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Energy Transition between Germany and China: A Comparative Study on the Extent of Progress in the Shift toward Renewable Energies

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Abstract:
This research aims to analyze energy transition pathways in Germany and China through a comparative study that seeks to evaluate their progress toward renewable energy adoption amid escalating environmental, economic, and geopolitical challenges. The study is based on a theoretical framework that clarifies the concept of energy transition, its main drivers, and indicators, highlighting its economic, technological, financial, and social dimensions as essential pillars for sustainable development and energy security.

The study adopts a comparative analytical methodology by examining public policies, regulatory frameworks, the evolution of the energy mix, and renewable energy production capacities in both countries. Results show that Germany represents a gradual and systematic energy transition model based on innovation and decentralized production within the framework of the “Energy Revolution,” whereas China reflects a rapid expansion model relying on long-term strategic planning and industrial dominance over global renewable energy value chains. The study concludes that successful energy transition depends more on the integration of policies and industrial and institutional capacities than on the mere availability of natural resources.

Keywords: Energy transition; Renewable energy; Energy mix; Germany; China; Energy security.

Introduction:

The world is witnessing a rapid strategic shift in energy production and consumption models, driven by increasing climate challenges, rising environmental awareness, and geopolitical developments that have reshaped the global energy security map. At the heart of this shift emerges the concept of energy transition (Energy Transition) as a strategic framework guiding the systematic move from a fossil-fuel-based energy model to a more sustainable model focused on renewable energies and energy efficiency. This transition has become a cornerstone for achieving sustainable development goals and reducing carbon emissions, especially in light of the Paris Climate Agreement and the United Nations 2030 Agenda.

In this context, Germany and China emerge as two pioneering and distinctive experiences. Germany, through its “Energiewende” policy, represents an advanced industrial model aiming for carbon neutrality through technological innovation and decentralized production. China, as the world’s largest energy consumer and producer, represents the “Energy Revolution” model combining massive renewable energy capacity expansion with pressures from significant economic growth.

Research Problem:

The world today faces complex energy challenges due to overreliance on fossil fuels, which exacerbate climate change and continuously threaten energy security. This has made the transition to renewable energies a strategic imperative for achieving sustainable development. In this context, leading international experiences in energy transition have emerged, including the German experience, which represents an advanced industrial economy based on incentivizing policies and technological innovation, and the Chinese experience, characterized by massive production expansion that strengthens its dominance over global renewable energy supply chains. However, differences in economic, technological, and geopolitical contexts between the two countries raise questions about the nature of this transition and its limits in each case. This study thus raises the following research question:

To what extent do energy transition pathways in Germany and China reflect actual progress in the shift toward renewable energies, and what are the key factors, policies, and structural determinants that explain similarities and differences between the two experiences in terms of energy mix and achieved outcomes?

Research Objectives:

This research aims to provide an in-depth comparative analysis of energy transition in Germany and China by:

- Clarifying the theoretical and conceptual framework of energy transition and its environmental, economic, and geopolitical drivers and key indicators;
- Analyzing German energy transition policies, instruments, frameworks, and the evolution of its renewable energy mix;
- Analyzing Chinese renewable energy strategies, production expansion, and associated value chains;
- Conducting a systematic comparison between the two experiences in terms of policies, energy mix composition, challenges, and results;
- Extracting practical lessons applicable to other countries, especially developing and resource-rich nations, for designing more effective and sustainable energy transition policies.

The importance of this research stems from the relevance of energy transition in the global context as a key pillar for addressing climate change, ensuring energy security, and achieving sustainable development goals. Its significance also lies in focusing on two globally pioneering experiences, Germany and China, allowing a deep understanding of how to manage the transition from a fossil-fuel-based model to a renewable energy mix in an advanced industrial economy on the one hand and a rising economy with massive production capacity on the other.

Scientifically, this research enriches Arabic literature on energy transition by providing a comparative theoretical and analytical framework of renewable energy policies and strategies in two countries serving as international references, using modern quantitative and qualitative indicators. Practically, the study provides lessons and recommendations for policymakers in developing and resource-rich countries, useful for designing more effective energy transition policies, particularly regarding energy mix diversification, attracting renewable energy investments, and building supportive legislative and institutional frameworks, thereby reducing fossil fuel dependence and enhancing resilience to future energy crises.

1) Theoretical Framework: Energy Transition between Concept and Theory

1.1 Concept of Energy Transition:

The term energy transition (Energy Transition) refers to the gradual process of restructuring energy production, distribution, and consumption systems, from heavy reliance on fossil energy sources (oil, gas, coal) to more sustainable energy sources such as solar, wind, biomass, and hydropower. This transition involves technical, economic, and institutional aspects aiming to achieve a low-carbon, more efficient, secure, and sustainable energy system. Definitions of energy transition include:

- Smil (2010) defines it as: "A change in the composition of primary energy supply by gradually moving from a particular supply model to a new energy system state" (p. 192).
- Rojey (2008) considers it: "The shift from a model heavily dependent on fossil fuels to a new energy model dominated by low-carbon energies" (p. 218).
- Bigot (2013) defines it as: "The shift from a model largely dependent on depletable fossil energies to a model dominated integrally by renewable and nuclear energies, integrating three elements: rationalization, efficiency, and decarbonization" (pp. 300–301).

Energy transition refers to moving from a national energy production and consumption model to another according to a comprehensive vision. Main objectives include:

- Diversifying macroeconomic resources;
- Preserving fossil energy resources;
- Diversifying energy sources and reducing dependency on fossil fuels;
- Protecting the environment and contributing to international carbon emission reduction efforts.

According to the International Renewable Energy Agency (IRENA), energy transition is "a fundamental change in the way energy is produced and consumed, balancing economic development, environmental protection, and energy security." It is a central component in climate change mitigation strategies, confirmed by the IPCC, which emphasizes reducing carbon emissions by at least 45% by 2030 compared to 2010 levels to stay within 1.5°C global warming.

Energy transition thus entails moving from a traditional (fossil) energy system to a renewable, abundant, low-carbon energy mix that preserves the environment and meets future generations' needs.

1.2 Global Drivers of Energy Transition:

Environmental Drivers:

Environmental factors are primary drivers of energy transition worldwide, largely due to industrial growth effects and excessive consumption of fossil fuels (oil, gas, coal). Global warming is a central environmental challenge, making it a primary driver for global energy transition. IPCC evidence confirms that human activity, especially fossil fuel combustion, is the main source of greenhouse gas emissions, leading to climate changes such as global temperature rise, extreme heatwaves, floods, droughts, and wildfires. These effects threaten economic and social stability, making the transition to sustainable energy systems a strategic necessity (IPCC, 2021).

Economic Drivers:

- **Oil price volatility and energy market instability:** Sharp fluctuations in oil and gas prices significantly affect energy market stability, encouraging countries to seek secure alternatives and adopt energy transition policies, particularly in energy-importing countries (e.g., 2008 oil crisis, 2020 COVID-19 pandemic, 2022 Russia-Ukraine war) (Albulescu, 2020, p. 32). Renewables help reduce external dependence and enhance energy independence by diversifying sources and distributing risk.
- **Green growth and job creation:** Low-carbon economic transition offers growth and employment opportunities, especially in solar, wind, energy efficiency, and green hydrogen sectors. According to IRENA and ILO, renewable energy jobs rose to 13.7 million in 2022 from 7.3 million in 2012, projected to reach 42 million by 2050 (ILO, 2023, p. 15).

Geopolitical Drivers:

Energy transition is a strategic challenge intersecting environmental, economic, and geopolitical factors. Reducing energy dependency, securing strategic resources for renewable technologies, and dominating green industries (solar cells, lithium batteries, EVs) are key drivers. China dominates over 80% of the solar value chain, while the EU (Green Deal) and USA (Inflation Reduction Act) aim to strengthen technological independence and reduce Chinese dominance (IEA, 2025).

1.3 Dimensions of Energy Transition:

Energy transition involves technological, economic, social, environmental, political, and financial dimensions.

- **Economic:** Diversifies production, develops green industries, creates jobs, reduces fossil fuel dependence, and strengthens macroeconomic stability (IRENA, 2023).
- **Technological:** Enhances energy production efficiency, modernizes infrastructure, integrates renewables and smart grids, and employs AI and big data (IRENA, 2023).
- **Financial:** Requires unprecedented investments (~$4–5 trillion annually), green bonds, blended finance, and international financial institution support (IEA, 2021; World Bank, 2023).
- **Social:** Impacts employment, social equity, and welfare; necessitates just transition policies and workforce retraining (IRENA, 2023; ILO, 2023).

1.4 Energy Transition Indicators:

Key indicators include: energy intensity, per capita CO_2 emissions, CO_2 intensity of energy mix, electricity generation by source, low-carbon electricity share, net solar and wind capacity additions, solar and wind electricity generation, residential and transport energy intensity, EV sales share, and energy R&D expenditure share of GDP (IEA, 2025).

2) Leading International Experiences: Germany vs. China

2.1 German Energy Transition Model:

Germany is a global leader in energy transition through its Energiewende policy aiming for carbon neutrality by 2045 (BMWK, n.d.) via reducing fossil fuel and nuclear dependency, promoting renewables, and enhancing energy efficiency. Nuclear phase-out began in the 1990s, formalized in 2000 via the Renewable Energy Sources Act (EEG). The Federal Climate Change Act targets a 65% reduction in energy sector emissions by 2030, 88% by 2040, and carbon neutrality by 2045. Nuclear plants were closed post-Fukushima by 2022 (World Nuclear Association, 2021).

In January 2025, Germany introduced measures to integrate solar, boost wind production, and extend cogeneration (Appunn, Wettengel, & Wehrmann, 2024). Renewable energy investments reached €37.3 billion in 2023 (BMWK, n.d.). Expanding national grids requires €650 billion by 2045 for thousands of km of transmission lines (Bardt & Hüther, 2024).

Renewable Energy Capacities in Germany:

- **Solar Energy:** Germany's solar sector benefits from high-efficiency PV cells, affordability, and easy rooftop installation. In 2022, 478 projects received €70.14 million in funding, and 105 new research projects were approved. In 2023, over 1 million new solar systems (14 GW) were installed, half on rooftops, 31% in open spaces, 18% on commercial roofs, totaling ~3.7 million systems generating ~55 TWh (12% of national electricity). In 2024, solar PV supplied 59.5 TWh (13.8% of domestic output), reaching half of the 2030 expansion target (107.5 GW), with a projected 215 GW target (BSW, 2025; Fraunhofer ISE, 2025).
- **Wind Energy:** Wind is a core pillar of Germany's energy transition, producing ~139.8 TWh in 2023 (32% of renewable output). Wind energy includes onshore (most widespread) and offshore (rapid technological growth) sources. Offshore capacity reached 9.2 GW

with 1,639 turbines producing 25.7 TWh (5.9% of national electricity) in 2024. Targets are 30 GW by 2030 and 70 GW by 2045 (GmbH, 2025).

- **Biomass:** Biomass provides flexibility and stability, compensating for solar/wind fluctuations. Resources include agricultural residues, wood, organic waste, and biogas. In 2023, biomass produced ~255 TWh (49% of renewable energy; ~12% of total final energy). Heating consumes 171 TWh (67%), electricity 49 TWh (19%), transport 35 TWh (14%) (AGEE-Stat, 2024).
- **Geothermal Energy:** Geothermal energy is stable, non-intermittent, supports energy security, and reduces carbon emissions. Applications include shallow (heat pumps) and deep geothermal (electricity and heat). Effective use can cover ~25% of national heating demand (BMWK, 2024; Schellschmidt, Sanner, Jung, & Schulz, 2007). Post-2022 energy crisis, Germany accelerated local energy projects and passed the 2024 Geothermal Energy Act, providing administrative, financial, and legislative support (Weber, Born, Huenges, & et al., 2022).

Other supplementary sources include hydro and marine energy, with limited current contribution. Table 1 shows Germany's renewable energy capacities and relative shares in 2023.

Type of Renewable Energy	Total Capacity (GW)	Share (%) within Germany	Share (%) Globally
Solar Energy	81.7	49%	5.8%
Wind Energy	69.5	41.6%	6.8%
Biomass Energy	10	6%	6.6%
Hydropower	11.2	6.7%	0.8%
Geothermal Energy	0.05	0.1%>	1%>
Marine Energy	Very small	<0.1%	Very small
Total	167	100%	4.3%

Note: Data compiled from: Fraunhofer ISE (2023); AGEE-Stat (2024); IRENA (2023); UBA (2024).

Table 01 shows that Germany's renewable energy mix is dominated by solar and wind energy, which together account for about 90% of the total installed capacity of 167 GW. Biomass (6%) and hydropower (6.7%) play a complementary role in providing stable capacity to support grid flexibility, while other sources such as geothermal and marine energy remain limited in impact. Globally, Germany's capacities represent about 4.3% of total renewable energy, reflecting its leading position in implementing energy transition policies within major industrial economies.

b) Energy Transition in China and Renewable Energy Sources:

In recent decades, China has undergone a deep strategic transformation in its energy system, moving from heavy reliance on coal and fossil fuels to adopting an integrated model of clean and renewable energy. After decades of industrial growth based on conventional sources, which made it the largest coal consumer and one of the major contributors to global carbon emissions, Chinese leadership adopted what is known as the Energy Revolution, based on principles of sustainability, innovation, and resource efficiency.

The Renewable Energy Law of 2006 marked the official starting point for this transformation, establishing the legislative and institutional framework to develop and regulate the clean energy sector. This was followed by the medium- and long-term development plan for renewable energy (2007), which set a target to raise the contribution of renewable energy to 15% of the total energy mix by 2020. The Energy Production and Consumption Revolution Strategy of 2017 reflected the shift from quantitative expansion to quality and efficiency through rationalizing consumption, improving supply structure, enhancing technological innovation, reforming market mechanisms, and supporting international cooperation to ensure energy security and sustainability (NDRC, 2017).

By 2021, China launched a new phase of its energy transition by adopting a modern energy system that places renewable energy at the core of its strategy to achieve peak carbon emissions before 2030 and reach carbon neutrality by 2060 (UNFCCC, 2021), in line with its commitments under the Paris Agreement. The decision to stop financing coal plants abroad under the Belt and Road Initiative marked a symbolic shift toward green diplomacy (Mallapaty S., 2021), as China redirected investments toward clean energy, especially solar, wind, and green hydrogen.

- **Solar Energy:**

Solar energy is the largest and fastest-growing renewable energy source in China, exceeding 885 GW by the end of 2024, approximately one-third of global capacity (International Energy Agency, 2025). This massive expansion is attributed to a set of incentive measures supported by annual investments exceeding $130 billion and industrial positioning that allowed China to develop a complete value chain from raw silicon production to photovoltaic cell and panel manufacturing, controlling over 80% of the global solar panel market (IEA, 2024).

The widespread deployment of solar power plants in western regions such as Xinjiang, Qinghai, and Gansu has enhanced national energy security and reduced dependence on coal, while distributed rooftop solar projects in cities have integrated clean energy into urban grids, in line with the state's vision to peak emissions before 2030 and achieve carbon neutrality by 2060 (IRENA, 2024).

- **Wind Energy:**

China has achieved a strategic breakthrough in wind energy development, placing it at the forefront of global clean energy production. By the end of 2024, total installed capacity reached about 440 GW, including approximately 37 GW of offshore wind, ranking first globally in installed capacity and investments, with annual investments exceeding $90 billion in 2023 (International Energy Agency, 2024).

This rapid expansion is attributed to supportive policies set by the Chinese government aimed at increasing electricity production from wind and solar to over 1.2 TW by 2030 (Reuters, 2020). The International Energy Agency reports that China alone accounted for about two-thirds of global annual additions in 2023, representing over 60% of global growth in this field, thanks to deep industrial integration across the wind turbine supply chain, from design and production to installation and operation (2030, 2024).

According to the Global Wind Energy Council, 2024 set a global record with the addition of 117 GW of new capacity, of which about 79.8 GW was in China alone, raising total installed capacity to about 521 GW, equivalent to 45.8% of global capacity. Offshore wind also expanded significantly with pioneering projects such as Jiangsu and Guangdong complexes, allowing China to surpass Europe in total offshore installed capacity.

This development confirms that wind energy has become a central element in China's carbon neutrality strategy and a pillar for energy security and global green economy competitiveness.

- **Hydropower and Biomass Energy:**

Hydropower and biomass represent two functional pillars, though unequal in scale, within China's energy transition strategy. Hydropower, which harnesses river flow, constitutes the historical cornerstone and stable backbone of the renewable electricity sector. With installed capacity exceeding 425 GW, it remains the largest source of actual generation, providing essential baseload power (IHA, 2024). Its contemporary importance extends beyond mere quantitative generation; its strategic role is most evident in the massive expansion of pumped-storage plants, which act as grid-scale batteries enabling safe expansion of intermittent sources such as solar and wind by absorbing surplus generation and ensuring grid stability.

Biomass, despite modest installed capacity ranging between 36–46 GW, plays a strategic qualitative role embodying the principles of the circular economy (IEA, 2023). Rather than competing in large-scale electricity production, its value lies in achieving multiple simultaneous objectives: converting agricultural waste from an environmental burden to an energy resource, contributing to rural energy security, and reducing potent greenhouse gas emissions like methane. Hence, biomass importance is measured not only in GW added to the grid but in its capacity to create value from wasted resources and provide integrated energy and environmental solutions. Hydropower guarantees system stability at the macro level, while biomass drives sustainability and efficiency at the micro and local levels; both are indispensable components in China's pursuit of carbon neutrality.

To understand China's renewable energy mix structure and compare it with global capacities, Table 02 presents installed capacities by renewable energy type based on the International Renewable Energy Agency's 2023 data.

Type of Renewable Energy	**Total Capacity (GW)**	**Share (%) within China**	**Share (%) Globally**
Solar Energy	609.5	41.9%	42.9%
Wind Energy	441.9	29.3%	43.4%
Hydropower	422	29.9%	28.8%
Biomass Energy	32	2.4%	23.9%
Marine Energy	5	0.34%	0.0095%
Geothermal Energy	0.05	0.1%	1%>
Total	1458	100%	37.7%

Source: Prepared by the researcher based on International Renewable Energy Agency (IRENA, 2024) data.

The table above, according to IRENA data, shows the total distribution of renewable energy capacities in China in 2023. Solar and wind energy dominate the renewable energy mix, followed to a lesser extent by hydropower and biomass, while contributions from other sources such as marine and geothermal energy remain very limited. This distribution reflects China's reliance on major high-capacity sources, with limited presence of emerging sources.

Conclusion:

This comparative analysis of energy transition paths in Germany and China reveals key findings highlighting the differing and converging dynamics shaping the future of global energy. The study shows that despite differences in economic and political contexts, both countries are key drivers of the renewable energy transition, guided by a combination of urgent environmental considerations, economic incentives linked to green growth, and geopolitical stakes concerning energy security and technological sovereignty.

The German model (Energiewende) is characterized by a gradual and systematic approach, supported by a solid legislative framework and early political will to phase out nuclear and coal energy, with particular focus on technological innovation and decentralized production, especially in the solar and wind sectors. Despite challenges, including the 2022 energy crisis, the German model remains a benchmark for balancing environmental sustainability and industrial security.

In contrast, the Chinese model reflects a rapid and comprehensive transition, transforming from the largest coal consumer to the largest global producer and investor in renewable energy, with near-total dominance over global solar and wind value chains, leveraging a directed industrial strategy and extensive government support. This quantitative superiority makes China a pivotal player in the global energy equation, with its installed capacities representing a substantial share of the global total.

Overall, both experiences offer integrated lessons: Germany demonstrates how an advanced industrial economy can lead a deep and sustainable transition, while China illustrates how an emerging economic power can leverage energy transition as a strategic tool to achieve economic growth, technological leadership, and geopolitical dominance. The future of global energy systems is likely to be strongly influenced by the interaction between these two models, opening the door for future studies aimed at unifying standards and coordinating policies to ensure a fair and sustainable global energy transition.

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