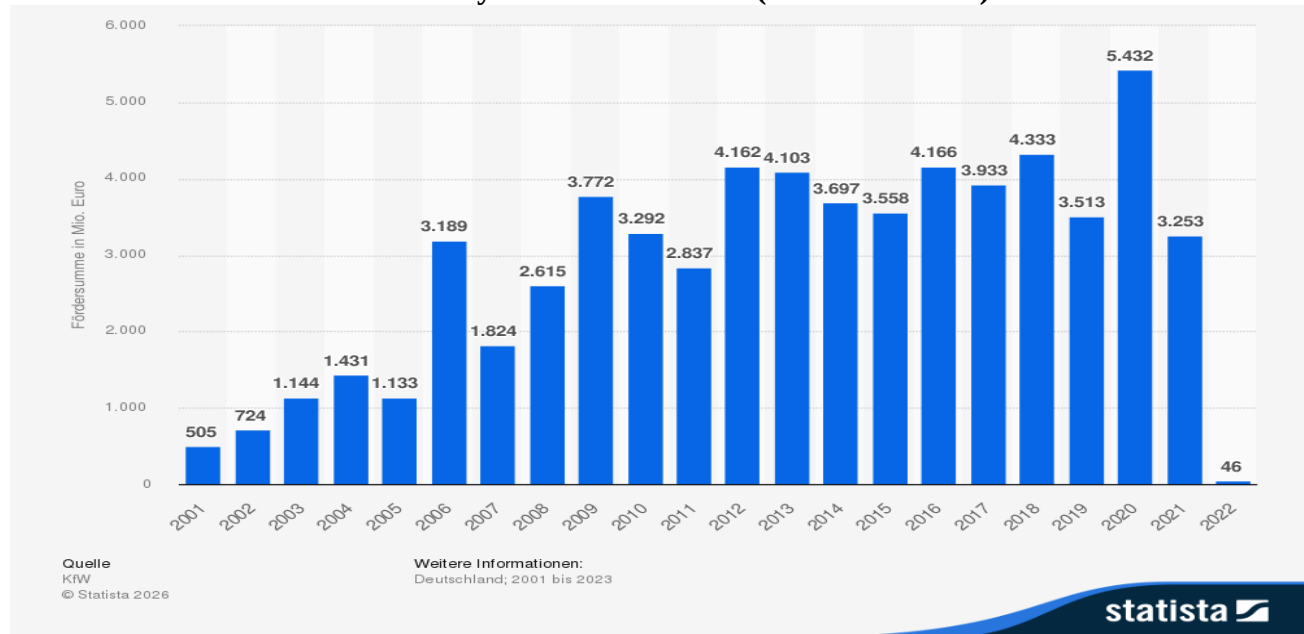
From 2022 onwards, a structural shift becomes observable. The entry of major automotive corporations significantly increased both the number of issuances and total market volume. The number of transactions rose sharply from 3 in 2021 to 11 in 2022 and further to 16 in 2023. This rise indicates market broadening rather than mere scaling of sovereign activity.

The year 2023 represents the peak of diversification, characterised by the inclusion of supply-chain actors and mobility-focused industrial firms. This pattern suggests that green finance expanded beyond public infrastructure funding toward private-sector industrial transformation.

Although the total volume in 2024 appears lower compared to 2023, the number of issuances remains high. This indicates a transition from volume concentration toward instrument diversification, including sustainability-linked bonds and sector-specific financing tools.

While green bond markets reflect capital market mobilisation, Germany's sustainable finance model is equally shaped by long-standing development banking interventions, particularly through KfW programmes.

Figure (2): Funding volume of the KfW program "Energy-Efficient Refurbishment"* in Germany from 2001 to 2023 (in million euros)



Source: Statista. (n.d.). KfW CO₂ -Gebäudesanierungsprogramm — Ausgaben in Deutschland von 2001 bis 2023 (in Milliarden Euro).

<https://de.statista.com/statistik/daten/studie/70375/umfrage/kfw-co2-gebaeudesanierungsprogramm-ausgaben-seit-2001/>

The figure illustrates the evolution of the promotional funding volume allocated by KfW under the “*Energieeffizient Sanieren*” (energy-efficient refurbishment) programme in Germany between 2001 and 2023. The time series reveals three distinct phases that reflect the interaction between financial instruments, regulatory frameworks, and broader climate policy objectives.

In the initial phase (2001–2005), funding volumes increased steadily from €505 million to over €1.1 billion. This gradual expansion corresponds to the early institutional embedding of energy efficiency within Germany's environmental policy agenda. During this formative period, financial support mechanisms were being consolidated, signalling the growing recognition of building refurbishment as a critical component of carbon mitigation strategy.

The second phase (2006–2019) is characterised by a substantial upward shift and relative stabilisation of funding at a structurally higher level. From 2006 onwards, annual volumes generally exceeded €3 billion, with peaks of €4.16 billion in 2012 and €4.33 billion in 2018. This sustained scale of investment reflects the consolidation of KfW's role as a central financial intermediary within the *Energiewende* framework. The relative stability of allocations during this period indicates a mature institutional environment in which long-term policy credibility reduced uncertainty and facilitated predictable capital flows into energy-efficient renovation. The consistency of funding

suggests that promotional banking operated as a quasi-automatic stabiliser for green investment, insulating the sector from short-term market volatility.

The third phase (2020–2023) demonstrates pronounced volatility with significant institutional implications. Funding peaked at €5.43 billion in 2020, likely influenced by enhanced climate commitments and economic stimulus measures linked to pandemic recovery. However, the subsequent collapse to approximately €46 million in 2022, followed by a further reduction to around €5 million in 2023, reflects the temporary suspension and restructuring of federal subsidy schemes. The magnitude of this contraction underscores the sensitivity of green promotional finance to regulatory recalibration and fiscal policy adjustments. It reveals that even well-established sustainable finance mechanisms remain highly contingent upon governmental continuity and policy coordination.

From a structural perspective, the figure highlights the pivotal role of KfW as a risk-sharing and coordination mechanism translating climate policy objectives into tangible capital allocation. The long-term upward trend until 2020 supports the argument that development banking can significantly amplify energy efficiency investment under stable institutional conditions. Conversely, the sharp retrenchment after 2021 illustrates that sustainable finance effectiveness is not self-sustaining; rather, it depends critically on regulatory coherence, fiscal commitment, and policy credibility.

4.2 Structural Characteristics of the Sustainable Finance Market in Germany

Drawing on statistical evidence from Statista, the Forum Nachhaltige Geldanlagen (FNG), and the Climate Bonds Initiative, the German sustainable finance market exhibits a structurally mature, institutionally anchored, and increasingly diversified ecosystem.

As of 2024, the total volume of sustainable investments in Germany reached approximately €673 billion. This scale confirms that sustainable finance is no longer a peripheral niche but has attained macro-financial relevance within the German capital market. The structural composition of this volume reveals a dominant role for mandates and special funds (€312.8 billion), accounting for roughly 46 per cent of total sustainable assets. Public funds follow at €241.7 billion (approximately 36 per cent), while customer deposits and proprietary investments represent smaller but meaningful shares.

This distribution indicates that Germany's sustainable finance architecture is primarily institutionalised. Large asset managers, pension funds, and insurance companies function as the main transmission channels of ESG-integrated capital allocation. The strong presence of professionally managed mandates suggests that sustainable finance is embedded within long-term portfolio management strategies rather than short-term thematic allocations.

The asset class distribution further reinforces this interpretation. Corporate bonds constitute the largest share (31 per cent), closely followed by equities (29 per cent). Government bonds account for 16 per cent, real estate investments for 13 per cent, and other asset classes for 11 per cent. The prominence of corporate bonds reflects a debt-oriented financing structure aligned with Germany's liability-driven institutional investor base. At the same time, the substantial equity share indicates

that ESG integration is also exercised through ownership-based governance mechanisms, suggesting a dual-channel model of capital provision and corporate influence.

The structure of labelled debt instruments confirms the environmental concentration of Germany's sustainable finance model. As of 2023, total green, social, and sustainability (GSS) bond issuance amounted to approximately USD 334 billion, of which green bonds alone accounted for USD 287.1 billion—roughly 86 per cent of total GSS issuance. This dominance highlights the climate-oriented nature of Germany's sustainable debt market, where capital mobilisation is primarily directed towards renewable energy, energy efficiency, and low-carbon infrastructure rather than broader social financing.

Investor composition over time reveals a significant structural transformation. Between 2010 and 2018, institutional investors dominated the sustainable investment market, consistently accounting for more than 80 per cent of total allocations and reaching a peak of 93 per cent in 2018. However, from 2019 onwards, private investor participation expanded considerably, rising to 43 per cent by 2023. This convergence indicates a gradual democratisation of sustainable finance, transitioning from a highly institutionalised niche to a mainstream investment segment. Nevertheless, institutional investors remain slightly dominant (57 per cent in 2023), preserving long-term capital stability within the market.

The role of development banking further distinguishes Germany's sustainable finance ecosystem. KfW's promotional programmes, particularly in energy-efficient refurbishment, historically channelled annual funding volumes between €3 and €5 billion prior to 2021. This quasi-public risk-sharing mechanism reinforced capital stability and supported renewable energy and building efficiency investments. However, the sharp contraction in 2022–2023 following regulatory restructuring underscores the structural sensitivity of green finance to policy continuity and fiscal coordination.

Taken together, the empirical evidence suggests that Germany's sustainable finance market operates through three interdependent pillars:

1. Capital market instruments (green and GSS bonds);
2. Institutional asset management (mandates and special funds);
3. Development banking and promotional finance (KfW).

The interaction of these pillars creates a multi-layered financing architecture capable of mobilising large-scale capital for climate transition. At the same time, the system remains conditionally dependent on regulatory coherence, investor confidence, and policy stability.

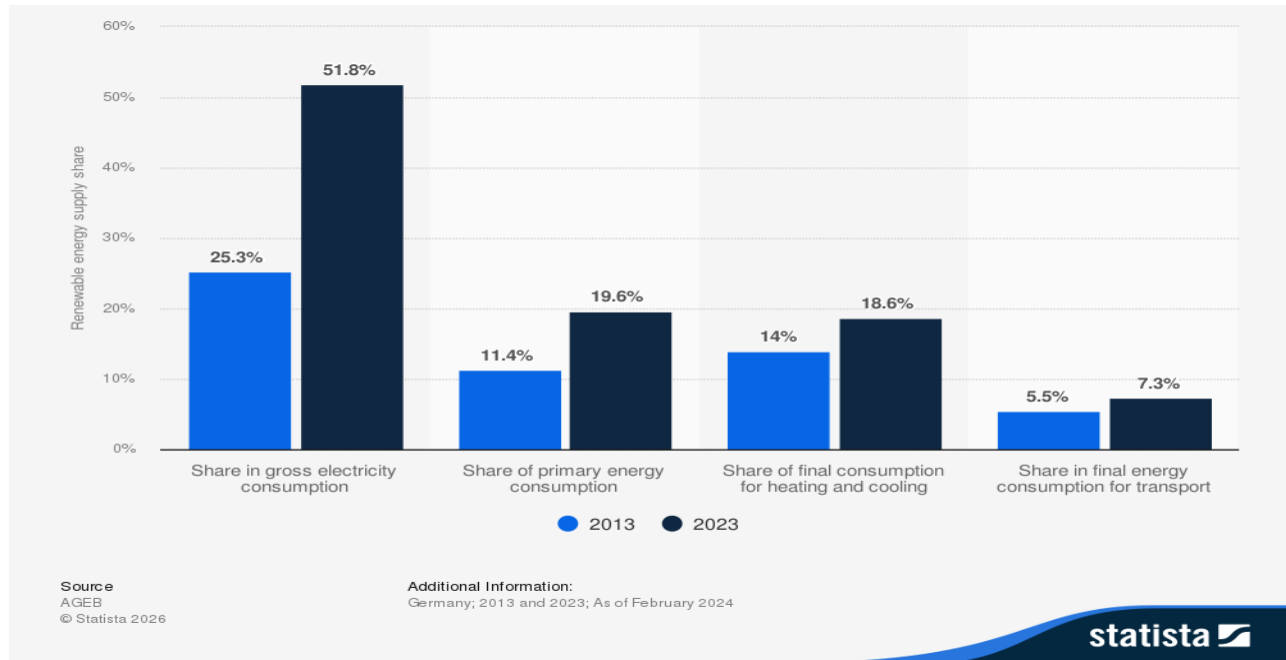
Overall, Germany's sustainable finance market demonstrates structural maturity, institutional depth, and environmental concentration. Its evolution reflects a coordinated integration of ESG principles into mainstream financial intermediation, positioning sustainable finance as a central mechanism supporting long-term decarbonisation and energy transition objectives.

4.3 Renewable Energy Development Trends and Structural Transformation

The evolution of renewable energy shares across major consumption sectors between 2013 and 2023 reflects the differentiated pace of Germany's energy transition. According to AGEBA data

published by Umweltbundesamt (2024), the share of renewables in gross electricity consumption increased from 25.3 per cent in 2013 to 51.8 per cent in 2023. This expansion represents the most substantial structural shift within the German energy system over the past decade.

Figure (3): Share of renewable energy in energy supply in Germany in 2013 and 2023, by sector



Source: Statista (2026). *Share of renewable energy in energy supply in Germany in 2013 and 2023, by sector*. Based on data from AGE B; published by Umweltbundesamt (2024). Available at: <https://www.statista.com/statistics/583160/renewable-energy-supply-share-by-sector-germany/> (Accessed: 26 February 2026).

In contrast, renewable energy's share in primary energy consumption rose more moderately, from 11.4 per cent to 19.6 per cent during the same period. This divergence highlights the structural complexity of decarbonising the broader energy base, where fossil fuels remain deeply embedded in transport, industrial production, and heating systems. Electricity generation has therefore advanced more rapidly than total energy transformation.

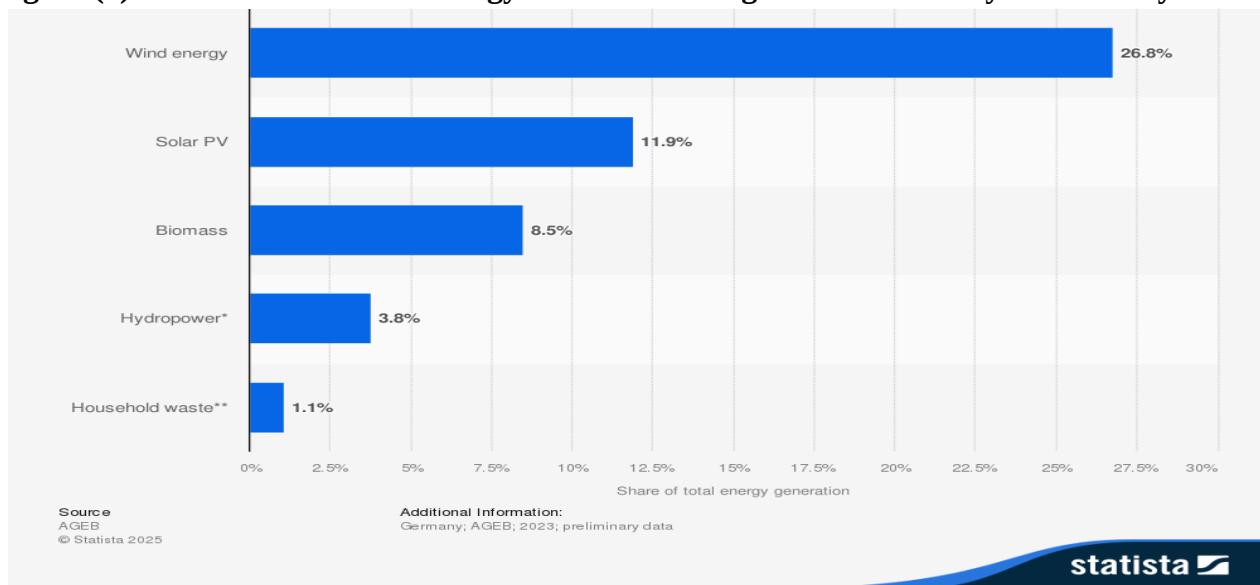
A similar pattern is observable in heating and cooling, where the renewable share increased from 14 per cent to 18.6 per cent. Although progress is evident, the pace remains gradual due to long capital cycles in the building sector and the high upfront costs associated with refurbishment and system conversion. By comparison, transport exhibits the slowest transition, rising only from 5.5 per cent to 7.3 per cent. Infrastructure lock-in, fuel dependency, and slower electrification dynamics constrain faster decarbonisation in this sector.

Taken together, the data reveal a sectorally asymmetric transition process. Renewable expansion has achieved systemic scale in electricity, while other sectors continue to lag behind. This asymmetry suggests that energy transformation is highly conditional upon technological scalability, regulatory coherence, and capital allocation efficiency.

When viewed alongside the expansion of Germany's sustainable finance market — including significant growth in ESG assets and green bond issuance — the electricity sector's rapid decarbonisation appears closely aligned with capital-intensive investment flows. However, the slower progress in heating and transport underscores that financial mobilisation alone does not guarantee uniform sectoral transformation. Institutional, infrastructural, and technological constraints remain decisive mediating factors.

Overall, the 2013–2023 trajectory confirms that Germany has achieved substantial decarbonisation in the power sector, yet the broader energy system continues to exhibit structural inertia. The transition therefore remains uneven, reinforcing the need for sector-specific financial and policy instruments to accelerate comprehensive energy system transformation.

Figure (4): Share of renewable energy sources used to generate electricity in Germany in 2023



Source: AGE B (2024). *Bruttostromerzeugung in Deutschland*. Published by Statistisches Bundesamt; retrieved via Statista (ID 736670). Available at:

<https://www.statista.com/statistics/736670/renewable-energy-sources-electricity-generation-germany/> (Accessed: 26 February 2026).

The internal composition of renewable electricity generation in 2023 reveals a highly concentrated technological structure dominated by wind energy. Wind power accounted for 26.8 per cent of total electricity generation, positioning it as the central pillar of Germany's renewable power system. This dominance reflects the scalability, relative cost competitiveness, and long-term policy support associated with onshore and offshore wind deployment.

Solar photovoltaic (PV) generation contributed 11.9 per cent, bringing the combined share of wind and solar to over 38 per cent of total electricity production. The prominence of these two technologies indicates that Germany's power transition is structurally anchored in variable renewable energy sources. While this configuration enhances decarbonisation outcomes, it

simultaneously increases systemic reliance on grid flexibility, storage capacity, and balancing mechanisms.

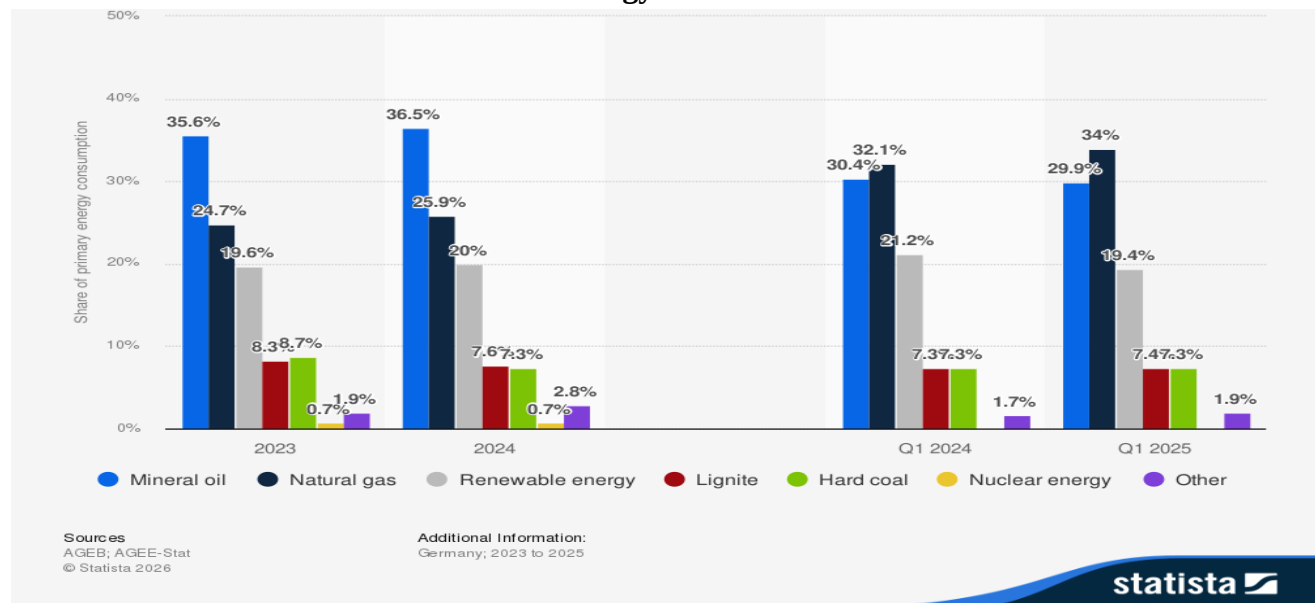
Biomass (8.5 per cent) and hydropower (3.8 per cent) play a complementary stabilising role within the renewable mix. Unlike wind and solar, these sources provide comparatively dispatchable generation, contributing to load balancing and supply security. Electricity derived from the biogenic portion of household waste (1.1 per cent) further illustrates the integration of circular economy principles within the electricity system, albeit at a limited scale.

The technological distribution therefore reveals a dual structure: a dominant, capital-intensive variable component (wind and solar) supported by smaller but operationally stabilising renewable sources. This composition underscores that Germany's electricity decarbonisation is not merely a function of aggregate renewable growth, but of specific technology pathways that require parallel investment in system integration infrastructure.

From a structural standpoint, the 2023 renewable mix demonstrates that the electricity sector has transitioned into a high-renewable regime. However, the concentration in variable technologies implies increasing exposure to intermittency risks and market volatility. Consequently, the next phase of the transition is likely to depend less on expanding generation capacity and more on strengthening storage systems, grid modernisation, hydrogen integration, and cross-sector coupling.

Overall, the 2023 electricity composition confirms that Germany's renewable expansion has reached systemic relevance, while simultaneously redefining the technical and financial priorities of the energy transition.

Figure (5): Structure of primary energy consumption in Germany from 2023 to 2025, by energy source



Source: AGEb; AGEE-Stat (2025). *Primary energy consumption structure in Germany (2023–2025).*

Published by AGEb; retrieved via Statista (ID 583157). Available at:

<https://www.statista.com/statistics/583157/primary-energy-consumption-structure-germany/> (Accessed: 26 February 2026).

The structure of primary energy consumption between 2023 and early 2025 provides a critical benchmark for assessing the depth of Germany's energy transition. Unlike electricity shares, primary energy captures the full spectrum of energy demand before conversion losses and therefore reflects the structural composition of the entire energy system.

Renewable energy accounted for 19.6 per cent of primary energy consumption in 2023 and 20 per cent in 2024, before declining slightly to 19.4 per cent in the first quarter of 2025. Although this represents steady progress relative to historical levels, renewables remain a minority component within the overall energy structure. The limited variation over the observed period indicates that structural change at the primary energy level is gradual rather than transformative.

Fossil fuels continue to dominate. Mineral oil and natural gas jointly account for more than half of total primary energy demand across all observed years. In 2023, oil represented 35.6 per cent and gas 24.7 per cent; by 2024, both shares increased modestly. Preliminary data for Q1 2025 show natural gas rising to 34 per cent, underscoring the continued reliance on gas for heating and industrial processes. This persistence reflects structural lock-in effects within transport, residential heating, and energy-intensive industries.

Coal usage exhibits a declining trajectory, consistent with Germany's phase-out commitments. Both lignite and hard coal shares fell between 2023 and 2024, signalling incremental decarbonisation within conventional power generation. Nuclear energy remains marginal following the completion of Germany's nuclear exit, thereby increasing adjustment pressures on both fossil fuels and renewables.

The contrast between electricity transformation and primary energy structure reveals a systemic imbalance in the transition process. While the power sector has entered a high-renewable phase, the broader energy system remains fossil-intensive due to slow electrification of transport, limited penetration of heat pumps, and the continued centrality of gas-based infrastructure.

Short-term fluctuations, particularly the rise in natural gas in early 2025, suggest sensitivity to seasonal demand and market dynamics. However, these cyclical movements do not alter the underlying structural reality: decarbonisation beyond electricity requires deep reconfiguration of end-use sectors rather than incremental supply-side adjustments.

From a strategic perspective, the data imply that the next stage of Germany's energy transition must prioritise electrification, sector coupling, hydrogen deployment, and building renovation at scale. Without structural transformation in these domains, gains achieved in renewable electricity generation will translate only partially into reductions at the primary energy level.

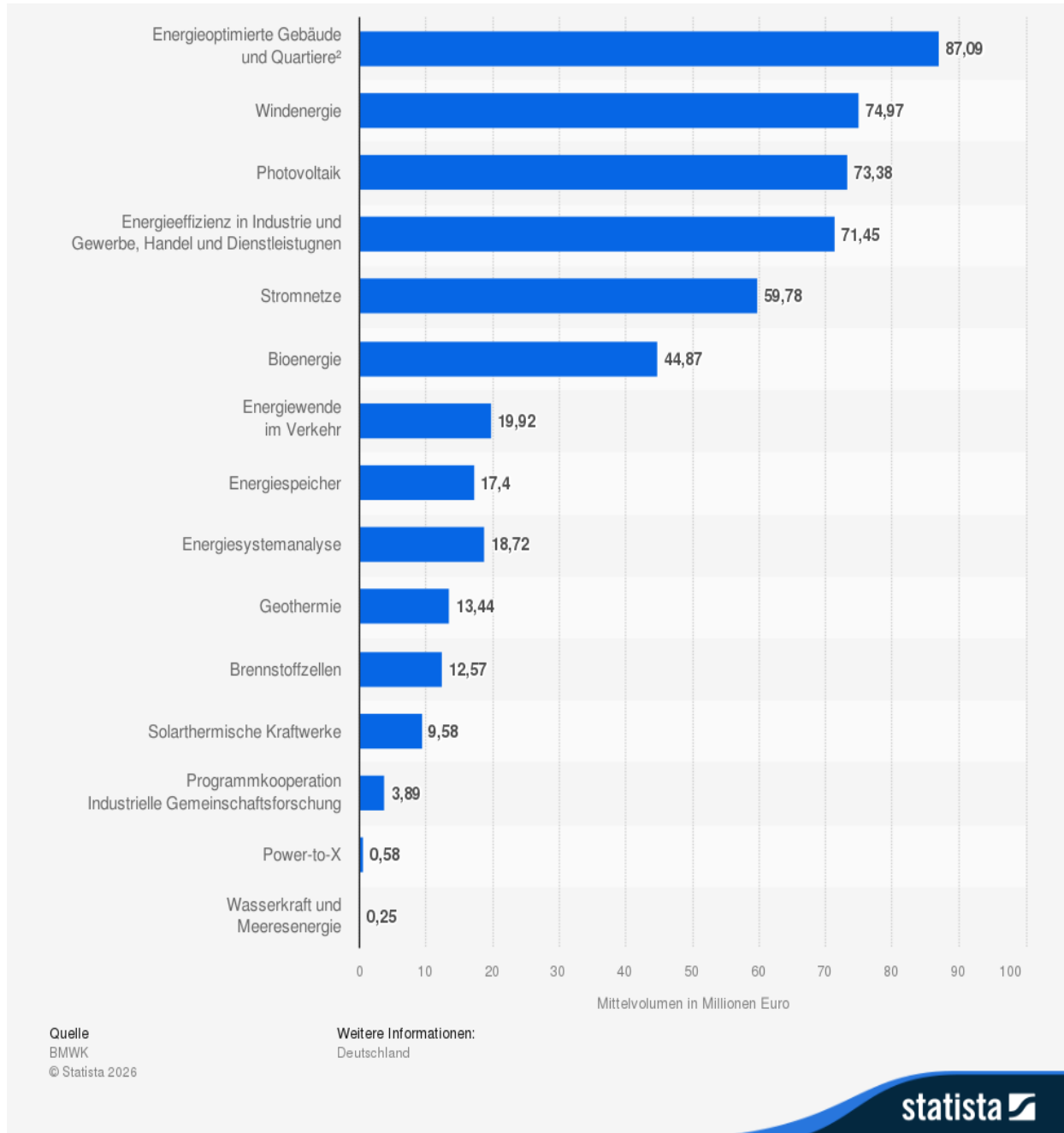
Overall, the 2023–2025 evidence confirms that Germany's transition has achieved sectoral success in electricity but remains structurally incomplete when assessed across the entire energy system. The persistence of fossil fuel dominance underscores the magnitude of the transformation challenge and highlights the necessity of targeted, sector-specific policy and financing mechanisms.

4.4 Innovation and Institutional Support

The distribution of public funding for newly approved energy transition research projects in 2023 provides important insights into Germany's strategic innovation priorities. The allocation

pattern suggests a diversified but targeted approach to supporting both mature renewable technologies and systemic transformation areas.

Figure (6): Mittelvolumen für neu bewilligte Forschungsprojekte¹ für die Energiewende nach Forschungsbereichen in Deutschland im Jahr 2023(in Millionen Euro)



Source: Source: BMWK (2024). Bundesbericht Energieforschung 2024, p. 77 ff. Federal Ministry for Economic Affairs and Climate Action. Retrieved via Statista (ID 861397): “Mittelvolumen für neu bewilligte Forschungsprojekte für die Energiewende nach Forschungsbereichen in Deutschland

im Jahr 2023.” Available at: <https://www.statista.com/statistics/861397/funding-volume-new-energy-transition-research-projects-by-area-germany/> (Accessed: 26 February 2026).

The largest funding volume was allocated to energy-optimised buildings and districts (€87.09 million), indicating a clear institutional recognition of the building sector as a critical bottleneck in decarbonisation. Given the structural inertia observed in heating and primary energy consumption, the prioritisation of building-related innovation reflects an attempt to address demand-side transformation rather than solely expanding supply-side renewable generation.

Wind energy (€74.97 million) and photovoltaic research (€73.38 million) received nearly equivalent funding levels. This allocation reinforces the central role of these technologies within Germany’s renewable electricity framework. Continued research investment in these relatively mature sectors suggests a focus on efficiency improvements, system integration, and cost reduction rather than basic technological development.

Energy efficiency in industry and commercial sectors (€71.45 million) also received substantial support, highlighting the policy emphasis on industrial decarbonisation. Since industry remains heavily dependent on fossil-based processes, innovation in efficiency and electrification technologies is essential for reducing primary energy intensity.

Funding for electricity grids (€59.78 million) further indicates recognition that renewable expansion requires parallel infrastructure adaptation. Grid modernisation, digitalisation, and smart system management are necessary to accommodate high shares of variable renewable energy.

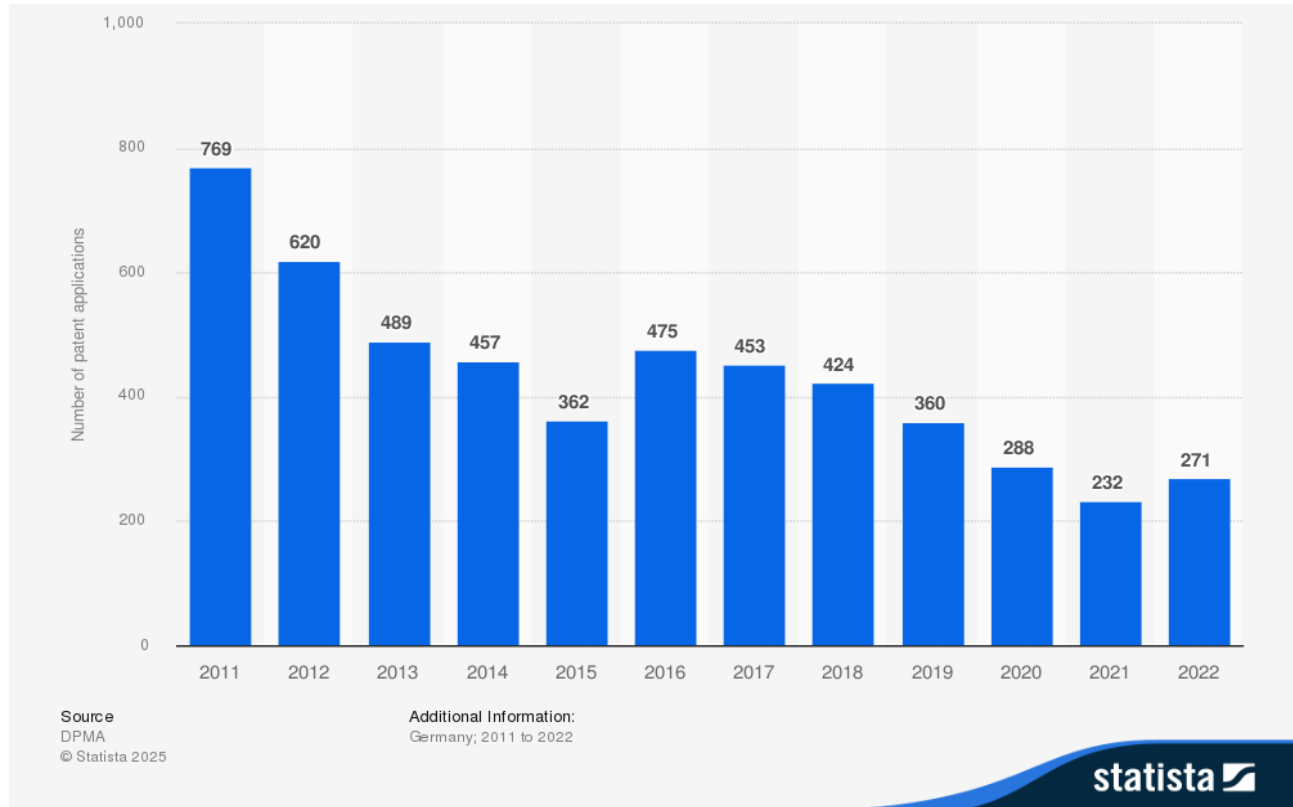
By contrast, funding for storage (€17.40 million), hydrogen-related Power-to-X technologies (€0.58 million), and fuel cells (€12.57 million) appears comparatively modest. This distribution may reflect either earlier-stage market deployment outside direct R&D programmes or a strategic concentration on near-term scalable technologies. However, given the increasing need for flexibility solutions and sector coupling, the relatively lower allocation to these areas may signal a structural imbalance between generation expansion and integration technologies.

From an institutional perspective, the data illustrate a coordinated state-led innovation strategy in which public R&D funding acts as a catalyst for technological upgrading and market readiness. Rather than concentrating exclusively on breakthrough technologies, Germany’s research funding structure combines incremental optimisation of established renewables with targeted support for system-level transformation.

When interpreted alongside the expansion of sustainable finance and renewable deployment, the 2023 R&D allocation suggests a complementary relationship between capital markets and public innovation policy. While green finance facilitates large-scale infrastructure investment, public research funding underpins technological refinement and long-term competitiveness.

Overall, the 2023 funding distribution confirms that Germany’s energy transition strategy integrates institutional innovation support with financial mobilisation. However, the relative allocation across research areas indicates that future transformation may depend increasingly on strengthening investment in storage, hydrogen, and cross-sector integration technologies to address systemic bottlenecks beyond electricity generation.

Figure (7): Number of patent applications in the field of renewable energy in Germany from 2011 to 2022



Source: DPMA (2024). Number of patent applications in the field of renewable energy in Germany from 2011 to 2022. Published by Agentur für Erneuerbare Energien; retrieved via Statista (ID 583735). Available at: <https://www.statista.com/statistics/583735/patent-applications-renewable-energy-germany/> (Accessed: 26 February 2026).

The evolution of renewable energy patent applications in Germany between 2011 and 2022 indicates a substantial decline in recorded innovation activity within the sector over the observed period. Patent applications decreased from 769 in 2011 to 271 in 2022, representing a reduction of approximately 65 per cent over eleven years. The contraction was particularly pronounced between 2011 and 2015, when applications fell from 769 to 362. Although a temporary increase occurred in 2016 (475 applications), the overall downward trajectory resumed thereafter, reaching a low point in 2021 (232 applications) before a modest recovery in 2022.

This pattern may reflect a structural transformation in Germany's renewable energy innovation dynamics. The early 2010s coincided with rapid technological development in wind and solar technologies, supported by strong feed-in tariff regimes and early-mover advantages. As these technologies matured and approached cost competitiveness, the intensity of patentable incremental

innovations may have moderated, suggesting technological consolidation rather than outright stagnation.

Another possible explanation relates to shifts in global production structures and value chains. As segments of renewable manufacturing—particularly photovoltaic production—expanded in Asian markets, domestic patent activity in Germany may have weakened even as domestic renewable deployment continued to grow. This divergence between patent output and installation capacity highlights the increasingly globalised character of renewable technology development.

The continued decline after 2018 also overlaps with regulatory adjustments and phases of market stabilisation within Germany's renewable policy framework. Periods of policy recalibration can influence private R&D investment decisions, particularly in sectors dependent on long-term regulatory certainty. While direct causality cannot be established within the scope of this analysis, the temporal coincidence warrants consideration.

The moderate recovery observed in 2022 may be associated with renewed strategic attention to energy security and accelerated climate targets at both European and national levels. However, given the limited time horizon of the rebound, it remains premature to interpret this as a sustained reversal of the longer-term trend.

From a structural perspective, the data point to a potential divergence between innovation output and deployment expansion. While renewable electricity generation increased substantially over the past decade, domestic patent activity declined. This suggests that Germany's energy transition during this period may have relied increasingly on diffusion, scaling, and optimisation of existing technologies rather than on continuous growth in patent-intensive domestic invention.

Within the broader research framework, this trend implies that sustainable finance expansion and capital mobilisation appear to be more directly associated with infrastructure deployment than with measurable increases in domestic patent output. In this context, public R&D funding assumes heightened strategic importance in sustaining long-term innovation capacity and preventing structural erosion of technological leadership.

Overall, the 2011–2022 patent trajectory suggests a transition from an innovation-intensive expansion phase to a more maturity-driven scaling phase within Germany's renewable sector. While such a shift may reflect technological stabilisation, it also underscores the importance of reinforcing next-generation innovation in storage, hydrogen systems, digital grids, and sector-coupling technologies to maintain long-term competitiveness.

V.CONCLUSION:

This study provides a comprehensive structural assessment of the evolution of green finance in Germany and its interaction with renewable energy deployment and technological innovation over the period 2001–2025. By integrating financial issuance data, energy transition indicators, and innovation metrics, the analysis contributes to the growing literature on sustainable finance by moving beyond descriptive trends toward a systemic interpretation of transition dynamics. The findings demonstrate that Germany has succeeded in institutionalizing a mature and diversified sustainable finance architecture. However, the results also reveal that financial expansion, while necessary, is not in itself sufficient to guarantee a fully balanced and innovation-driven energy transformation.

Empirically, four major insights emerge. First, Germany's green finance ecosystem has undergone structural deepening, evolving from a predominantly sovereign-driven framework into a diversified market increasingly characterized by corporate participation. The post-2020 phase marks a clear mainstreaming of sustainability within capital markets, as industrial actors-particularly from energy-intensive and automotive sectors-expanded their presence in green bond issuance.

Second, development banking has played a stabilizing yet politically sensitive role. Programmes led by KfW historically ensured continuity in energy-efficiency investments; however, the volatility observed in 2022–2023 illustrates the dependence of sustainable finance flows on regulatory coherence and fiscal alignment. This confirms that institutional credibility remains a critical determinant of investment stability.

Third, the study identifies a structural asymmetry between financial mobilization and the breadth of energy system transformation. While green capital flows strongly correlate with electricity sector decarbonization-where renewable penetration surpassed half of total generation—the transition in primary energy consumption remains uneven. Transport and heating sectors continue to exhibit structural rigidity, reflecting technological, infrastructural, and behavioral lock-ins that financial instruments alone cannot rapidly overcome.

Fourth, and most strategically significant, the analysis uncovers a divergence between deployment and domestic innovation performance. Despite accelerated renewable capacity expansion and rising sustainable finance volumes, renewable energy patent applications have declined since 2011. This pattern suggests that the German transition is currently driven more by the diffusion and scaling of mature technologies than by a renewed cycle of domestic technological invention. Such a dynamic raises important questions regarding long-term competitiveness, value-chain positioning, and technological sovereignty.

Based on these findings, several policy implications follow. Ensuring regulatory predictability and fiscal stability is essential to prevent investment discontinuities, particularly in building renovation and efficiency programmes. Financial instruments should be more explicitly designed to target hard-to-abate sectors, including transport and heating, through sector-specific bond standards and risk-sharing mechanisms. Moreover, revitalizing public support for research and development in next-generation technologies-such as advanced storage systems, hydrogen infrastructures, and smart grid digitalization-appears crucial to reconnect financial expansion with innovation renewal.

While this study offers a macro-structural perspective, future research should advance toward causal identification. Econometric analyses could assess whether green bond issuance effectively reduces firms' cost of capital or primarily functions as a reputational signaling mechanism. Comparative cross-country evaluations would further clarify the relative efficiency of national sustainable finance models. In addition, firm-level investigations are needed to determine how access to sustainable finance influences corporate R&D allocation, strategic investment decisions, and technology adoption patterns.

VI. REFERENCES:

- Ahmad, F., Boumaiza, A., Sanfilippo, A., & Al-Fagih, L. (2025). A detailed comprehensive role of digital technologies in green finance initiative for net-zero energy transition. *Advanced Energy and Sustainability Research*, 6(10), 2500066. <https://doi.org/10.1002/aesr.202500066>
- Bandna, Koundal, P., Hussain, I., Shah, M. A., & Bhalla, M. (2025). Principles and frameworks for sustainable finance: A pathway to global sustainability. In *Financial Innovation for Global Sustainability* (pp. 103–139). Wiley.
- Boyd, J. H. (2018). *Financial intermediation*.

- Devender, K., Kafila, M., & Manoharan, G. (2025). Green finance for sustaining tomorrow: Empowering environmental measures. In *Legal and Regulatory Considerations of Leveraging Sustainable Finance* (pp. 135–152). IGI Global.
- Diamond, D. W. (1984). Financial intermediation and delegated monitoring. *Review of Economic Studies*, 51(3), 393–414. <https://doi.org/10.2307/2297430>
- Dinda, S. (2004). Environmental Kuznets Curve hypothesis: A survey. *Ecological Economics*, 49(4), 431–455.
- Feil, F. D. E. F., Feijo, C., & Amorim Teixeira, F. (2025). Can BNDES finance the sustainable green transition? *Journal of Globalization and Development*, 16(2), 333–356.
- Ge, T., Cai, X., & Song, X. (2022). How does renewable energy technology innovation affect the upgrading of industrial structure? The moderating effect of green finance. *Renewable Energy*, 195, 682–695. <https://doi.org/10.1016/j.renene.2022.06.045>
- Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics*, 110(2), 353–377.
- He, L., Liu, R., Zhong, Z., Wang, D., & Xia, Y. (2019). Can green financial development promote renewable energy investment efficiency? A consideration of bank credit. *Renewable Energy*, 143, 974–984. <https://doi.org/10.1016/j.renene.2019.05.059>
- Hong, W., Luo, J., & Du, Y. (2024). Impact of green finance on hydropower investments: A perspective of environmental law. *Finance Research Letters*. <https://doi.org/10.1016/j.frl.2024.106178>
- Hossin, M. A., Alemzero, D., Abudu, H., Yin, S., Mu, L., & Panichakarn, B. (2024). Examining public–private partnership investment in energy. *Scientific Reports*, 14, 16398.
- Hou, H., Wang, Y., & Zhang, M. (2023). Green finance drives renewable energy development: Empirical evidence from 53 countries worldwide. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-023-28111-w>
- Hou, Y., et al. (2023). Green finance and renewable energy development.
- Irfan, M., Razzaq, A., Sharif, A., & Yang, X. (2022). Influence mechanism between green finance and green innovation. *Technological Forecasting and Social Change*, 182, 121882.
- Kaika, D., & Zervas, E. (2013). The environmental Kuznets curve theory. *Energy Policy*, 62, 1403–1411.
- Kijima, M., Nishide, K., & Ohyama, A. (2010). Economic models for the environmental Kuznets curve. *Journal of Economic Dynamics and Control*, 34(7), 1187–1201.
- Kuhn, B. M. (2022). Sustainable finance in Germany: Mapping discourses, stakeholders, and policy initiatives. *Journal of Sustainable Finance & Investment*. <https://doi.org/10.1080/20430795.2020.1783151>
- Lee, C.-C., & Lee, C.-C. (2022). How does green finance affect green total factor productivity? Evidence from China. *Energy Economics*, 107, 105863. <https://doi.org/10.1016/j.eneco.2022.105863>
- Li, M., Zhao, J., & Li, H. (2025). The impact of green credit policies on investment and financing behavior of renewable energy enterprises. *Polish Journal of Environmental Studies*. <https://doi.org/10.15244/pjoes/192931>
- Muhammad, S., & Hoffmann, C. (2024). From investment to impact: The role of green finance and technological innovation on German energy transition. *Renewable Energy*. <https://doi.org/10.1016/j.renene.2024.121665>
- Muhammad, S., & Hoffmann, C. (2024). From investment to impact: The role of green finance and technological innovation on German energy transition. *Renewable Energy*.
- Pata, U. K., Bulut, U., Balsalobre-Lorente, D., & Chovancová, J. (2025). Does income growth affect renewable energy first? *Energy Strategy Reviews*, 57, 101615.

- Rasoulnezhad, E., & Taghizadeh-Hesary, F. (2022). Role of green finance in improving energy efficiency and renewable energy development. *Energy Efficiency*, 15(2), 14. <https://doi.org/10.1007/s12053-022-10021-4>
- Rasoulnezhad, E., & Taghizadeh-Hesary, F. (2022). Role of green finance in improving energy efficiency. *Energy Efficiency*, 15(2), 14.
- Sarntisart, S., & Dunyo, S. K. (2025). Economic and political uncertainty and the EKC. *Global Journal of Emerging Market Economies*.
- Shafik, W. (2025). Green investment and sustainable finance. In *Value Creation and Circular Business Models*.
- Shi, X., & Shi, D. (2025). Impact of green finance on renewable energy technology innovation: Empirical evidence from China. *Sustainability*, 17(5), 2201. <https://doi.org/10.3390/su17052201>
- Shukla, R., et al. (2025). Financial strategies. In *AI Methods for Environmental Protection*.
- Simionescu, M. (2021). Revised environmental Kuznets Curve in CEE countries. *Environmental Science and Pollution Research*, 28, 60881–60899.
- Stern, D. I. (2004). The rise and fall of the Environmental Kuznets Curve. *World Development*, 32(8), 1419–1439.
- Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation. *World Development*, 24(7), 1151–1160.
- Surenthran, D. P., et al. (2024). The transformative journey of sustainable finance.
- Tachega, M. A., et al. (2021). Income heterogeneity and EKC turning points. *Sustainability*, 13(10), 5634.
- Taghizadeh-Hesary, F., & Yoshino, N. (2020). Sustainable solutions for green financing. *Energies*, 13(4), 788.
- Taher, H. (2024). Renewable energy and financial development and EKC. *Environmental Economics*, 15(2), 118–131.
- Yao, S., Zhang, S., & Zhang, X. (2019). Renewable energy and EKC perspective. *Journal of Cleaner Production*, 235, 1338–1352.
- Yu, C.-H., Wu, X., Zhang, D., Chen, S., & Zhao, J. (2021). Demand for green finance: Resolving financing constraints on green innovation in China. *Energy Policy*, 153, 112255. <https://doi.org/10.1016/j.enpol.2021.112255>
- Zhao, X., Jiang, S., & Gao, J. (2026). Spatial impacts of green finance reform pilot zones on renewable energy technology innovation: Pathways for accelerating low-altitude economic development. *Renewable Energy*. <https://doi.org/10.1016/j.renene.2025.125023>
- Zheng, M., Feng, G.-F., & Chang, C.-P. (2023). Is green finance capable of promoting renewable energy technology? Empirical investigation for 64 economies worldwide. *Oeconomia Copernicana*.
- Zia, H. M. Y., Özbay, F., Shah, S. A. R., Tekin, B., & Abbas, N. (2025). Investing in the future: Financial solutions for renewable energy and sustainable environment. *Geological Journal*. <https://doi.org/10.1002/gj.70142>