The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Comparative Policy Pathways for Energy Transition and Carbon Emissions Reduction to 2050: Evidence from Germany, China, and Saudi Arabia

Mohammad Jalili | Ziwei Zhang | Shibo Wei | Liu Yang | Yuping Wu ✉

School of Business Administration, Henan Polytechnic University, Jiaozuo 454003, China

Article Info

Article type:
Research Article

Article history:
Received: 1 December 2025
Revised: 6 January 2026
Accepted: 3 April 2026

Keywords:
Energy Transition;
Climate Policy;
Renewable Energy;
Policy Comparison;
Low-Carbon Pathways

ABSTRACT

The energy transition has become a pressing concern for governments, industries, and societies worldwide, driven by the need to address climate change. But nations approach this challenge in different ways. The examples of Germany, China, and Saudi Arabia are notable: one is a long-term leader in renewable energy, another is the world's largest energy consumer and emitter, and the third is a fossil-based economy undergoing diversification. This study examines how these three nations shape their future projections toward 2050. Our hybrid methodology, which combines scenario analysis and policy review, evaluates how each country manages the trade-offs between sustainability, affordability, and energy security. Given their significant contributions to global emissions, these pathways may also yield significant air quality co-benefits through the projected decline in fossil fuel use. The analysis identifies investment costs, technological uncertainty, and public acceptance as common barriers, while demonstrating how domestic political and economic structures lead to markedly different strategies. Although the study focuses on energy transition, the projected emission reductions also suggest co-benefits for improved air quality, especially in countries where coal or oil dominates the energy mix. Comparing these pathways highlights lessons for more effective policy design, the need for integrated instruments such as renewable subsidies and carbon pricing, and the importance of enhanced international cooperation. Overall, the research provides insights into how diverse national experiences can inform a just and sustainable energy future at the global level, with a focus on decarbonization pathways and their broader socio-economic implications.

Cite this article: Jalili, M., Zhang, Z., Wei SH., Yang, L., & Wu, Y. (2026). Comparative Policy Pathways for Energy Transition and Carbon Emissions Reduction to 2050: Evidence from Germany, China, and Saudi Arabia. *Pollution*, 12(2), 586-600.
https://doi.org/10.22059/poll.2026.407356.3219

DOI: https://doi.org/10.22059/poll.2026.407356.3219

INTRODUCTION

The transition to a low-carbon future is a key challenge of the 21st century, with countries adopting distinct strategies balancing environmental, economic, and energy security priorities. Germany, China, and Saudi Arabia exemplify different transition models shaped by their political and economic contexts. Comparing them reveals insights into technological investments, policy choices, and social adaptation toward sustainable energy by 2050. Achieving a global shift to 100% renewable energy is considered feasible, though challenges in policy coordination and infrastructure remain (Al-Shetwi et al., 2024). Decarbonization in Korea depends on heavy industries adopting electrification, hydrogen, bioenergy, and CCS, yet limited access to these technologies constrains progress (Lee et al., 2024). For China to reach carbon neutrality by 2060, an 80% reduction in energy emissions is required, driven by wind, solar, and CCS, with early action lowering costs (Qi et al., 2023). A comparison between Nepal and Singapore underscores the need for strong policy frameworks and regional cooperation to meet net-zero

*Corresponding Author Email: *wyp79055@hpu.edu.cn*

goals (Shah et al., 2024). In China, barriers to green construction include policy coordination, resource availability, and public engagement (Liu et al., 2025). Emissions trading has proven more effective than carbon taxes in promoting renewables, although both reduce fossil fuel use (Xu & Yang, 2024). Climate transition risks in Europe vary by sector, with policy uncertainty affecting markets (Olasehinde-Williams & Akadiri, 2025). An inclusive local discourse is essential for Germany's energy transition (Bugger & Henry, 2021). Successful low-carbon heating transitions in Europe depend on governance, public ownership, and finance (Salite et al., 2024). The global transition to low-carbon energy is central to policy agendas; however, pathways vary depending on governance, resources, and investment. Comparative studies between different transition models, such as Germany (a renewable leader), China (a carbon-intensive economy), and Saudi Arabia (a hydrocarbon-dependent economy), remain limited, hindering our understanding of how institutions and resources shape transitions. This study compares their energy pathways to 2050, focusing on renewables, emissions, and investments using three scenarios: Business-as-Usual, Moderate Transition, and Net-Zero. A hybrid framework links emissions outcomes to policy credibility and financial capacity, highlighting trade-offs between sustainability, affordability, and energy security. Results highlight the impact of governance and fossil fuel dependence on transition performance, providing policy guidance for context-sensitive net-zero strategies. Recent literature highlights policy and institutional factors. Binding renewable energy targets have been shown to significantly reduce emissions, in contrast to non-binding plans (Gao et al., 2025). Germany's bioeconomy policies are increasingly integrating environmental objectives (Gottinger & Proestou, 2025). Achieving a fully renewable energy system in Bolivia by 2050 is considered possible with solar PV and supportive policies (Lopez et al., 2021). Job growth in Europe's renewable sector is projected alongside losses in fossil-fuel-dependent regions (Emmerling et al., 2025). In Norway, non-financial barriers often limit household energy retrofits (Seljom et al., 2018). While societal drivers are crucial for achieving net-zero, risks include rising inequality and an overreliance on negative emissions technologies (Wiseman, 2018). Norway's continued reliance on fossil fuels and blue hydrogen could delay its alignment with EU climate goals (Cheng, 2023). India's path to net-zero has the potential to increase welfare and create jobs if supported by equitable policies (Kaze et al., 2025). A comparison of governance models in China suggests a hybrid approach offers the best balance of flexibility and security (Yang & Feng, 2026). Coordinated policies and a focus on renewables are emphasized as critical for achieving climate neutrality in Europe (Barani et al., 2026); Bogdanov et al., 2025). Tensions exist in Global South hydrogen transitions, particularly between export-oriented strategies and local development needs (Dietz et al., 2025; Angulo-Morales et al., 2025). At the urban scale, participatory governance in Kyoto has successfully enabled low-carbon lifestyles (Xu et al., 2026). Technology-focused studies highlight the importance of early action, comprehensive policy mixes, and widespread electrification (Simoes et al., 2017; Axsen et al., 2022; Morrison et al., 2015). Many have studied sustainability parameters (Mashaal et al., 2025; Abdelzaher et al., 2024; Jalili et al., 2025; Owaid et al., 2023; Abdelzaher et al., 2024; Jalili et al., 2024; Abdelzaher et al., 2022; Abbas et al., 2021). Gaps remain: few studies compare fundamentally different archetypes (e.g., Germany, China, Saudi Arabia); integrated frameworks combining quantitative and qualitative analysis are rare; harmonized cross-country scenarios (e.g., Business-as-Usual, Moderate Transition, Net-Zero) are limited; and policy consistency and governance roles are understudied. This paper addresses these by applying a hybrid framework and harmonized scenarios to systematically compare their 2050 pathways.

MATERIAL & METHODS

The study uses a mixed-methods research design that combines quantitative indicators of energy with qualitative analysis of policy to evaluate the energy transition pathways of Germany, China, and Saudi Arabia by 2050. The research design, case selection, data sources, analytical framework, scenario development, and limitations are the components of the methodology.

The study uses a comparative case study research methodology, with a scenario analysis. Quantitative analysis examines the shares of renewable energy, CO_2 emissions, and the trend of investment. Qualitative analysis examines domestic policies and plans that align with international commitments. Tables and charts are used to present the most important quantitative indicators used in this research.

The three chosen countries, Germany, China, and Saudi Arabia, are purposefully antithetical to one another in the world energy-transition landscape, and a combination of them provides a unique comparative value. Germany is one of the leading countries in the field of renewable energy application, thanks to the efforts of responsible institutions and the high level of acceptance among the population. China, in turn, is the world's largest energy user and CO2 emitter, the scale and power of its industries and investments making the global transition process significant. The case of Saudi Arabia is fundamentally different: this is a fossil-based economy in the process of rapid but structurally difficult diversification with Vision 2030. Although the justification for their choice is raised in the Introduction, Literature Review, and Case Selection sections, it is convenient to gather it here to explain the strategic reasoning behind this tri-country design. Collectively, these cases represent three different models of transition of a mature renewable leader, an industrial megalemitter, and a hydrocarbon-based economy in transition, in which a harmonized comparison is uncommon and seldom discussed in previous studies. Their strong contrasts help distinguish the policy stability, governance frameworks, investment potential, and dependence on resources as a set of factors that influence the decarbonization outcomes. In line with this, these three countries were not chosen randomly but rather selected in a way that provides a great deal of explanatory depth to the study and also enhances the comparative validity of the research.

The IEA, IRENA, the World Bank, and the BP Statistical Review serve as authoritative sources of quantitative data. These datasets include indicators such as the energy mix, installed renewable capacity, CO_2 emissions, and annual energy investment. Qualitative information is drawn from national strategic documents, including Germany's Climate Action Plan 2050, China's 14th Five-Year Plan, and Saudi Arabia's Vision 2030. The baseline values for 2020 and the indicative projections for 2030 and 2050 are derived from harmonized datasets of the IEA, IRENA, the World Bank, and the BP Statistical Review. For future years, the numerical values do not represent direct predictions from these agencies but are synthesized from their long-term outlooks and adjusted using the simplified emissions identity and logistic renewable-growth model described in Section 3.4. Where minor discrepancies existed between sources (e.g., IEA vs. IRENA capacity figures), we prioritized the more conservative estimate and applied consistent interpolation rules to ensure a harmonized baseline for 2020, which served as the anchor for scenario projections.

The framework combines both quantitative and qualitative estimates. The countries are rated on three levels: effectiveness in reducing emissions; feasibility (including economic, technological, and social impacts of emissions); and a simplified model. This aggregated, national-level approach is a deliberate choice to enable a high-level comparison across fundamentally different economies, though it necessarily masks important sectoral dynamics, such as the varied pace of coal phase-out across Chinese industries.

$$\sum_i EF_{i,t} \times A_{i,t} = E_t \quad (1)$$

Where:

- E_t = total emissions in year t
- $A_{i,t}$ = activity level of sector i in year t (e.g., energy consumption)
- $EF_{i,t}$ = emission factor of sector i in year t
- $\sum_i$ = summation across all sectors

$$\frac{K}{e^{-b(t-t_0)}+1} = R_t \tag{2}$$

Where:

- R_t = share or capacity of renewables at time t
- K = carrying capacity (maximum potential level)
- b = growth rate
- t_0 = inflection point (the time at which growth is fastest)
- e = mathematical constant (Euler's number)

These two equations in this section are simplified analytical tools that form the basis of the scenario projections further developed in the study. Directional changes in national CO_2 trajectories are estimated using the emissions identity (Equation 1), which associates aggregate activity levels with national emission factors. Although the research does not model the sectors individually, national-level 2020, 2030, and 2050 baselines from the IEA and the World Bank were applied to estimate the general changes in emissions based on the three assumptions of the scenarios. Whether decreases in activity levels or factors of emissions in the Net-Zero scenario constitute policy-driven mitigation, including efficiency gains, electrification, and the phase-down of fossil fuels. Conceptually, the logistic growth function (Equation 2) is used to form the trajectories of renewable energy in the BAU, Moderate, and Net-Zero paths. The logistic model is well-suited for modeling renewable-energy pathways as it captures the combined effects of technological learning, infrastructure limits, market adoption, and policy support, unlike linear or exponential models that either overestimate growth or imply endless expansion. Its S-shaped curve reflects the saturation effect critical to long-term energy transitions and aligns with innovation diffusion theory, IEA/IRENA integration studies, and historical growth patterns in markets like Germany and China. Parameters were systematically calibrated: carrying capacity (K) based on IEA/IRENA system-integration limits (~100% in Germany, 80–85% in China, 60–70% in Saudi Arabia); growth rate (b) fitted to historical deployment data (2010–2022) from the BP Statistical Review; and inflection point (t_0) set according to policy-driven acceleration timelines under each scenario (BAU, Moderate, Net-Zero). While not designed for precise prediction, this parameterization ensures scenarios reflect empirical trends and accepted potential ranges. The study employs a reduced-form quantitative approach rather than complex energy-system models like IAMs or TIMES to ensure cross-country comparability through harmonized assumptions, allowing quantitative analysis to complement, not overshadow, the core comparative policy analysis.

The quantitative indicators employed in the current research were constructed in a manner that allows for a consistent comparison of energy transition pathways in Germany, China, and Saudi Arabia. Data from the IEA, IRENA, World Bank, and BP were used to derive harmonized national baselines for 2020 and projected values for 2030 and 2050. The emissions formula linked activity data to emission factors, while renewable energy shares were modeled with a logistic growth curve. Investment indicators were based on historical spending and future plans from national strategies. All indicators were standardized (0-1 scale) for cross-country comparison. Equal weight was given to emissions, investment, and policy consistency to

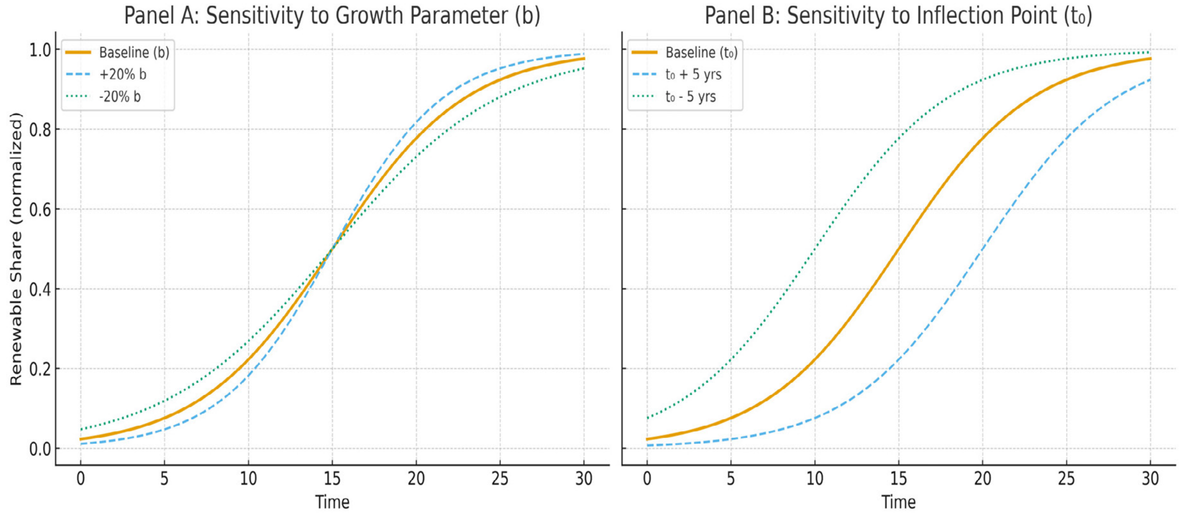

Fig. 1. Two-panel sensitivity analysis of the logistic renewable-energy growth function: Panel A shows the effect of ±20% changes in the growth parameter (b), while Panel B illustrates the impact of shifting the inflection point (t_0) by ±5 years.

Table 1. Policy Consistency Scoring Criteria (0–1 Scale)

Criterion	Description	Scoring Method (0–1)
Long-term policy stability	Existence of stable multi-year energy or climate strategies	0 = absent; 1 = fully present; 0.5 = partially present
Institutional coherence	Alignment between ministries, regulatory bodies, and national plans	0 = fragmented; 1 = coherent; 0.5 = mixed
Implementation record	Historical follow-through on energy targets	0 = weak; 1 = strong; 0.5 = moderate
Policy instruments	Presence of carbon pricing, subsidies, mandates, or regulatory tools	Scaled by count and strength (0–1)
Public acceptance & governance quality	Social support and transparency in decision-making	0 = low; 1 = high; 0.5 = medium

avoid bias. A sensitivity test adjusted the logistic function's growth rate (±20%) and adoption timing (±5 years). These changes affected early and mid-term trajectory levels but did not alter the overall curve shapes or country rankings. Germany is consistently the most adoptive of renewable energy, China ranks in between, and Saudi Arabia ranks as the lowest among all the variants that have been tested. These are summarized by the two-panel figure sensitivity (Figure 1). Panel A shows the influence of the growth parameter (b) change, and Panel B shows the influence of the inflection point (t 0) change. All these tests prove that the main findings of the comparative assessment are structurally sound and that they are not extremely sensitive to plausible changes in parameter assumptions.

To measure policy consistency across three countries, a simple and clear scoring system was developed based on five equally weighted indicators commonly used in comparative evaluations of energy policy: long-term political stability of policy, institutional consistency, track record of implementation, policymaking power, and popular appeal. All the criteria were rated on a normalized 0-1 scale, where 0 indicated no or very weak option, 1 indicated full or strong option, and 0.5 indicated partial alignment. The overall policy-consistency score of every nation will be the arithmetic mean of the five sub-indicators. Scores were assigned based on a review of primary policy documents (e.g., Climate Action Plan 2050, 14th Five-Year Plan, Vision 2030), secondary academic analyses, and major policy announcements from 2015-2023. A score of 1 indicates full alignment with the criterion, 0.5 indicates partial or inconsistent alignment, and 0 indicates the criterion is largely unmet. It is methodologically simple and reproducible as it enables heterogeneous political systems to be compared on a harmonized metric (Table

1). To ensure consistency, the scoring was conducted independently by two researchers. The initial inter-rater agreement was 85%, and the remaining discrepancies were resolved through discussion and consensus, with reference to the criteria definitions.

Three scenarios are developed:1. Business-as-Usual (BAU): continuation of current trends.

2. Moderate Transition: partial implementation of stronger policies.

3. Net-Zero Pathway: full-scale decarbonization with aggressive investment and carbon pricing.

The 'Moderate Transition' scenario assumes a continuation and moderate strengthening of current policy instruments (e.g., a 50% increase in renewable subsidies from 2020 levels, a carbon price of 50 \$/t CO_2 by 2030). In contrast, the 'Net-Zero Pathway' is characterized by aggressive, sustained intervention (e.g., a tripling of renewable subsidies, a carbon price rising to 150 \$/t CO_2 by 2050, and stringent sectoral mandates for electrification and efficiency). The quantitative indicators supporting these scenarios are presented in three tables. Table 2 summarizes the projected share of renewables in the energy mix for Germany, China, and Saudi Arabia for 2020, 2030, and 2050 (Figure 2). Table 3 presents CO_2 emissions trajectories for the three countries, illustrating the scale of reductions under different pathways. Table 4 reports the annual investment levels required to sustain renewable energy growth. It is important to note that the numerical values assigned to each scenario represent internally consistent estimations

Table 2. Renewable Energy Share (%)

Year	Germany (%)	China (%)	Saudi Arabia (%)
2020	45	15	1
2030	65	30	15
2050	95	70	50

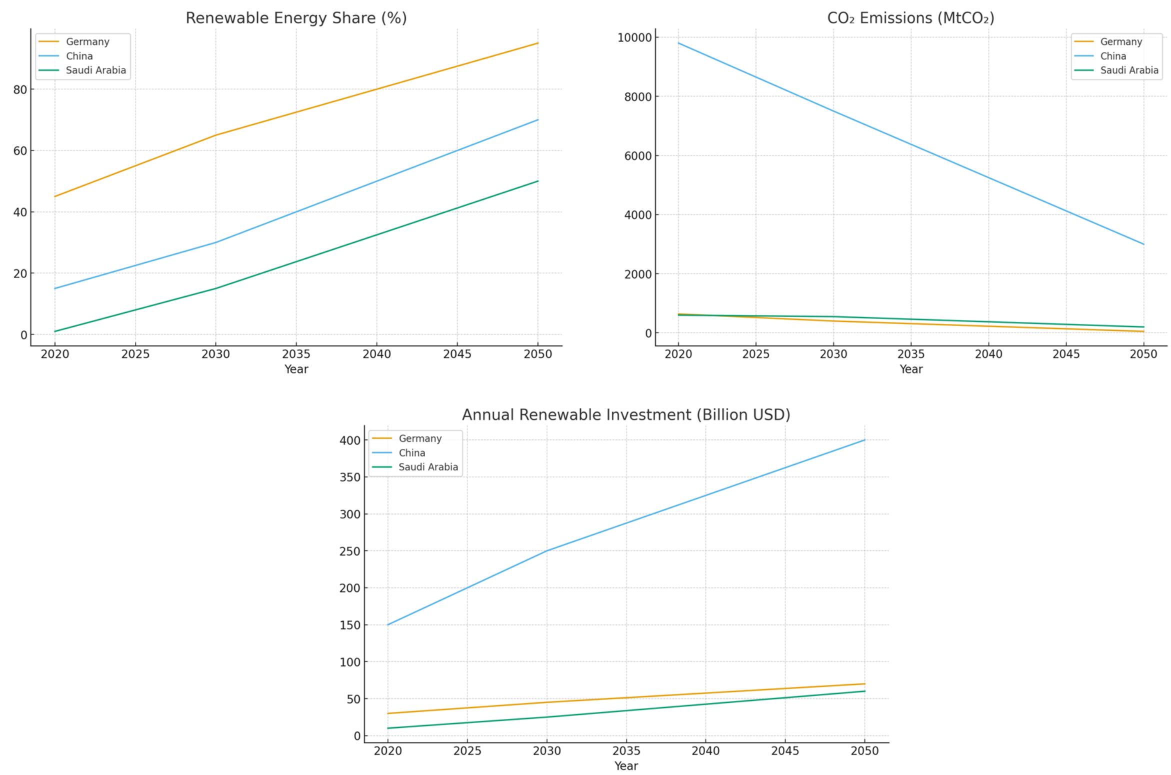

Fig. 2. Projected Renewable Energy, Projected CO_2 Emissions and Annual Renewable Energy Investment in Germany, China, and Saudi Arabia (2020–2050)

Table 3. CO_2 Emissions ($MtCO_2$)

Year	Germany ($MtCO_2$)	China ($MtCO_2$)	Saudi Arabia ($MtCO_2$)
2020	640	9,800	600
2030	400	7,500	550
2050	50	3,000	200

Table 4. Annual Investment in Renewables (Billion USD)

Year	Germany (Billion USD)	China (Billion USD)	Saudi Arabia (Billion USD)
2020	30	150	10
2030	45	250	25
2050	70	400	60

based on harmonized assumptions, rather than precise forecasts. The purpose is to enable cross-country comparability under a unified scenario logic, not to project exact national outcomes.

The analytical procedure in this research is a multi-stage, structured workflow used to incorporate quantitative markers alongside the qualitative policy appraisal of the three nations in the case study. There are four consecutive elements of the workflow.

The study evaluates national transition performance across three core dimensions:
(a) emissions reduction trajectory,
(b) renewable-energy investment requirements, and
(c) policy consistency and institutional stability.
These dimensions capture the interaction between technical, economic, and governance factors that shape the feasibility and speed of the transition.

All the indicators, including emissions (MtCO2), renewable investment (USD billion), and policy stability (qualitative consistency scores based on national plans), were placed on a 0-1 scale to allow cross-country comparison. The three dimensions have been weighted equally, and they represent the assumption that decarbonization results are the outcome of parallel and reinforcing drivers. Sensitivity tests were conducted to ensure that comparative rankings were not significantly varied by alternative weighting schemes. Equal weighting was applied since the reduction of emissions, investment in renewable energy, and consistency in policy are equally important pillars of the energy transition. Prioritizing any of these dimensions over the others would introduce a bias of normativity to a cross-country comparative framework. Bringing the indicators to a 0-1 scale also helps ensure that the indicators are proportionate, thereby avoiding scale-related distortions in the comparative evaluation.

Scenario Construction Method

Three 2050 Business-as-Usual (BAU), Moderate Transition, and Net Zero harmonized scenarios were constructed via a hybrid that sought to combine historical extrapolation of trends (in terms of emissions and investment), a combination of expert-judgment assumptions (policy ambition, sectoral prioritization), as well as simplified model-based projections guided by the logistic renewable-growth equation. The BAU prolongs existing paths; the Moderate presupposes partial reinforcement of policies; and Net Zero presupposes aggressive adherence to national carbon-neutrality commitments. To accommodate inherent uncertainties, our scenario design is complemented by a structured sensitivity analysis on key growth parameters, ensuring our comparative findings are robust across a plausible range of assumptions.

Model Limitations and Assumptions

There are a number of limitations that should be realized. To begin with, the results of scenarios are

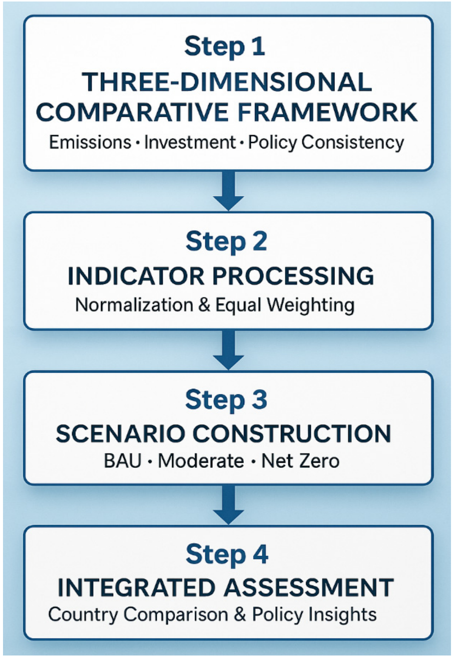

Fig. 3. Methodological Workflow of the Comparative Energy-Transition Analysis

not predictive but rather illustrative; they portray directionality rather than specific predictions. Second, policy-consistency scores are based on publicly available strategic documents, which may not accurately reflect all internal government processes. Third, lower data transparency and shorter historical time series for Saudi Arabia introduce greater uncertainty into its long-term projections. Consequently, its 2050 scenario values should be viewed as more illustrative of a strategic diversification pathway than as a firm forecast. Lastly, the simplified logistic and emissions equations are not replacements for integrated assessment models, but rather are used as transparent and comparable to cross-country analyses. This process provides a logical framework through which quantitative outcomes are connected to policy interpretation, facilitating a uniform comparative evaluation based on Germany, China, and Saudi Arabia. The general analysis procedure applied in this research is outlined in Figure 3, which demonstrates the chronologically structured workflow of the comparative framework, from indicator processing to scenario building and ultimate integrated evaluation.

The scenario projections (Tables 2-4) are best understood as central illustrations within a range of plausible outcomes; they do not include formal confidence intervals, reflecting the high uncertainty inherent in long-term socio-technical pathways. Furthermore, the simplified model primarily serves as a harmonized tool for comparing the direction and relative scale of transitions across countries, rather than as a predictive energy-system model. The scenarios are thus best seen as internally consistent illustrations of potential pathways. The sensitivity analysis shows the model's core findings are robust. Even with significant parameter changes, the relative performance of countries and the overall scenario trends stay consistent, confirming the reliability of the comparative insights. However, the methodology has inherent limitations. Data harmonization from multiple sources required simplifications, and data quality varies between countries, affecting granularity. The model's simplified framework captures broad trends but not the complex details of full energy systems. While transparent, the policy scoring involves some subjectivity and cannot capture all political nuances. Finally, the standardized scenarios are designed for comparison and thus cannot account for every nation-specific constraint. These factors mean the scenarios should be seen as illustrative, not predictive, but

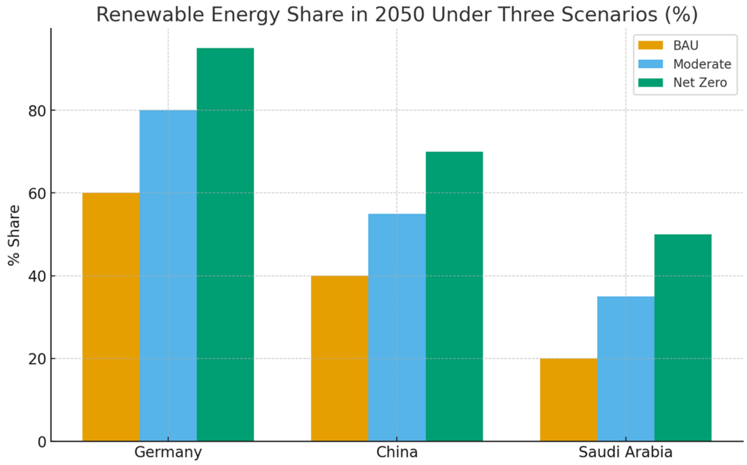

Fig. 4. Renewable energy shares in 2050 across BAU, Moderate, and Net Zero scenarios for Germany, China, and Saudi Arabia.

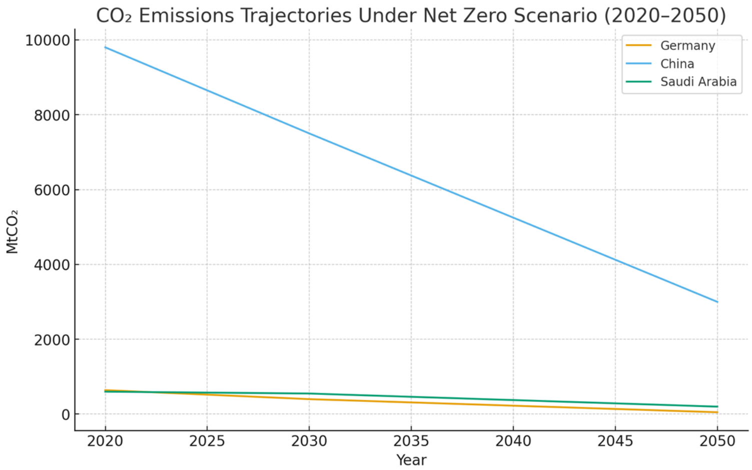

Fig. 5. Emission trajectories under the Net Zero scenario (2020–2050) for Germany, China, and Saudi Arabia.

they do not invalidate the comparative analysis.

RESULTS AND DISCUSSION

Figure 6 illustrates the estimated 2050 share of renewable energy for Germany, China, and Saudi Arabia in three harmonized transition scenarios: Business-as-Usual (BAU), Moderate Transition, and Net-Zero. The findings indicate that there is apparent cross-country and cross-situational divergence. Renewable penetration is low under BAU conditions, especially in Saudi Arabia, due to structural and policy limitations. In the Moderate Transition scenario, the three countries have larger shares of renewable energy, but there are differences in the scale of improvement. The most significant change is shown in the Net-Zero scenario, where Germany is close to full decarbonization (95%), China has a high rate of renewable deployment (70%), and Saudi Arabia experiences significant growth based on a low starting point (50%). It is through such a comparison that the direct impact of policy ambition on the magnitude and rate of renewable energy adoption in various national settings is revealed.

Figure 5 illustrates the CO2 emission trends of Germany, China, and Saudi Arabia between 2020 and 2050 under the Net-Zero scenario. The three nations have very different decarbonization strategies that are based on their structural and institutional settings. The sharpest drop is

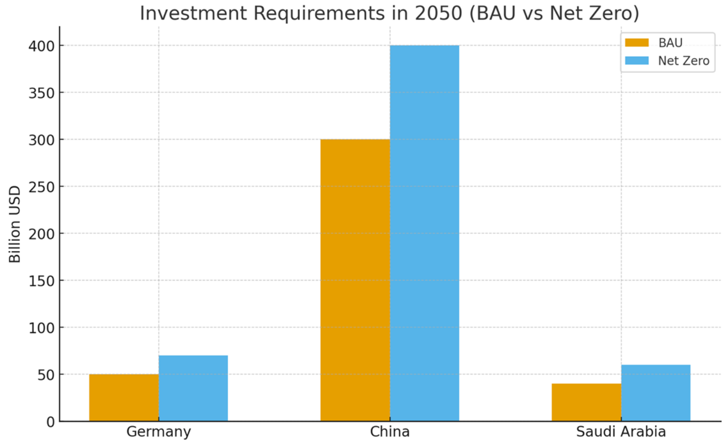

Fig. 6. Investment requirements in 2050 under BAU vs Net Zero scenarios for Germany, China, and Saudi Arabia.

Table 5. Comparative Policy and Performance Characteristics of Germany, China, and Saudi Arabia

Dimension	Germany	China	Saudi Arabia
Policy Consistency	Very high; long-term Energiewende, stable targets, strong social acceptance	High but state-centric; strong targets but flexible coal policy	Moderate; Vision 2030 provides direction but institutional stability is evolving
Governance Model	Democratic, decentralized but coordinated EU framework	Centralized state-led governance; rapid implementation capacity	Monarchical, centralized; strong top-down directives
Renewable Energy Strategy	Rapid expansion, grid integration, sector coupling	Massive investment scale, domestic manufacturing, export of technology	Diversification through solar mega-projects, green hydrogen plans
Investment Level (2050)	70 bn USD (Net Zero)	400 bn USD (Net Zero)	60 bn USD (Net Zero)
RE Share in 2050	95%	70%	50%
Emissions Reduction (2020–2050)	–92%	–69%	–67%
Key Barriers	Grid congestion, social resistance to infrastructure	Coal lock-in, energy security constraints	Oil-dependency, subsidies, low diversification

observed in Germany, where 640 $MtCO_2$ in 2020 will decrease to approximately 50 $MtCO_2$ in 2050, which means that the emissions of fossil fuels will be virtually phased out. China starts at a considerably high point (9,800 $MtCO_2$ in 2020), yet also ends up making a substantial decrease to about 3,000 $MtCO_2$ by the middle of the century, in line with its long-term carbon neutrality policy. Saudi Arabia shows a slower reduction of 600 $MtCO_2$ to approximately 200 $MtCO_2$ to indicate the challenges that continued to bog down the progress of hydrocarbon-based economies to deep decarbonization. Generally, the figure demonstrates that variations in economic framework, energy regime, and policy zeal determine the intensity and rate of emission cuts in the three nations.

Figure 6 illustrates the investment needs in Germany, China, and Saudi Arabia in 2050 under two scenarios: Business-as-Usual (BAU) and Net Zero. The findings indicate that the Net Zero target entails much more capital pledges in all three countries, but to a different degree. Germany's required investment rises from $50 billion (BAU) to $70 billion for a Net Zero pathway, reflecting the higher cost of a full system overhaul. In absolute terms, China experiences the largest increase, from $300 to $400 billion, consistent with its scale as the world's leading clean energy investor and the massive spending required to transition away

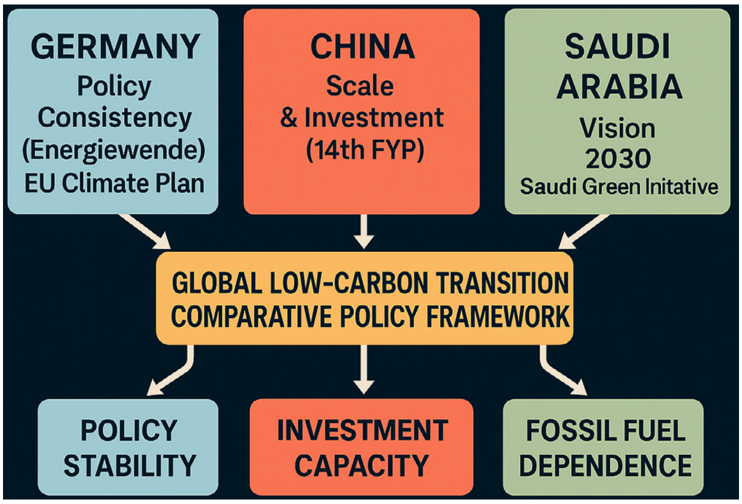

Fig. 7. Conceptual Policy Framework for the Energy Transition

from coal. Saudi Arabia shows the steepest relative jump, needing $40–60 billion to diversify its fossil-dependent economy. Overall, the Net Zero path demands substantially more funding, especially in China and Saudi Arabia, underscoring the crucial role of international finance and coordinated policy support.

Table 5 presents a comparative tabular summary of the key policy, economic, and technical aspects influencing the energy transition paths of Germany, China, and Saudi Arabia. The table illustrates the differences in policy consistency, forms of governance, investment capacity, renewable energy strategies, and structural constraints in relation to one another, allowing for the identification of specific outcomes of transition. The comparative map brings out some essential trends. Germany stands out for its long-term policy stability and high institutional coherence, which support rapid integration of renewable energy and deep emissions reductions. China's transition is primarily driven by large-scale state investment and industrial capacity, though structural dependence on coal slows its full decarbonization. Saudi Arabia, in contrast, exhibits strong strategic ambition but faces systemic challenges associated with hydrocarbon dependence and the early stages of institutional diversification. Overall, the table synthesizes these cross-country differences into a clear analytical framework, enabling a direct assessment of how policy choices and structural conditions shape renewable penetration, investment requirements, and emissions trajectories across the three national contexts.

DISCUSSION

The results suggest that Germany, China, and Saudi Arabia are very dissimilar in the transition process, as they possess disparate political environments, economic structures, and energy system histories. To synthesize the key drivers and outcomes of these divergent pathways, a conceptual framework is presented in Figure 7. This figure maps the distinct energy pathways of Germany, China, and Saudi Arabia. Each is driven by a unique national factor: Germany's strong policy consistency, China's massive state-led scale, and Saudi Arabia's push to diversify away from oil. These factors are analyzed through three mediating pillars: policy stability, investment capacity, and fossil fuel dependence. Ultimately, despite different starting points, all three show a clear, long-term shift toward renewable energy. This convergence underscores that global decarbonization is an expanding and irreversible trend.

Emission tracks also bring out structural differences in the three cases. The steep decline in Germany's emissions from 640 $MtCO_2$ in 2020 to around 50 $MtCO_2$ in 2050 demonstrates that developed economies with resourceful institutions can achieve almost full decarbonization. The reduction of China, which remains a huge emitter in the world, is estimated at a two-thirds reduction by 2050, which has dire climatic impacts on the rest of the world due to its size. The slow pace of the recent decline in the Saudi Arabian economy reflects the systemic constraints characteristic of fossil exporters, including domestic energy subsidies, excessive dependence on oil revenues in their fiscal strategies, and the immaturity of other sectors. All this means that the development of the global climate is not only pegged on the early adopters of global warming, like Germany, but it also depends on how the other major producers (China) of global warming and the resource-based economies (Saudi Arabia) can restructure their systems.

The forces and constraints of the transition process are reflected in the trends of investments. High and stable rates of investment in China attest to the fact that the country is a largest investor in the world in clean energy, and the external effects may involve the transfer of technology and saving of costs. The growth of investment in Germany is less institutionalized, and this means that it has a mature system whereby financial resources are directed towards optimization rather than growth. Saudi Arabia has emerged as a significant player in a short time due a its great strategic ambition, but it is also something to be concerned about in terms of its long-term financial sustainability, considering the extent of diversification that needs to be beachievede. The comparison underlines that in reaching Net Zero, it will take much more mobilization of capital than Business-as-Usual will and more so in China and Saudi Arabia. It refers to the need for international financing instruments, including green bonds, blended finance, and climate-related state-corporate partnerships. Furthermore, recent geopolitical tensions underscore how energy security concerns can accelerate policy shifts toward domestic renewables and efficiency, a factor that could make ambitious transition scenarios more politically viable.

This comparison of Germany, China, and Saudi Arabia explains the divergence in their energy transition pathways. Germany's success underscores the critical role of long-term, stable, and socially legitimized policy in creating an institutional environment where renewables can systematically replace fossil fuels. In contrast, China demonstrates the dual nature of scale. Its massive state-led investment and industrial capacity accelerate renewable adoption and drive down global technology costs. Yet, this very scale also reinforces structural lock-in through coal-dependent infrastructure and state-owned enterprises, ultimately slowing its full decarbonization.

Saudi Arabia's case highlights the constraints faced by late-moving, resource-intensive economies. Despite ambitious investments in solar, its progress is limited by deep-rooted hydrocarbon dependence, energy subsidies, and underdeveloped alternative industries. Theoretically, these variations align with socio-technical transition frameworks. Germany shows alignment between policy, innovation, and system change. China exhibits strong niche growth but persistent regime lock-in. Saudi Arabia represents a system where global pressures for change are still constrained by a dominant fossil fuel regime. Ultimately, there is no universal path to a low-carbon future. Each country's transition is shaped by a unique interplay of governance quality, investment capacity, and structural dependencies. Effective strategies must therefore be context-specific, though interconnected through global technology markets and shared lessons. This comparative analysis provides a unified framework to understand these diverse pathways under consistent scenarios, filling a gap between isolated country studies and broad theoretical models.

CONCLUSION

This study also analyzed the energy-transition processes in Germany, China, and Saudi Arabia using a hybrid analysis tool that combined both quantitative indicators and policy-based analysis. The results indicate that both nations have their own path to take based on their political economy, institutional stability, and resource endowments. Germany is pursuing a course that represents the aggregate effect of a long-term policy consistency and popular favor, which allows it to be almost decarbonized by 2050. China portrays the revolutionary nature of massive state investment and indigenous ability, even when its continuing structural reliance on coal restricts the intensity of the emissions reduction. This apparent duality stems from the state's parallel objectives: ensuring immediate energy security and industrial output through its domestic coal fleet, while strategically investing to dominate future global clean energy markets. The lock-in is thus less a technical barrier and more an institutional one, embedded in the political economy of state-owned enterprises and regional development goals. The development of Saudi Arabia highlights the opportunities and limitations of fossil-based economies: the diversification process is accelerating the adoption of renewables, but the hydrocarbon-based climate still poses a threat to Saudi Arabia's long-term transformation. Comparatively, the findings highlight that no one-size-fits-all model can be used to achieve a low-carbon future. Rather, the interaction of quality of governance, investment capacity, and readiness of the technique determines transition outcomes. Germany is a great example of how much stability in the policy and carbon-pricing mechanisms can help; China is a great example of how differently big the industry becomes and how technology spreads across the world, and Saudi Arabia is a great example of how much national strategies should be coupled with structural reforms and international financial aid.

The comparative findings bring out a number of lessons to policymakers that are quite concrete. To begin with, the German case reminds us of the importance of consistency in policies and long-range planning. Tools like stable feed-in tariffs, carbon pricing, and inclusion in EU climate systems have been the means of predictability to the investor and faster decarbonization. On the part of emerging economies, this implies that the credibility of institutions is equivalent to technological advances. Second, the path of China can illustrate the strength of massive investment in government, on a large scale, in developing clean energy markets worldwide. Its ability to move finance and industrial strength has lowered expenses all over the globe and created technology spillovers. Nevertheless, coal still remains a part of the Chinese energy system, indicating that investment cannot work without similar efforts to retire fossil infrastructure. Third, Saudi Arabia provides an example of the problems as well as prospects of hydrocarbon-related economies. The high-target renewable plans and measures represent a strategic shift, but sustaining the pace will require structural changes, and the diversification of this sector extends beyond the energy sector, as well as the availability of international climate financing. For other fossil fuel exporters, this case underscores the importance of aligning domestic reforms with the global response in the energy market. Lastly, the results taken together underscore the fact that global development is not only reliant on the leaders of this process, such as Germany, but also on powerhouses like China and fossil fuel producers like Saudi Arabia. To prevent the disintegration of transitions, the mechanisms of international cooperation, financial support, and technology transfer will be necessary.

In the future, research indicates that it is imperative for the world to coordinate more effectively in response to improve the rate at which it invests in renewable technologies and supports fossil-dependent economies, ensuring that disparities in decarbonization are not exacerbated. Future studies should expand the comparative structure to include other nations, conduct sector-level analyses, and assess sensitivity to geopolitical, technological, and market uncertainties. In general, the results affirm that global restructuring towards net-zero is necessary and can be successful, but its success will rely on raising awareness and embracing the differentiated capacities and constraints that define national pathways.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Research Center of Energy Economics at Henan Polytechnic University for providing a supportive and conducive research environment that made this work possible.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Abdelzaher, M. A., Farghali, A. A., & Hamouda, A. S. (2024). Effective impact of nano-plastic-waste incorporated with nanotitina on the physical, mechanical and microstructural properties of white cement pastes composites for progressing towards sustainability. *Scientific Reports, 14*(1), 12581.
Abdelzaher, M. A., Farghali, A. A., & Hamouda, A. S. (2024). Effective impact of nano-plastic-waste incorporated with nanotitina on the physical, mechanical and microstructural properties of white cement pastes composites for progressing towards sustainability. *Scientific Reports, 14*(1), 12581.
Abdelzaher, Mohamed Abuelseoud, Asmaa Sayed Hamouda, Ibrahim Mohamed El-Kattan, and Ahmed Baher. "Laboratory study for accelerating the CKD mineral carbonation." *Egyptian Journal of Chemistry* 65, no. 3 (2022): 491-499.

Abbas, Ramadan, Nabila Shehata, Essam A. Mohamed, Hamdy Salah, and Mohamed Abdelzaher. "Environmental safe disposal of cement kiln dust for the production of geopolymers." *Egyptian Journal of Chemistry* 64, no. 12 (2021): 7529-7537.

Al-Shetwi, A. Q., Abidin, I. Z., Mahafzah, K. A., & Hannan, M. A. (2024). Feasibility of future transition to 100% renewable energy: Recent progress, policies, challenges, and perspectives. *Journal of Cleaner Production, 478*, 143942.

Angulo-Morales, A., Fajardo, C., & Roa, M. (2025). Local value creation or export orientation? Tensions in green hydrogen strategies of the Global South. *Energy Research & Social Science, 127*, 104301.

Awan, M. M. A., & Kirmani, F. U. D. (2025). Achieving Low-Carbon Future through CO2 Storage: A Comprehensive Review of Global Projects and Policies. *Petroleum Research*.

Axsen, J., Bhardwaj, C., & Crawford, C. (2022). Comparing policy pathways to achieve 100% zero-emissions vehicle sales by 2035. *Transportation Research Part D: Transport and Environment, 112*, 103488.

Barani, M., Löffler, K., del Granado, P. C., Moskalenko, N., Panos, E., Hoffart, F. M., ... & Tomasgard, A. (2026). European energy vision 2050 and beyond: Designing scenarios for Europe's energy transition. *Renewable and Sustainable Energy Reviews, 225*, 116074.

Bogdanov, D., Ram, M., Satymov, R., Lopez, G., Mensah, T., Sadovskaia, K., & Breyer, C. (2025). Costs and benefits of highly ambitious energy transition pathways for Europe. *Energy*, 138477.

Brugger, H., & Henry, A. D. (2021). Influence of policy discourse networks on local energy transitions. *Environmental Innovation and Societal Transitions, 39*, 141-154.

Cheng, C. S. W. (2023). Does time matter? A multi-level assessment of delayed energy transitions and hydrogen pathways in Norway. *Energy Research & Social Science, 100*, 103069.

Dietz, K., Dorn, F. M., & Schneider, E. (2025). Towards a global perspective on interrelated green hydrogen transitions: The case of Colombia. *Political Geography, 122*, 103395.

Emmerling, J., Drouet, L., Jewell, J., Nacke, L., Pai, S., & Zerriffi, H. (2025). Green jobs and just transition: Employment implications of Europe's Net Zero pathway. *Energy Research & Social Science, 127*, 104292.

Gao, X., Ge, Y., Qu, J., Han, J., Maraseni, T. N., Liu, C., ... & Li, H. (2025). How renewable energy policies cut greenhouse gas emissions: Insights from advanced data analysis techniques. *Journal of Environmental Management, 389*, 125946.

Gottinger, A., & Proestou, M. (2025). Policy learning and unlearning towards a transition to a sustainable bioeconomy: the case of Germany. *Journal of Environmental Management, 392*, 126607.

Jalili, M., Varedi, S., & Jafari Kelarijani, S. A. (2024). Providing a growth model based on clean energy with an emphasis on the government's general policy with a qualitative approach. *Journal of Industrial and Systems Engineering, 16*(2), 154-164.

Jalili, Mohammad, Shayesteh Varedi, and Seyed Ahmad Jafari Kelarijani. "Presenting a Sustainable Development Model Focus on Renewable Energy and Role of Government Policies." *Iranica Journal of Energy & Environment* 16, no. 3 (2025): 456-469.

Kaze, K., Balta-Ozkan, N., & Shrimpton, E. (2025). Connecting power to people: Integrating community renewable energy and multi-level governance towards low-carbon energy transition in Nigeria. *Energy Research & Social Science, 121*, 103938.

Lee, H., McJeon, H., Yu, S., Liu, Y., Kim, H., & Eom, J. (2024). Decarbonization pathways for Korea's industrial sector towards its 2050 carbon neutrality goal. *Journal of Cleaner Production, 476*, 143749.

Liu, Z., Zhou, L., Qian, Q. K., Visscher, H., & Zhang, G. (2025). Towards sustainable development: Analyzing policy frameworks and barriers in China's green construction transition. *Sustainable Energy Technologies and Assessments, 82*, 104499.

Lopez, G., Aghahosseini, A., Bogdanov, D., Mensah, T. N. O., Ghorbani, N., Caldera, U., ... & Breyer, C. (2021). Pathway to a fully sustainable energy system for Bolivia across power, heat, and transport sectors by 2050. *Journal of Cleaner Production, 293*, 126195.

Mashaal, N. M., Abdelzaher, M. A., Awad, M. M., Elwakeel, K. Z., & Hassan, A. A. (2025). Towards sustainability and circular economy: conceptual design model for the water-energy-food nexus in Ferdaws Village, Western Desert, Egypt. *Innovative Infrastructure Solutions, 10*(6), 223.

Morrison, G. M., Yeh, S., Eggert, A. R., Yang, C., Nelson, J. H., Greenblatt, J. B., ... & Zapata, C. B. (2015). Comparison of low-carbon pathways for California. *Climatic Change, 131*(4), 545-557.

Olasehinde-Williams, G., & Saint Akadiri, S. (2025). European-transition climate risk pricing in international clean energy markets: Evidence from quantile dependence and directional predictability. *Journal of Environmental Management, 392*, 126936.

Owaid, K. A., Ghazal, R. Y., & Abdelzaher, M. A. (2023). Study of the effect of modification of asphalt on the rheological properties employing microwave radiation—an aging study. *Recycling, 8*(5), 65.

Qi, Y., Liu, T., & Jing, L. (2023). China's energy transition towards carbon neutrality with minimum cost. *Journal of Cleaner Production, 388*, 135904.

Salite, D., Miao, Y., & Turner, E. (2024). A comparative analysis of policies and strategies supporting district heating expansion and decarbonisation in Denmark, Sweden, the Netherlands and the United Kingdom–Lessons for slow adopters of district heating. *Environmental Science & Policy, 161*, 103897.

Seljom, P., Rosenberg, E., Peng, Y., & Klöckner, C. A. (2025). Modelling household barriers to retrofits and solar energy-Quantifying the hidden cost in the Norwegian energy transition. *Energy Research & Social Science, 127*, 104260.

Shah, M., Singh, V., & Prajapati, M. (2024). A roadmap to 2050 for Nepal and Singapore with comparative energy market study for net-zero greenhouse gas emissions. *Sustainable Energy Technologies and Assessments, 71*, 103954.

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., & Thiel, C. (2017). Comparing policy routes for low-carbon power technology deployment in EU–an energy system analysis. *Energy Policy, 101*, 353-365.

Wiseman, J. (2018). The great energy transition of the 21st century: The 2050 Zero-Carbon World Oration. *Energy research & social science, 35*, 227-232.

Xu, L., & Yang, J. (2024). Carbon pricing policies and renewable energy development: Analysis based on cross-country panel data. *Journal of Environmental Management, 366*, 121784.

Xu, Z., Yang, Y., Nakajima, H., Inoue, T., Nakagawa, M., & Koizumi, H. (2026). Rationales, resources, and diffusion in the local institutionalization of low-carbon practices: A community-based pathway in Kyoto, Japan. *Cities, 169*, 106494.

Yang, K., & Feng, K. (2026). The changing role of the state: two governance models of China's low-carbon energy transitions. *Environmental Innovation and Societal Transitions, 58*, 101057.