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Energy Transition, Climate Change, and a Five-State Markov Analysis in the U.S. and China

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Abstract: This article examines the dynamic interplay between energy returns and sectoral CO_2 emissions in the context of the energy transition in the United States and China. Its principal contribution lies in applying a multivariate five-state Markov regime-switching framework capable of capturing nonlinear dynamics, regime persistence, and structural transitions across fossil and renewable energy sources, as well as across major emitting sectors. By distinguishing between Very Down, Down, Normal, Up, and Very Up regimes, the approach offers a granular characterization of contraction, stability, and expansion phases that conventional linear models are unable to detect. The empirical analysis draws on daily data from January 2019 to December 2025, encompassing fossil energy sources (coal, oil, and natural gas), renewable sources (hydropower, solar, and wind), and sectoral CO_2 emissions from industry, electricity generation, and residential use in both economies. Information-criterion-based selection confirms the suitability of a five-regime specification for all return series. The findings point to a common regime structure across the two countries, suggesting shared nonlinear dynamics despite marked differences in their energy systems. Extreme regimes display strong persistence; most notably for fossil energy sources and emission-intensive sectors; implying that major shocks produce durable effects. Comparative results further reveal greater regime mobility in the United States, reflecting higher system flexibility, whereas China exhibits more pronounced persistence and asymmetry, consistent with stronger structural and institutional inertia. From a policy standpoint, these results indicate that sustained reductions in CO_2 emissions require not only expanding renewable energy capacity

but also weakening the persistence of unfavorable regimes. Enhancing system flexibility, accelerating effective substitution away from fossil fuels, and adopting responsive stabilization mechanisms are essential to reinforcing the effectiveness and credibility of long-term energy transition strategies.
Keywords: Energy Transition; Sectoral CO_2 Emissions and Markov Regime Switching
JEL Classification : C32, Q43, Q53, Q54, O13

1. Introduction

Global climate change and the accelerating urgency of decarbonization have placed energy systems at the core of economic and environmental policy debates. As major contributors to greenhouse gas emissions, energy production and consumption patterns; particularly in carbon-intensive sectors such as industry, electricity generation, and residential use; play a decisive role in shaping national and global climate trajectories. In this context, the transition from fossil fuel–based energy systems toward low-carbon and renewable alternatives have emerged as a central pillar of climate mitigation strategies. Despite the growing deployment of renewable energy technologies, recent events; including the COVID-19 pandemic, heightened geopolitical tensions, and disruptions in global energy markets; have underscored the fragility, volatility, and nonlinear adjustment processes characterizing contemporary energy systems.

Against this backdrop, understanding how energy transitions affect sectoral CO_2 emissions over time remains a key research challenge. Existing empirical studies often focus on average relationships between energy consumption, economic activity, and emissions, relying predominantly on linear or static modeling frameworks. While such approaches provide valuable insights, they tend to overlook the inherently nonlinear and regime-dependent nature of energy and environmental dynamics, particularly during periods of abrupt shocks or structural change. Energy markets and emission trajectories frequently alternate between phases of relative stability, adjustment, and extreme volatility, suggesting that transition processes are neither smooth nor monotonic. Capturing these dynamics requires analytical tools capable of accounting for persistence, asymmetry, and endogenous regime shifts.

This article addresses this gap by investigating the dynamic interactions between energy returns and sectoral CO_2 emissions in the United States and China, the world's two largest energy consumers and emitters. These two countries exhibit markedly different energy structures, policy frameworks, and transition pathways, making them particularly well suited for comparative analysis. While the United States has experienced a more market-driven transition characterized by substitution between fossil fuels and renewables, China's transition has largely followed a centralized and incremental strategy in which renewable energy sources have so far complemented rather than rapidly displaced fossil generation. Examining these contrasting dynamics through a unified analytical framework provides a unique opportunity to deepen our understanding of how structural inertia, policy interventions, and exogenous shocks jointly shape emission trajectories.

The originality of this study lies in its adoption of a multivariate Markov chain model with five regimes to analyze energy returns and sectoral CO_2 emissions simultaneously. By distinguishing between *Very Down, Down, Normal, Up,* and *Very Up* states, this framework allows for a fine-grained characterization of contraction, stability, and expansion phases, while explicitly modeling regime persistence and transition probabilities. Unlike conventional approaches, the Markov regime-switching framework captures nonlinear behavior, path dependence, and abrupt transitions induced by economic, health-related, and geopolitical shocks. To the best of our knowledge, this study is among the first to apply a unified multi-regime Markov framework to both energy returns and sectoral emissions, across fossil and renewable energy sources, in a comparative U.S.–China context using high-frequency data. From a theoretical perspective, our article contributes to the literature by framing the energy transition as a regime-dependent and path-dependent process rather than a smooth adjustment toward a single equilibrium. The results highlight the coexistence of extreme and intermediate regimes and emphasize the structural inertia embedded in energy systems, particularly in fossil-fuel-dependent sectors. This perspective complements existing transition theories by emphasizing the role of volatility regimes and shock persistence in shaping long-term decarbonization outcomes. Empirically, our study provides several novel insights. First, it identifies a common five-regime structure across all energy sources and sectoral CO_2 emissions in both countries, suggesting the presence of shared underlying dynamics despite substantial structural differences. Second, the estimated transition probability matrices reveal strong persistence of extreme regimes, especially in fossil energy markets and emission-intensive sectors, indicating that negative and positive shocks tend to have long-lasting effects. Third, the comparative analysis shows that the U.S. energy system exhibits greater mobility across intermediate regimes, whereas China's system is characterized by stronger persistence and asymmetry, reflecting institutional rigidity and centralized planning. These findings have important implications for the speed and effectiveness of energy transition policies.

Methodologically, the analysis is based on daily data spanning January 2019 to December 2025, covering major fossil energy sources (coal, oil, and natural gas), renewable energy sources (hydropower, solar, and wind), and sectoral CO_2 emissions (industry, electricity generation, and residential sectors). Optimal regime selection is conducted using standard information criteria (AIC and BIC), ensuring robustness in model specification. The Markov framework is complemented by descriptive statistics, correlation analysis, and a detailed examination of regime persistence and transition dynamics.

The remainder of our article is structured as follows. Section 2 reviews the related literature on energy transitions, sectoral emissions, and nonlinear modeling approaches. Section 3 describes the data, variables, and preliminary statistical properties of energy returns and emissions in the United States and China. Section 4 presents the multivariate Markov chain methodology and discusses the identification of optimal regimes. Section 5 analyzes regime dynamics, transition probabilities, and comparative results for both countries, with particular attention to the role of extreme regimes and structural inertia. Finally, Section 6 concludes by summarizing the main findings and discussing their implications for energy and climate policy, highlighting the conditions required to accelerate transitions toward low-carbon regimes and to reduce the persistence of unfavorable emission states.

2. Literature Review

The growing intensity and frequency of climate change have significantly accelerated the global shift from fossil-based energy systems toward renewable energy sources, which are now widely regarded as indispensable to decarbonization efforts. Scholarly research highlights that climate trajectories are influenced by a diverse set of interrelated factors, including sector-specific energy demand patterns, technological differentiation, policy and regulatory frameworks, and wider structural and institutional transformations. Despite these insights, the existing literature remains fragmented across disciplines, research traditions, and geographical contexts, resulting in limited cross-national and cross-cultural comparative analyses. While a substantial portion of sectoral climate research focuses on major greenhouse gas emitters such as the United States and China, other studies draw on heterogeneous national and regional case studies, often yielding inconsistent or context-specific conclusions. To address this lack of coherence and integration, this literature review is structured around three key analytical dimensions: the sectoral and structural drivers shaping climate trajectories, energy transition processes and sector-specific decarbonization pathways, and the social, institutional, and methodological factors that condition and influence transition outcomes.

Recent empirical and methodological contributions underline the growing recognition that sectoral emission trajectories are shaped by complex energy dynamics that vary across regions and technological systems. Mgadmi et al. (2026) examine the relationship between renewable and non-renewable energy evolution and sectoral CO_2 emissions in the European Union, Russia, and India using LSTM-based predictive models over the 2019–2024 period. Their findings reveal pronounced sectoral heterogeneity: fossil fuel–intensive sectors, particularly transport and aviation, exhibit persistently high and volatile emissions, whereas more electrified sectors, notably power generation and residential energy use, display relatively stable emission paths. Moreover, the study identifies substantial regional disparities that reflect differences in energy structures and stages of transition. While the analysis advances sectoral understanding beyond single-country studies, its exclusion of major global emitters constrains its contribution to a fully comparative assessment of global climate trajectories. In a complementary system-oriented approach, Fong and Fung (2026) assess the feasibility of deep decarbonization in Ontario's power sector using a techno-economic optimization framework. Their results demonstrate that hybrid energy systems combining renewable generation, nuclear energy, and storage technologies outperform single-technology pathways in both cost efficiency and system reliability. The study further emphasizes the critical role of energy storage and demand-side flexibility in mitigating the intermittency of renewable sources. These findings suggest that power sector decarbonization depends not only on expanding renewable capacity but also on effective system integration and operational optimization. However, the focus on a single provincial case limits the generalizability of the results to broader national or international contexts.

Extending the analysis of energy system integration, Ucok (2026) conducts a systematic review of renewable energy applications in hydrogen refueling infrastructure for sustainable transport. The review shows that system performance and cost structures are highly context-specific, driven primarily by renewable resource availability, infrastructure maturity, and grid connectivity rather than by technology selection alone. The study highlights the benefits of hybrid system configurations and smart energy management in enhancing cost efficiency and reliability, while recognizing hydrogen's dual role as a low-carbon fuel and an energy storage medium. Nonetheless, the findings also underscore persistent barriers to large-scale deployment, including high capital costs and infrastructural constraints. At a more technical level, Liao et al. (2026) propose an adaptive inverter control strategy that enables seamless transitions between grid-following and grid-forming modes under varying grid-strength conditions. Their results show that conventional single-mode control systems are prone to instability in both weak and strong grids, while the proposed hybrid strategy significantly improves system robustness and minimizes switching disturbances. Although the study provides valuable insights into maintaining power system stability under high renewable penetration, its narrow technical focus limits its engagement with broader comparative debates on sectoral decarbonization and climate trajectories. Broader cross-country perspectives are offered by Alamri et al. (2026), who apply Index Decomposition Analysis to investigate sectoral energy structures and emission drivers across major greenhouse gas–emitting economies, including China and the United States, from 2000 to 2023. Their findings reveal persistent sectoral heterogeneity, emissions, and the sector remains the principal source of emissions, while transport and industry continue to exhibit high carbon intensity due to structural demand and fossil fuel dependence. The analysis further indicates that the United States has achieved emission-intensity reductions primarily through efficiency gains and structural adjustments, whereas China's emissions remain elevated in several sectors because of rapid economic expansion. While the comparative scope is extensive, the breadth of coverage limits deeper investigation into the specific policy and institutional mechanisms shaping these divergent trajectories. Collectively, these studies highlight the growing recognition that understanding emission dynamics requires sector-specific and system-level perspectives. Nevertheless, the existing evidence remains dispersed across disciplinary and empirical contexts, hindering the development of a coherent and comparative framework for analyzing climate trajectories. Addressing the social and institutional dimensions of transition, Berberi et al. (2026) conduct a scoping review of living labs as an open-innovation mechanism for sustainability transitions. Their findings demonstrate that successful outcomes depend heavily on collaborative governance structures, stakeholder engagement, and iterative co-creation processes, while key challenges include coordination costs, technological limitations, and difficulties in sustaining long-term impacts. The study highlights that transition performance is shaped as much by social interactions and governance arrangements as by technological innovation, although the absence of standardized evaluation frameworks constrains the assessment of long-term effectiveness.

From a mitigation technology perspective, Homaei et al. (2026) analyze the role of carbon capture and storage (CCS), particularly high-capture-rate technologies, in decarbonizing the European power sector using a capacity-expansion model. Their results indicate that cost-effective decarbonization pathways involve combining renewable energy with fossil-based generation equipped with CCS, especially under stringent emission-reduction targets. High-capture-rate CCS improves cost efficiency and reduces carbon prices compared to conventional CCS options, although the study notes that complete decarbonization remains economically suboptimal without complementary carbon removal technologies. Intersectoral interactions are further explored by Tosatto et al. (2026), who investigate building-sector decarbonization within a broader energy system transformation framework. Their scenario-based analysis reveals that the effectiveness of electrification strategies is highly contingent upon the underlying power generation mix, as insufficient renewable capacity may shift emissions from buildings to the electricity sector. The study emphasizes the importance of energy storage and system flexibility in managing seasonal mismatches between supply and demand, reinforcing the interconnected nature of sectoral emission trajectories. Finally, Sharma et al. (2026) examine long-term emission dynamics in India's manufacturing sector using a combined Tapio decoupling and LMDI decomposition approach over the period 2001–2023. Their analysis identifies persistent weak decoupling across industrial subsectors, suggesting that emissions continue to grow alongside economic output, albeit at a reduced rate. Output expansion and energy intensity emerge as the primary drivers of emissions, particularly in capital-intensive industries such as steel and chemicals, where reliance on fossil fuels remains substantial. While the study provides valuable sectoral insights, its national scope restricts broader cross-country comparisons. Taken together, this body of research demonstrates that identifying the structural and energy-related determinants of sectoral emission trajectories requires an integrated application of system-based modeling approaches and decomposition techniques. However, the fragmentation of evidence across sectors, regions, and methodological traditions continues to limit the development of a unified and comparative understanding of global decarbonization pathways.

Literature increasingly shows that transport decarbonization is shaped by the interaction of technological innovation, policy design, and broader energy-system transformation. Pan et al. (2026) examine the influence of zero-emission vehicle policy stringency on electric mobility transitions and their implications for energy use and CO_2 emissions across major world regions, including the United States and China. Using the Global Change Analysis Model, the authors demonstrate that stronger policy support and lower non-energy costs can significantly accelerate electric vehicle adoption and reduce emissions from the transport sector. However, the study also shows that electrification can displace emissions toward electricity generation and hydrogen supply if the decarbonization of upstream energy systems does not occur simultaneously. These findings indicate that transport-sector mitigation depends not only on vehicle substitution, but also on the pace and depth of energy-system restructuring. Although our article offers a valuable comparative and forward-looking perspective, its analytical scope remains centered largely on passenger vehicle electrification.

A similar emphasis on policy; technology interaction is found in Meng et al. (2026), who review China's transport decarbonization pathway within the framework of the country's "dual carbon" strategy. Their analysis identifies electrification, renewable energy integration, and intelligent transport systems as the principal transition mechanisms, supported by policy instruments such as carbon trading and green finance. The study also highlights China's growing international influence through technological diffusion and declining clean-energy costs. While these insights underscore the importance of coordinated governance and technological deployment, the study remains primarily descriptive and provides limited quantitative evidence regarding the magnitude of emission reductions. Taken together, these studies suggest that transport decarbonization is not solely a matter of technological replacement, but rather a multidimensional process requiring alignment between innovation, public policy, and energy supply transformation.

This interpretation is consistent with earlier work by Smith and Davies (1996), who analyze the evolution of transport emissions in the United States. Their findings show that technological improvements, including catalytic converters and stricter vehicle standards, were insufficient to offset the increase in emissions caused by higher levels of vehicle ownership, growing travel demand, and urban congestion. The study demonstrates that efficiency gains can be neutralized by structural growth in transport activity, thereby sustaining long-term emission pressures. As such, these authors argue that meaningful decarbonization cannot rely on technological progress alone, but must also address patterns of mobility demand, infrastructure provision, and urban development. Although limited to road transport, this historical perspective remains highly relevant, as it reinforces the broader argument that transport transitions are embedded in structural and behavioral dynamics rather than determined exclusively by technological substitution.

Beyond transport, recent research also emphasizes the importance of structural and network-based drivers of carbon emissions. Wen et al. (2026), for example, examines the carbon dynamics of China through a carbon-flow super-network that combines multi-regional input-output analysis with network theory. The study reveals persistent carbon lock-in associated with coal-based electricity, heavy industrial activity, and interregional trade linkages. Emissions are shown to be geographically concentrated in inland resource-rich regions, while coastal provinces function as major consumption hubs, thereby reproducing both spatial and sectoral inequalities in carbon responsibility. These findings demonstrate that emissions areembedded in broader production and trade systems, suggesting that climate trajectories are shaped not only by sector-specific energy choices, but also by supply-chain interdependencies and territorial economic organization. However, the study's exclusive focus on China limits the extent to which its conclusions can be generalized across diverse national contexts.

A related perspective is offered by Li and Xu (2026), who investigate the effects of industrial park–based energy transition policies on urban carbon intensity in China using a multi-period difference-in-differences approach. Their results show that these policies significantly reduce carbon intensity, primarily through improvements in energy efficiency and green technological innovation. The study further identifies strong regional heterogeneity, with more pronounced effects in areas characterized by stricter environmental regulation and lower dependence on natural resources. These findings highlight the importance of targeted industrial policy as a mechanism for sectoral decarbonization. At the same time, the case-specific nature of the policy framework limits broader comparative interpretation. Nevertheless, the study provides important evidence that institutional design and local regulatory conditions can substantially shape the effectiveness of transition measures.

The structural constraints of industrial decarbonization are further explored by Inah et al. (2026), who analyze South Africa's industrial sector through an integrated framework combining Kaya–LMDI decomposition, scenario forecasting, and optimization modeling. Their findings indicate that emissions are driven primarily by economic expansion and continued fossil fuel dependence, particularly in relation to industrial process heat, which generates strong carbon lock-in effects. Although gains in energy efficiency and renewable deployment contribute to emission reduction, these improvements are frequently outweighed by the scale of economic growth. The study also demonstrates that even ambitious renewable energy scenarios may fail to achieve absolute emission declines if structural economic drivers remain unchanged. Consequently, the authors argue that incremental approaches are insufficient and that deep industrial decarbonization requires direct fossil fuel substitution and broader structural transformation. While the South African focus constrains generalizability, the study provides a valuable reminder that technological and efficiency gains alone may be inadequate in contexts where carbon-intensive development patterns remain deeply entrenched.

In addition to environmental and structural concerns, the transition to low-carbon systems also generates significant fiscal and institutional challenges. Noll et al. (2026) examine the implications of transport electrification for fuel tax revenues across 168 countries and find that the diffusion of electric vehicles may create substantial fiscal imbalances, particularly in low-income economies that depend heavily on fuel taxation and possess limited capacity to implement alternative revenue mechanisms. The study highlights considerable cross-country variation, showing that high-income economies are generally better positioned to offset revenue losses through policy instruments such as carbon pricing or road-user charges. These findings broaden the decarbonization debate by demonstrating that climate transitions have important fiscal consequences that extend beyond emissions outcomes. However, the study does not directly engage with sectoral emission dynamics or with the interaction between transport electrification and wider energy-system change.

Policy frameworks also play a decisive role in shaping renewable energy transitions across sectors. Rajanikant et al. (2026) provide a cross-country analysis of bioenergy development and show that expansion in this sector depends strongly on institutional quality, governance effectiveness, and the presence of stable policy support rather than market forces alone. Their findings identify instruments such as feed-in tariffs, tax incentives, renewable fuel mandates, and carbon pricing as central mechanisms for reducing investor uncertainty and improving economic viability. The study further demonstrates that countries with coherent and long-term policy frameworks, such as Brazil and Sweden, tend to experience more consistent growth trajectories than those with fragmented governance arrangements. In addition to supporting decarbonization, bioenergy is shown to contribute to energy security and rural development, particularly in resource-rich economies. Nevertheless, the authors stress that policy effectiveness remains context-dependent, as differences in governance capacity and socioeconomic conditions limit the direct transferability of policy models across countries.

Overall, this body of literature makes clear that decarbonization trajectories are shaped by far more than technological substitution alone. Across transport, industry, and renewable energy systems, the evidence points to the importance of structural economic conditions, supply-chain relations, fiscal institutions, and governance arrangements in determining the pace and effectiveness of transition. The reviewed studies collectively show that decarbonization is a multi-scalar and multi-sectoral process in which technological innovation must be embedded within broader institutional and systemic transformation. However, the literature remains fragmented across methodological approaches, sectoral emphases, and national contexts. This fragmentation limits the development of an integrated comparative understanding of how structural, policy, and energy-system factors interact to shape climate trajectories across countries and sectors.

3. Preliminary analyses

Our study investigates the impacts of renewable and non-renewable energy sources on climate change dynamics in the United States and China using daily data spanning from 1 January 2019 to the end of 2025. Non-renewable energy is represented by electricity generation from coal, natural gas, and oil, while renewable energy includes hydropower, solar energy, and wind power. The analysis focuses on three key sectors that contribute substantially to climate change through their energy consumption patterns and greenhouse gas emissions.

The industrial sector constitutes a major source of emissions due to its heavy reliance on fossil fuels, particularly coal and natural gas. As a result, it generates significant levels of carbon dioxide (CO_2) and sulfur dioxide (SO_2), thereby exacerbating global warming and contributing to acid rain formation. The electricity generation sector, historically dominated by thermal power plants, remains one of the largest contributors to CO_2 emissions, despite the increasing integration of renewable energy technologies and the gradual restructuring of power systems in both economies. In addition, the residential sector plays a non-negligible role in greenhouse gas emissions, primarily through heating and cooling demands, underscoring the importance of electrification strategies and improvements in energy efficiency to mitigate climate impacts. Reducing the carbon footprint of these sectors relies largely on technological innovation, the expansion of clean energy sources, and the implementation of policies aimed at enhancing energy efficiency. A detailed description of the variables, their measurement methods, and data sources related to different energy types and sectoral CO_2 emissions is provided in the Appendix. From a methodological perspective, the analysis employs a range of statistical indicators to characterize the behavior of sectoral returns associated with renewable energy, non-renewable energy, and climate change variables in both China and the United States. These indicators include measures of central tendency, volatility, skewness, kurtosis, as well as tests of normality and stationarity, alongside autocorrelation diagnostics. **Table 1** reports the full set of descriptive statistics for the United States–based variables considered in this study.

Table 1. Descriptive Statistic indictors US

	Industry	Power	Residential	Coal	Gas	Oil	Hydroelectricity	Solar	Wind
Mean	0.000	0.005	0.010	-0.014	0.014	-0.071	-0.004	0.067	0.015
Variance	41.671	57.443	72.796	4.414	3.291	88.144	1.343	6.526	35.2

Skewness	0.236***	0.249***	0.084*	-0.248***	-0.078	0.503***	0.184***	0.159***	-0.009
Kurtosis	1.666***	0.556***	2.541***	1.018***	1.211***	14.123***	0.662***	3.366***	0.428***
JB	318.998***	59.332***	690.251***	136.637***	158.526***	21332.817***	61.166***	1216.062***	19.517***
ERS	-8.354***	-5.674***	-4.882***	-11.001***	-8.250***	-15.491***	-6.159***	-1.865*	-2.827***
Q(20)	697.438***	972.274***	557.278***	3436.502***	2689.249***	2490.906***	2804.190***	1710.852***	2065.457***
$Q^2(20)$	175.564***	129.205***	708.605***	2325.299***	1244.678***	1204.844***	1088.779***	829.177***	693.692***

Table 1 reports the descriptive statistics of daily returns for the industrial, electricity generation, and residential sectors, as well as for different renewable and non-renewable energy sources in the United States over the study period. These indicators provide an initial assessment of the fundamental statistical properties of the series and offer preliminary insights into their dynamic behavior in the context of climate change and the ongoing energy transition. Overall, mean returns are relatively small and close to zero, a characteristic commonly observed in high-frequency financial and energy-related time series. The industrial, electricity generation, and residential sectors exhibit slightly positive mean values, suggesting moderate growth or stable trends over the period analyzed. By contrast, certain fossil energy sources; particularly coal and oil; display negative mean returns, reflecting a relative decline consistent with energy transition policies and the gradual reduction of fossil fuel dependency in the United States. Conversely, renewable energy sources, especially solar and wind power, record positive mean returns, underscoring their increasing dynamism and their central role in the decarbonization of the electricity sector.

Analysis of variance reveals significantly higher volatility in sectors associated with final energy demand; namely industry, electricity generation, and residential consumption; as well as in oil markets, compared to other energy sources. This elevated volatility can be attributed to the sensitivity of these sectors to macroeconomic fluctuations, demand shocks, extreme weather events, and regulatory changes. In contrast, renewable sources such as hydropower, along with natural gas, exhibit relatively lower variance, indicating more stable dynamics, although they remain influenced by exogenous factors such as climatic conditions and infrastructure constraints.

The skewness coefficients indicate that most series are asymmetrically distributed, with positive skewness observed for most sectors and renewable energy sources, suggesting the prevalence of more frequent or more pronounced positive shocks. In comparison, coal and gas-related series display negative or near-zero skewness, reflecting a greater incidence of downward movements in returns. This pattern is consistent with the declining role of these energy sources within the U.S. energy mix. Excess kurtosis is positive and statistically significant across all series, indicating leptokurtic distributions characterized by fat tails. This result highlights the presence of extreme events and sharp fluctuations, particularly for oil and solar energy markets, emphasizing their vulnerability to climatic, geopolitical, and technological shocks. The Jarque–Bera test confirms rejection of the null hypothesis of normality for all return series, thereby justifying the application of robust econometric techniques that explicitly account for non-normal return distributions.

Stationarity is assessed using the Elliott–Rothenberg–Stock (ERS, 1996) unit root test, which indicates that all return series are stationary at conventional significance levels. This property supports their use in dynamic econometric models without the risk of spurious relationships. Furthermore, the Ljung–Box Q(20) and $Q^2(20)$ statistics are statistically significant for all variables, revealing persistent autocorrelation in both returns and conditional variances. Such temporal dependence suggests the presence of complex conditional dynamics, including conditional heteroskedasticity, which is frequently observed in energy and environmental time series. Overall, these empirical results are consistent with the sectoral analysis presented earlier. They highlight the nonlinear, volatile, and asymmetric nature of returns associated with energy and climate-related sectors in the United States. Importantly, they reinforce the relevance of distinguishing between renewable and non-renewable energy sources when assessing their differentiated contributions to climate change and the energy transition, while also justifying the use of advanced econometric models capable of capturing their dynamic interactions.

Table 2 presents a detailed descriptive analysis of returns associated with renewable energy, non-renewable energy, and sectoral CO_2 emissions in China. The purpose of this analysis is to highlight the main statistical properties of these return series, including their mean, volatility, skewness, and distributional shape, to provide a more precise characterization of the behavior of the different energy sectors. It also allows for an examination of the dynamics of CO_2 emissions linked to each energy source by identifying patterns of emission growth or decline and assessing their associated economic and environmental implications. These descriptive elements are particularly important for understanding the complex interactions among energy sectors, environmental performance, and emission-reduction policies within a context shaped by energy transition and sustainable development objectives in China. In addition, the analysis accounts for the effects of major exogenous shocks; most notably the COVID-19 pandemic and international geopolitical tensions; which significantly influenced volatility, return structures, and emission trajectories over the study period.

Table 2. Descriptive Statistic indictors China

	Mean	Variance	Skewness	Kurtosis	JB	ERS	Q(20)	Q2(20)
Industry	0.014	26.595	0.564***	21.309***	48457.633***	-17.545***	513.188***	736.205***
Power	0.000	32.62	-0.565***	10.240***	11293.543***	-21.461***	929.860***	2995.824***
Residential	-0.019	130.894	-1.113***	12.797***	17954.908***	-26.706***	2160.655***	1346.247***

Coal	0.004	1.223	-0.357***	4.234***	1961.926***	-12.995***	4551.857***	5357.525***
Gas	0.022	2.401	-0.286***	10.643***	12088.445***	-13.767***	4411.281***	2805.619***
Oil	-0.006	1.237	-0.460***	4.354***	2107.199***	-13.254***	4458.359***	5236.864***
Hydroelectricity	0.005	2.868	-1.070***	6.571***	5082.703***	-15.503***	3949.354***	2526.015***
Solar	0.061**	2.102	0.392***	4.259***	1995.910***	-15.101***	3980.469***	3624.602***
Wind	0.043	3.165	0.227***	8.541***	7785.122***	-15.297***	4079.578***	3534.079***

Table 2 reports the descriptive statistics of daily returns for sectoral CO_2 emissions in China; namely the industrial, electricity generation, and residential sectors; as well as for renewable and non-renewable energy sources. The results reveal marked differences in statistical behavior, volatility, and return distributions, reflecting the structural characteristics of the Chinese energy system and its exposure to economic, health-related, and geopolitical shocks.

Overall, mean returns are relatively small, which is consistent with the high-frequency nature of the data. The industrial sector exhibits a positive mean return, indicating sustained growth in both emissions and industrial activity over the study period. By contrast, the residential sector displays a negative mean return, suggesting a relative decline that may be associated with energy-efficiency policies, the gradual electrification of end uses, and the lingering effects of mobility and activity restrictions during the COVID-19 pandemic. About energy sources, positive average returns are observed for natural gas, hydropower, solar, and wind energy, highlighting their increasing importance in China's energy mix. Oil, on the other hand, records a negative mean return, pointing to a comparatively weaker dynamic for this fossil fuel source.

Variance analysis reveals substantial heterogeneity across sectors. Residential sector emissions exhibit particularly high volatility (130.894), far exceeding that observed in the industrial and electricity generation sectors, which suggests strong sensitivity to economic conditions, climatic variability, and exogenous shocks. Among energy sources, fossil fuels such as coal, gas, and oil display relatively low variances, indicating a more regulated and planned production structure. In contrast, renewable energy sources; especially wind and hydropower;show greater volatility, largely due to their dependence on meteorological conditions and technical constraints.

The skewness coefficients indicate that the return distributions are asymmetric across all series. The electricity generation and residential sectors display significant negative skewness, implying a higher frequency of adverse shocks, possibly related to reduced activity, restrictive environmental policies, or lockdown episodes. By contrast, solar and wind energy exhibit positive skewness, reflecting more frequent or more pronounced upward movements in return. This pattern is consistent with the rapid expansion of these technologies, supported by public investment and China's climate policy objectives.

Excess kurtosis is high and statistically significant for all return series, with particularly pronounced values in the industrial sector and for natural gas. This finding indicates leptokurtic distributions characterized by fat tails and the presence of extreme events. The Jarque–Bera test systematically rejects the null hypothesis of normality, underscoring the strong non-normality of the return series and the need to employ econometric methods capable of accommodating asymmetric distributions and extreme shocks.

The Elliott–Rothenberg–Stock (ERS, 1996) unit root test indicates that all return series are stationary at conventional significance levels, allowing their inclusion in dynamic analyses without the risk of spurious regression. In addition, the Ljung–Box Q(20) and $Q^2(20)$ statistics are statistically significant for all variables, revealing persistent autocorrelation in both returns and conditional variances. These results point to the existence of temporal dependence and conditional heteroskedasticity effects, which are commonly observed in energy and environmental time series.

Taken together, the findings reported in **Table 3** highlight the pronounced statistical instability of energy returns and sectoral emissions in China, amplified by major exogenous shocks such as the COVID-19 pandemic and international geopolitical tensions. They also illustrate the contrast between the relatively controlled dynamics of fossil energy sources and the greater volatility of renewable energy within the context of rapid energy transition. These characteristics underscore the importance of distinguishing between energy sources to better assess their respective contributions to CO_2 emissions and their role in China's sustainable development strategy.

We examine the dependence relationships between renewable energy sources, non-renewable energy sources, and sectoral CO_2 emissions in the United States using the Pearson total correlation matrix presented in **Figure 1**. This approach makes it possible to assess both the strength and the direction of the linear relationships among these energy and environment related returns, thereby providing an initial overview of the structural interactions within the U.S. energy system.

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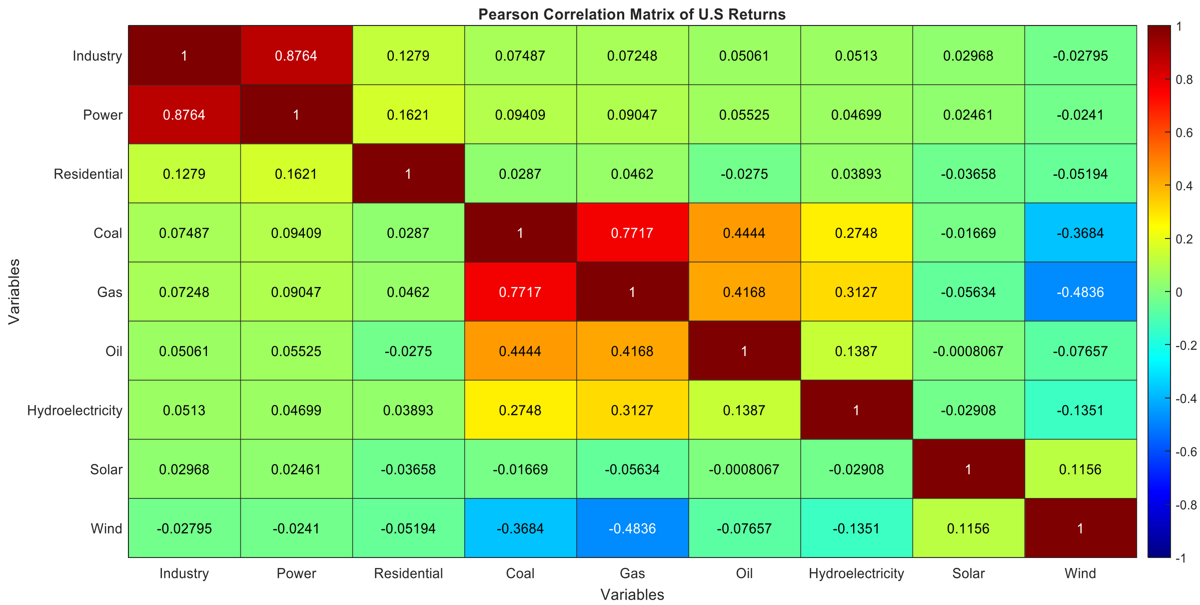


Figure 1 presents the Pearson total correlation matrix between the returns of sectoral CO_2 emissions; namely the industrial, electricity generation, and residential sectors; and the main renewable and non-renewable energy sources in the United States. This analysis makes it possible to identify the linear interdependencies within the U.S. energy system and to better understand the transmission mechanisms linking energy production dynamics to sectoral emission patterns. The results first reveal a strong positive correlation between industrial emissions and emissions from the electricity generation sector, suggesting a marked structural interdependence between these two sectors. This relationship reflects the central role of industry in electricity demand, as well as the continued reliance of the power mix on fossil-based generation. By contrast, the correlations between industrial and residential emissions are considerably weaker, indicating differentiated emission dynamics and less synchronized demand cycles across these sectors.

With respect to non-renewable energy sources, the **Figure** highlights particularly strong positive correlations between coal and natural gas, as well as between coal and oil. These results point to a pronounced co-movement among fossil fuel sources, likely driven by common determinants such as international energy prices, geopolitical shocks, and short-term production adjustments. The relative complementarity observed among these energy sources also suggests limited short-run flexibility in the fossil-based energy system, where adjustments tend to occur in a synchronized rather than a substitutive manner.

By contrast, the correlations between renewable and fossil energy sources are generally weak or negative. Wind energy displays negative correlations with both coal and natural gas, indicating a gradual substitution effect between these sources. This finding is consistent with decarbonization objectives and public policies aimed at reducing fossil fuel dependence in favor of low-carbon energy alternatives. Similarly, hydropower exhibits moderate correlations with coal and natural gas, pointing to a more nuanced interaction that may reflect technical constraints and climatic variability.

Correlations among renewable energy sources themselves remain relatively weak, especially between solar and wind power, which underscores the technological diversification of the U.S. renewable energy sector. This limited co-movement suggests that the returns associated with these energy sources respond to distinct underlying drivers, including source-specific weather conditions, regional heterogeneity, and differentiated regulatory frameworks. Such diversification may strengthen the overall resilience of the energy system in the face of exogenous shocks. Finally, the relatively weak correlations between sectoral CO_2 emissions and renewable energy sources suggest that, although the energy transition is underway, its effects on emission reduction remain partial and non-immediate. This pattern reflects the structural inertia of the U.S. energy system and the continued coexistence of conventional and renewable energy sources during the transition phase.

Overall, the correlation matrix reveals a clear divide between the fossil energy block, characterized by strong internal interdependencies, and the renewable energy block, marked by more autonomous and heterogeneous dynamics. These findings underscore the importance of econometric approaches capable of capturing nonlinear and time-varying relationships, particularly in a context shaped by energy transition, intensifying climate risks, and persistent geopolitical uncertainty.

We examine the interdependence relationships between different energy sources and sectoral CO_2 emissions in China using the Pearson correlation matrix, the results of which are presented in **Figure 2**. This analysis makes it possible to identify both the strength and the direction of the linear relationships among the components of China's energy mix and the associated emission dynamics, thereby providing an initial understanding of the mechanisms of co-evolution and substitution within the broader context of the energy transition.

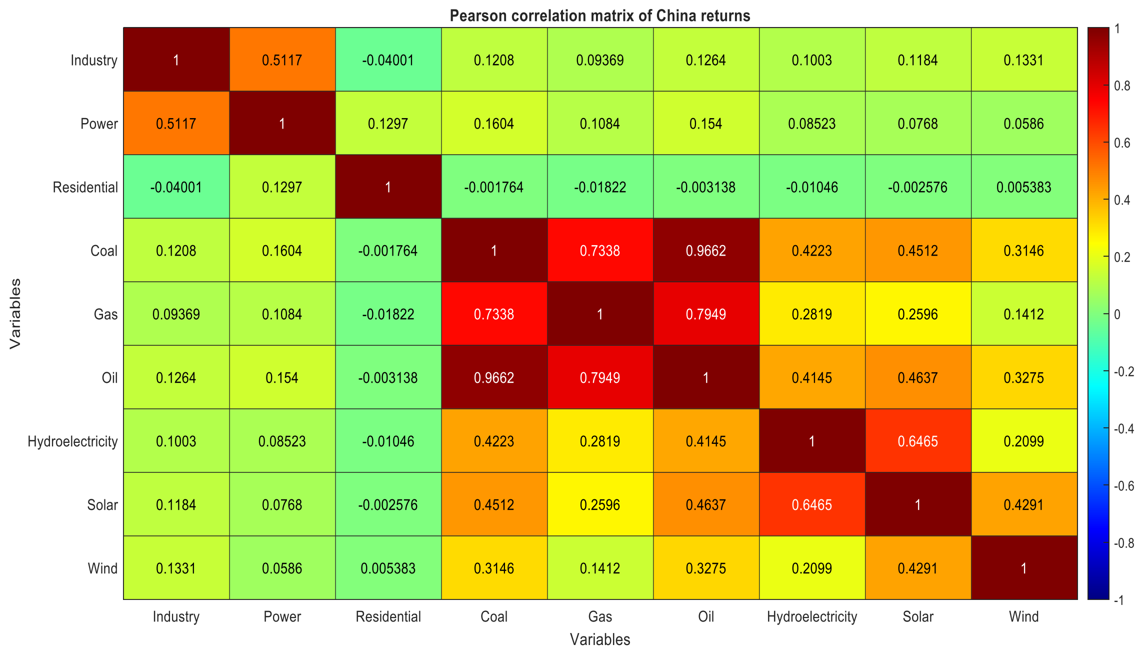


Figure 2 presents the Pearson total correlation matrix between the returns of sectoral CO_2 emissions; namely the industrial, electricity generation, and residential sectors; and the main

renewable and non-renewable energy sources in China. The matrix reveals distinct patterns of interdependence that reflect the structure of the Chinese energy system and its transition trajectory. The results first indicate a moderate positive correlation between industrial emissions and those from the electricity sector, suggesting a strong structural relationship between industrial production and electricity demand. This interdependence reflects the central role of manufacturing in the Chinese economy, which continues to rely heavily on an electricity system historically dominated by fossil fuels. By contrast, residential emissions appear only weakly correlated, or even slightly negatively correlated, with those of the other sectors, pointing to a relatively autonomous dynamic shaped by targeted energy-efficiency policies, controlled urbanization, and the gradual electrification of household energy use.

A particularly salient finding from the matrix is the extremely high correlation observed among fossil energy sources, especially between coal and oil, as well as between coal and gas and between gas and oil ($\rho \approx 0.79$). These strong correlations indicate a pronounced co-movement of fossil fuels in China, suggesting that these markets are driven largely by common determinants such as centralized energy planning, aggregate economic growth, domestic supply conditions, and international exogenous shocks. This high degree of synchronization also highlights the difficulty of rapidly substituting one fossil energy source for another in a system characterized by substantial structural inertia.

Renewable energy sources exhibit moderate positive correlations with fossil fuels, particularly between hydropower and coal and between solar energy and oil. Unlike the pattern observed in the United States, these positive correlations suggest that renewable energy in China still evolves largely in a complementary relationship with fossil fuels rather than functioning as a direct substitute. This result reflects the gradual transition strategy adopted by Chinese authorities, in which renewable capacities are integrated into the existing energy system to meet rapidly growing energy demand, rather than immediately displacing carbon-intensive sources. In addition, the relatively high correlation between hydropower and solar energy, as well as between solar and wind power, points to a certain degree of internal coherence within the renewable energy block. This suggests that investment in these technologies is being driven by common public policy frameworks, coordinated climate objectives, and industrial strategies aimed at strengthening energy security and technological independence. Nevertheless, these correlations remain lower than those observed among fossil fuels, underscoring the greater heterogeneity in the determinants of renewable energy returns. Finally, the positive but moderate correlations between sectoral CO_2 emissions and the various energy sources indicate that, despite significant decarbonization efforts, economic and energy growth continue to exert upward pressure on emission levels. This configuration suggests that the environmental gains associated with renewable energy expansion are partly offset by the increase in total energy demand. Overall, **Figure 2** reveals a highly integrated Chinese energy system, characterized by strong interdependence among fossil energy sources and an energy transition that remains largely complementary rather than substitutive. These findings underscore the importance of dynamic and nonlinear analyses to better understand the future evolution of interactions between energy sources, CO_2 emissions, and climate policies in a context marked by sustained economic growth and persistent geopolitical uncertainty.

4. Dynamic Interactions Between Energy Returns and Sectoral CO_2 Emissions: A Multivariate Markov Chain Analysis

The use of a multi-regime Markov chain model in our study makes it possible to accurately capture the complexity of the dynamics governing energy markets and sectoral CO_2 emissions, while clearly distinguishing between periods of stability and instability. This methodological framework proves particularly well suited for analyzing the effects of major economic and geopolitical shocks; most notably the COVID-19 pandemic, the Russia–Ukraine conflict, and the war involving Iran, Israel, and the United States; on energy returns in the United States and China. We employ information criteria to determine the optimal number of regimes for each return series considered in our analysis. **Table 3** reports the selected number of regimes for the different fossil and renewable energy returns, as well as for sectoral CO_2 emissions in the United States.

Table 3. Optimal Markov regime for each mentioned return in the United States			
Returns	Optimal_K	Min_AIC	Min_BIC
Industry	5	3527.368	3539.059
Power	5	3496.445	3508.135
Residential	5	3430.260	3441.951
Coal	5	2512.350	2524.040
Gas	5	2788.141	2799.832
Oil	5	2919.981	2931.672
Hydroelectricity	5	2742.500	2754.191
Solar	5	3119.846	3131.537
Wind	5	3133.341	3145.032

Table 3 reports the results of selecting the optimal number of Markov regimes for energy returns and sectoral CO_2 emissions in the United States, based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). The estimates consistently indicate that all the return series under investigation; including those related to the industrial, power generation, and residential sectors, as well as the main fossil and renewable energy sources;are characterized by an optimal specification with **five regimes**. This homogeneity in the selected number of regimes suggests the presence of common volatility dynamics and shared structural transition patterns simultaneously affecting the different segments of the U.S. energy system. Moreover, the minimum AIC and BIC values obtained for the five-regime model confirm the superiority of this specification in capturing nonlinear behaviors and regime shifts associated with recent economic, health, and geopolitical shocks.

Sectors associated with CO_2 emissions; namely industry, electricity generation, and residential use; exhibit relatively high values of the information criteria, reflecting substantial dynamic complexity and pronounced sensitivity to fluctuations in economic activity and changes in energy demand. In particular, the electricity generation sector displays comparatively lower AIC and BIC values than the industrial and residential sectors, suggesting a more stable volatility structure, albeit punctuated by occasional structural breaks linked to supply constraints and adjustments in the energy mix. Regarding fossil energy sources, coal records the lowest AIC and BIC values, indicating dynamics characterized by clearly identifiable regimes, reflecting their structural decline and heightened exposure to environmental regulations and climate policies. By contrast, oil and natural gas exhibit higher information criteria, signaling persistent volatility and frequent regime transitions, which are further amplified by international shocks in global hydrocarbon markets.

Renewable energy sources; hydropower, solar, and wind; also exhibit a five-regime structure, indicating that despite their more sustainable nature, these sources are not immune to instability. Solar and wind energy returns display relatively high AIC and BIC values, suggesting heightened sensitivity to climatic conditions, technological developments, and adjustments in policy support mechanisms related to the energy transition. Overall, these findings confirm the relevance of a **multi-regime Markov framework** for analyzing energy returns and CO_2 emissions in the United States. The adoption of a five-regime specification enables a fine-grained identification of periods of stability, adjustment, and pronounced instability, thereby providing a robust analytical framework for evaluating energy and environmental risks, as well as for designing public policies tailored to the cyclical phases of the energy system.

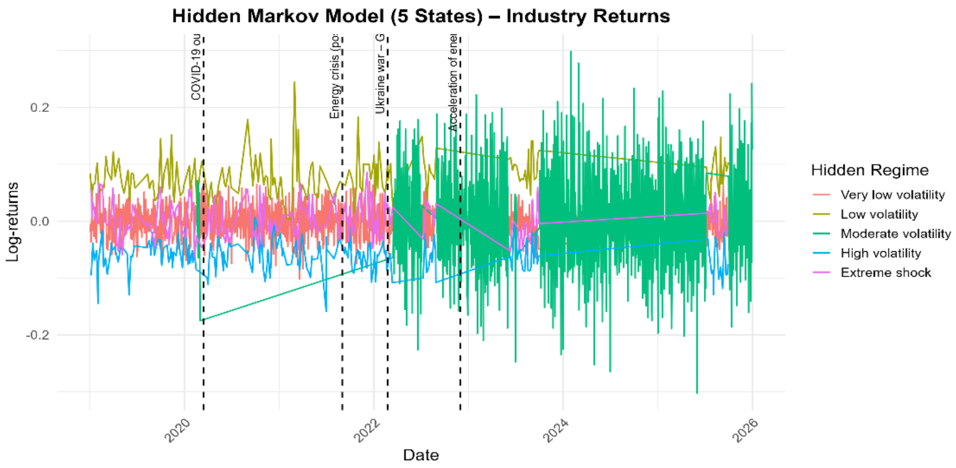
In line with the analysis conducted for the United States, we identify the optimal number of Markov regimes for each fossil and renewable energy return, as well as for sectoral CO_2 emissions in China. The results of this regime selection procedure are reported in **Table 4**.

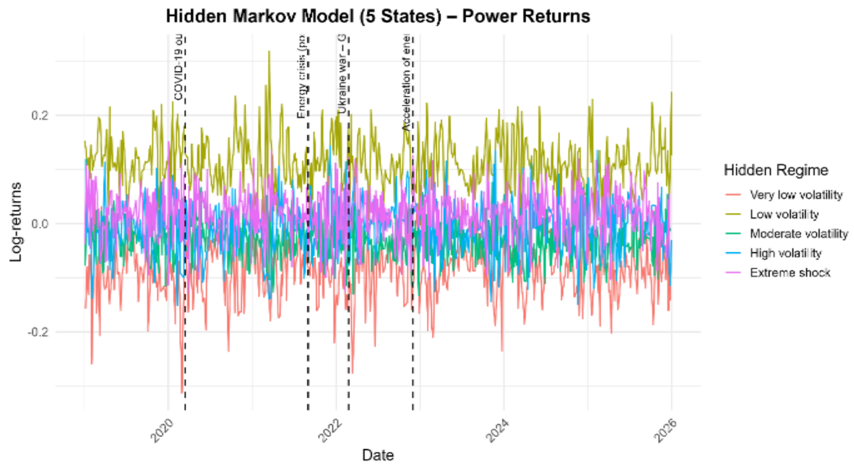
Table 4. Optimal Markov regime for each mentioned return in the China

Returns	Optimal_K	Min_AIC	Min_BIC
Industry	5	3539.052	3550.743
Power	5	3512.658	3524.349
Residential	5	3426.831	3438.522
Coal	5	2260.592	2272.283
Gas	5	2240.712	2252.402
Oil	5	2260.592	2272.283
Hydroelectricity	5	2286.776	2298.467
Solar	5	2344.364	2356.055
Wind	5	2356.917	2368.608

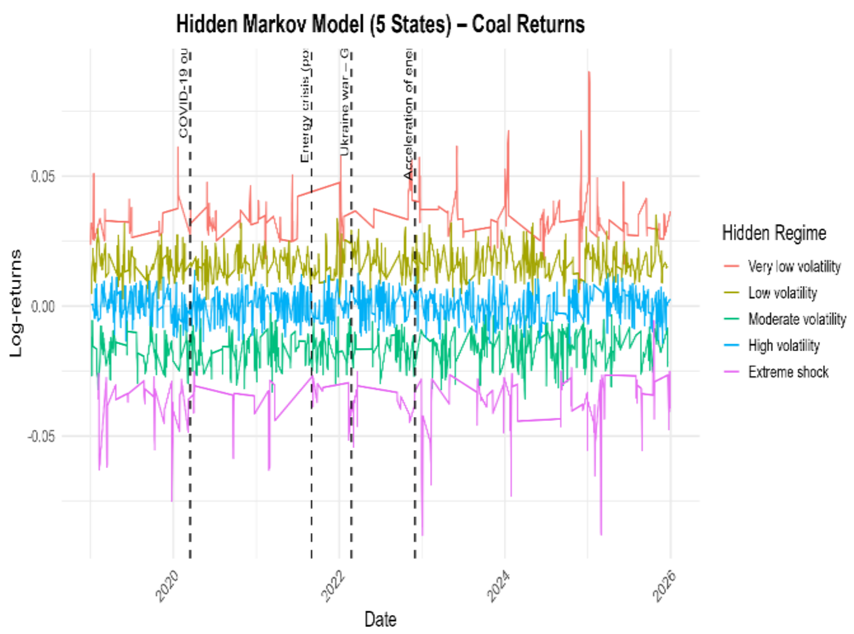
Table 4 reports the results of the selection of the optimal number of Markov regimes for fossil and renewable energy returns, as well as for sectoral CO_2 emissions in China, based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). As in the U.S. case, the results unanimously indicate that the optimal specification corresponds to a **five-regime model** for all the series analyzed. This convergence toward a common number of regimes highlights the presence of complex and shared structural dynamics affecting the various segments of the Chinese energy system. The minimum AIC and BIC values obtained for the five-regime specification further confirm its ability to effectively capture nonlinear

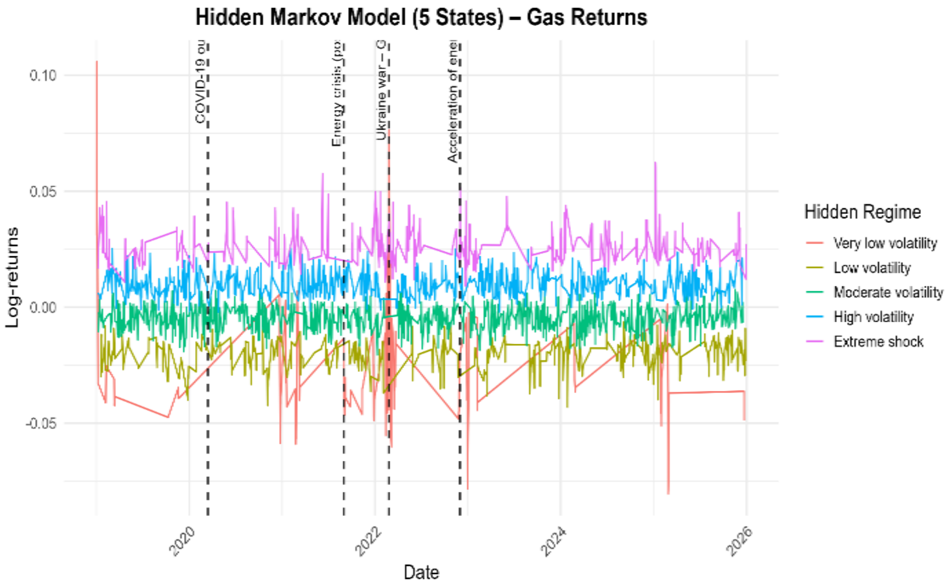
behaviors, episodes of heightened instability, and regime transitions induced by exogenous shocks such as the COVID-19 pandemic and international geopolitical tensions.
Sectors associated with CO_2 emissions; namely industry, electricity generation, and residential use; exhibit relatively high levels of the information criteria, indicating substantial variability and heightened sensitivity to fluctuations in economic and industrial activity. The industrial sector records the highest AIC and BIC values, reflecting the central role of heavy industry in the Chinese economy and its persistent reliance on highly carbon-intensive energy sources. With respect to fossil energy, coal, oil, and natural gas display dynamics characterized by five distinct regimes, with relatively similar AIC and BIC values across these energy sources. This structure reflects the inherent volatility of the Chinese energy mix, which is marked by a strong dependence on coal and increasing exposure to fluctuations in international hydrocarbon markets. The results further suggest that energy policy adjustments, together with external supply constraints, have contributed to intensifying transitions between volatility regimes.
Renewable energy sources; hydropower, solar, and wind; also exhibit a five-regime structure, indicating that despite their growing role in China's energy transition strategy, their returns remain subject to significant instability. Higher values of the information criteria for solar and wind energy reflect heightened sensitivity to climatic conditions, technological developments, and adjustments in public support policies. Overall, the results reported in **Table 4** confirm the relevance of a five-regime Markov model for analyzing energy returns and sectoral CO_2 emissions in China. This approach enables a fine-grained identification of phases of stability, transition, and heightened volatility, thereby providing a robust analytical framework for the assessment of energy and environmental risks. It also offers important insights for the design of energy transition strategies and climate policies tailored to the cyclical dynamics and structural shocks characterizing the Chinese economy.
Considering the results obtained for both countries, it emerges that a **five-regime Markov specification** represents the optimal choice for all fossil and renewable energy returns, as well as for sectoral CO_2 emissions, in both the United States and China. This methodological convergence highlights the presence of energy and environmental dynamics characterized by multiple phases of stability and instability that are common to both economies, despite their distinct energy systems. Retaining five regimes allows for a fine-grained characterization of nonlinear behaviors, abrupt transitions, and episodes of heightened volatility driven by economic, health-related, and geopolitical shocks. This homogeneity in the selected number of regimes enhances the comparability of the analyses between the United States and China and provides a robust foundation for the interpretation of the empirical findings and their implications for energy and climate policy design. **Figure 3** illustrates the five-state Markov chain associated with each energy return and sectoral CO_2 emission considered for the United States.

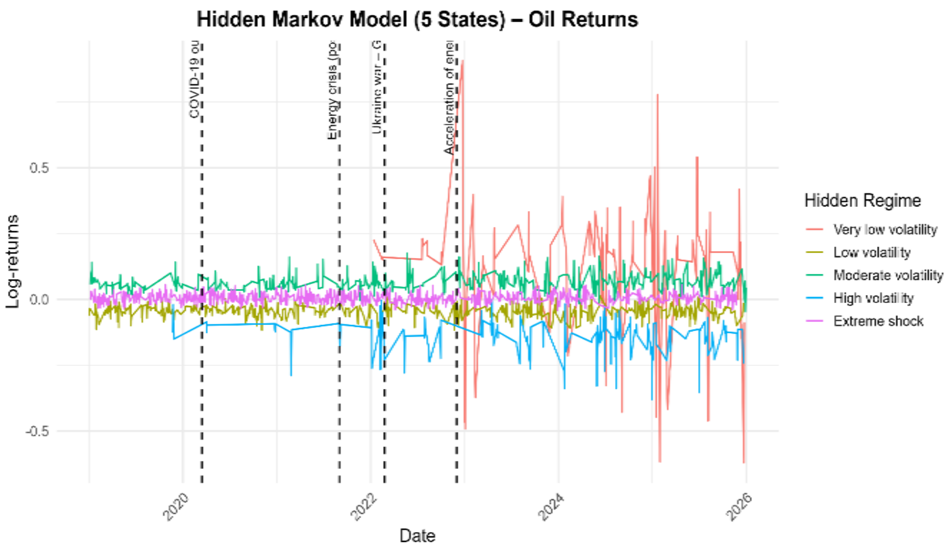

Hidden Markov Model (5 States) – Industry Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock
COVID-19 ou
Energy crisis (po
Ukraine war – G
Acceleration of ener
0.2
0.0
-0.2
2020
2022
2024
2026

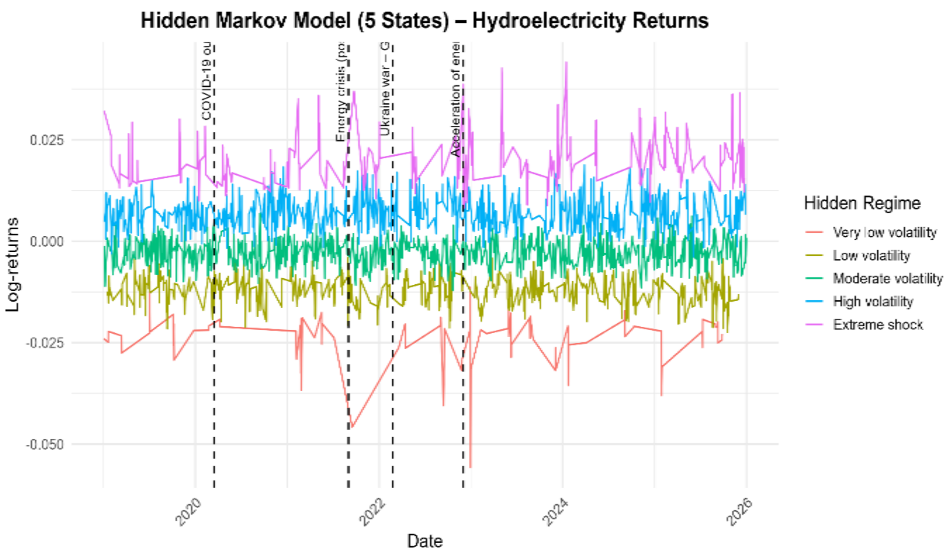

Hidden Markov Model (5 States) – Power Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock


Hidden Markov Model (5 States) – Residential Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock


Hidden Markov Model (5 States) – Coal Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock


Hidden Markov Model (5 States) – Gas Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock


Hidden Markov Model (5 States) – Oil Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock


Hidden Markov Model (5 States) – Hydroelectricity Returns
Log-returns
Date
Hidden Regime
Very low volatility
Low volatility
Moderate volatility
High volatility
Extreme shock

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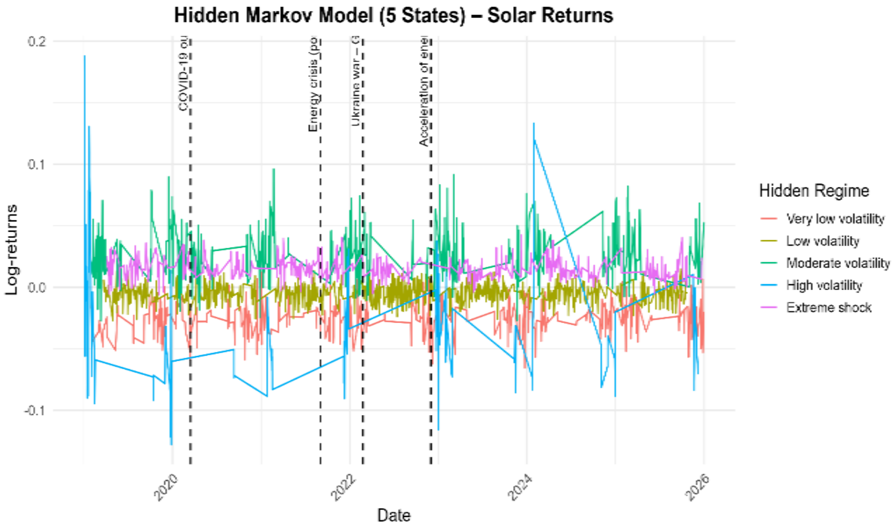

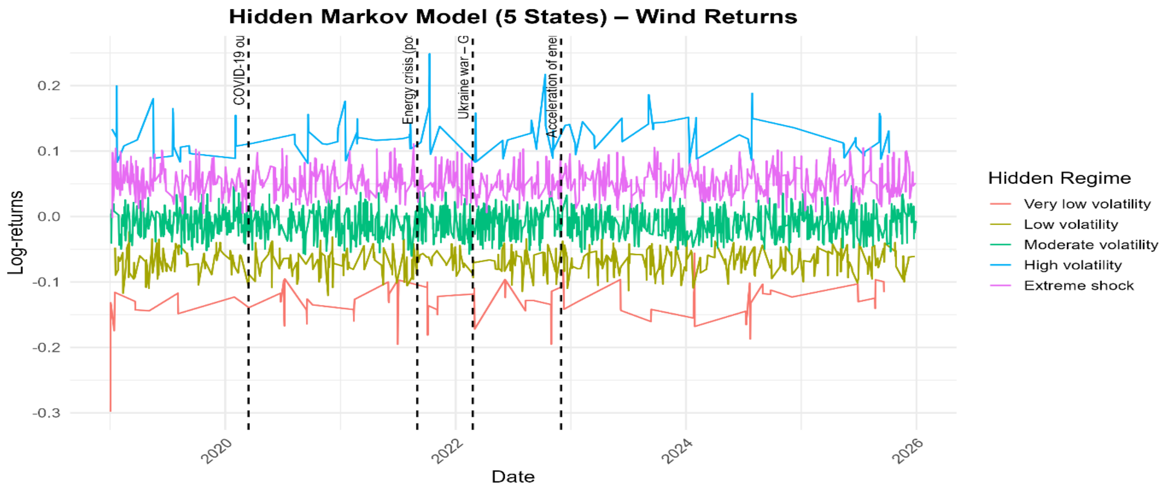

Figure 3 presents the estimated five-state Markov chains for energy returns and sectoral CO_2 emissions in the United States. Each panel illustrates the temporal evolution of returns across distinct Markov regimes, reflecting different levels of volatility and stability within the U.S. energy and environmental system. The identification of five states makes it possible to clearly distinguish several recurring market phases, ranging from periods of low volatility; associated with relatively stable returns; to regimes of high or extreme instability corresponding to episodes of economic, health-related, or geopolitical shocks. Low-volatility regimes generally reflect phases of normal market functioning, characterized by gradual adjustments in the energy mix and relatively predictable demand conditions. By contrast, high and extreme volatility regimes are marked by abrupt fluctuations, indicative of structural disruptions such as the COVID-19 pandemic, tensions in international energy markets, or uncertainties arising from recent geopolitical conflicts.

For sectoral CO_2 emissions (industry, electricity generation, and residential use), **Figure 3** highlights a recurrent alternation between stable and unstable regimes, underscoring the strong sensitivity of these sectors to fluctuations in economic activity and changes in energy supply conditions. The electricity generation sector appears to be frequently exposed to rapid regime

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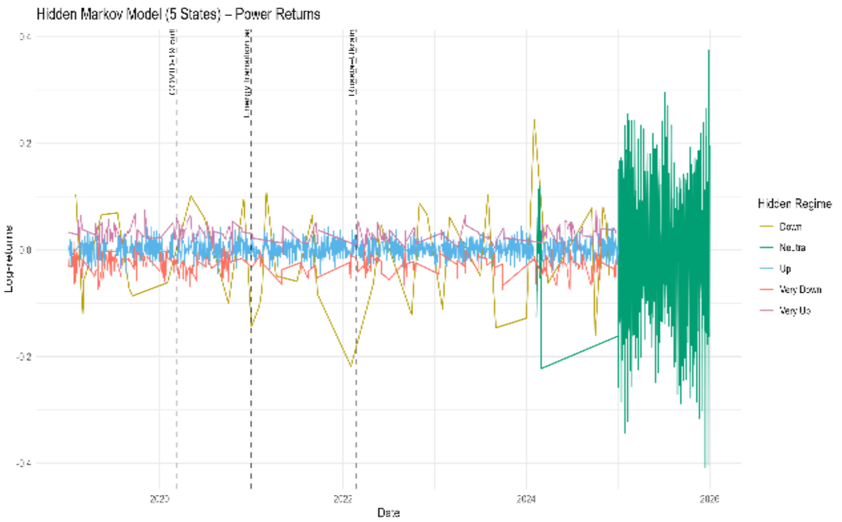
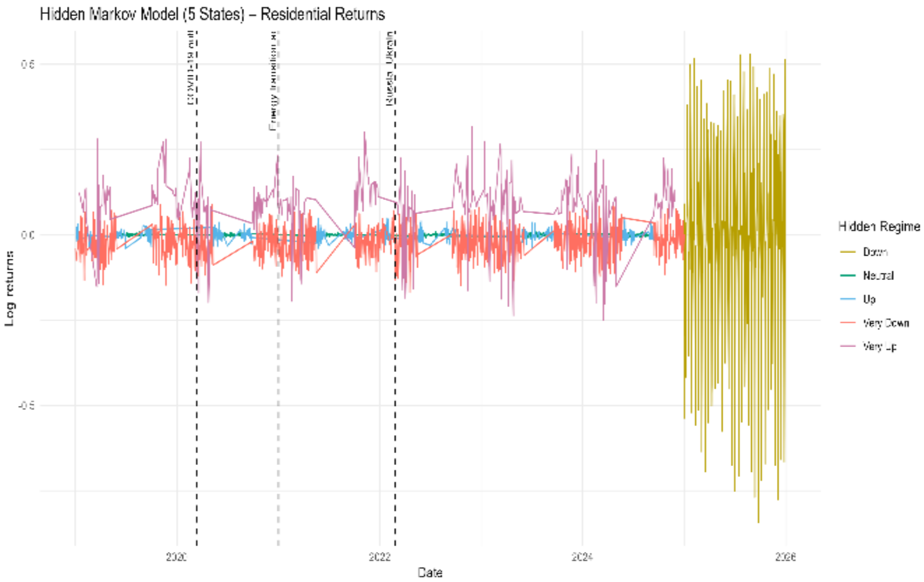
transitions, reflecting ongoing adjustments in the electricity mix between fossil and renewable sources, as well as grid balancing constraints. The industrial sector, by contrast, exhibits prolonged episodes of high-volatility regimes, capturing its direct exposure to business cycle fluctuations and shocks in global demand.

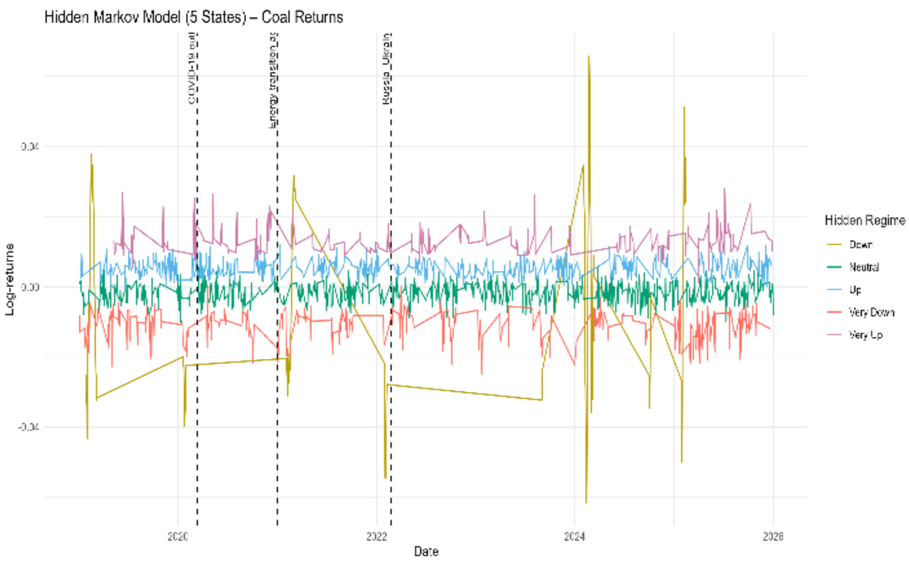
Regarding energy sources, this **Figure** reveals differentiated regime dynamics between fossil fuels and renewable energies. Returns on coal, oil, and natural gas exhibit more pronounced instability regimes, characterized by frequent transitions toward high-volatility states, particularly during periods of heightened stress in international hydrocarbon markets. By contrast, renewable energy sources; hydropower, solar, and wind; display a more nuanced alternation between intermediate and extreme regimes. While these sources benefit from phases of relative stability, they nevertheless remain sensitive to climatic conditions, technological developments, and adjustments in support policies, which occasionally lead to shifts toward more unstable regimes.

Overall, **Figure 3** highlights the deeply nonlinear and cyclical nature of energy returns and sectoral CO_2 emissions in the United States. The presence of frequent transitions among the five regimes confirms that the U.S. energy system is subject to successive phases of stability, adjustment, and severe disruption. These findings provide strong justification for the use of a multi-regime Markov model and underscore the importance of accounting for temporal dependence and regime shifts in the analysis of energy and climate-related risks. From a public policy perspective, this dynamic regime-based interpretation offers a relevant framework for anticipating periods of heightened vulnerability within the energy system and for adapting investment, regulatory, and transition strategies toward more sustainable energy sources.

Figure 4 presents the five-state Markov chain associated with the various energy returns of fossil and renewable sources, as well as with sectoral CO_2 emissions considered for China.


Hidden Markov Model (5 States) – Power Returns
Log-returns
Date
2020
2022
2024
2026
Hidden Regime
Down
Neutral
Up
Very Down
Very Up


Hidden Markov Model (5 States) – Residential Returns
Log returns
0.5
0.0
-0.5
Date
2020
2022
2024
2026
Hidden Regime
Down
Neutral
Up
Very Down
Very Up


Hidden Markov Model (5 States) – Coal Returns
Log-returns
Date
2020
2022
2024
2026
Hidden Regime
Down
Neutral
Up
Very Down
Very Up

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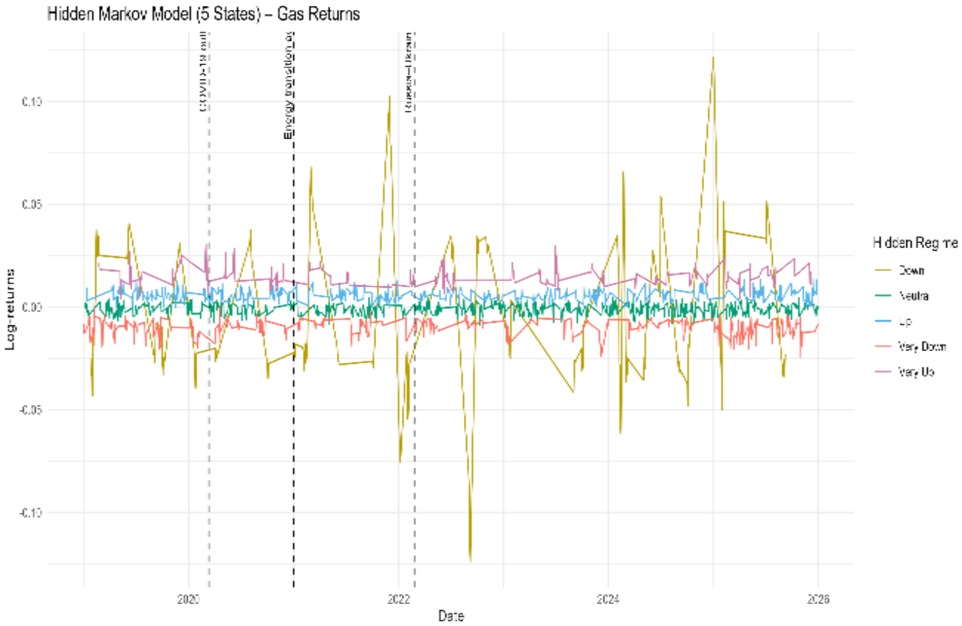

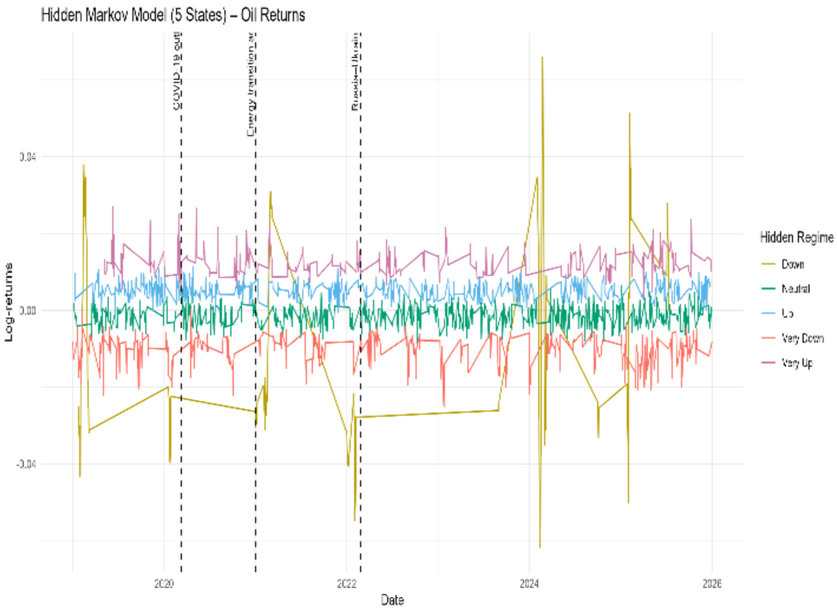

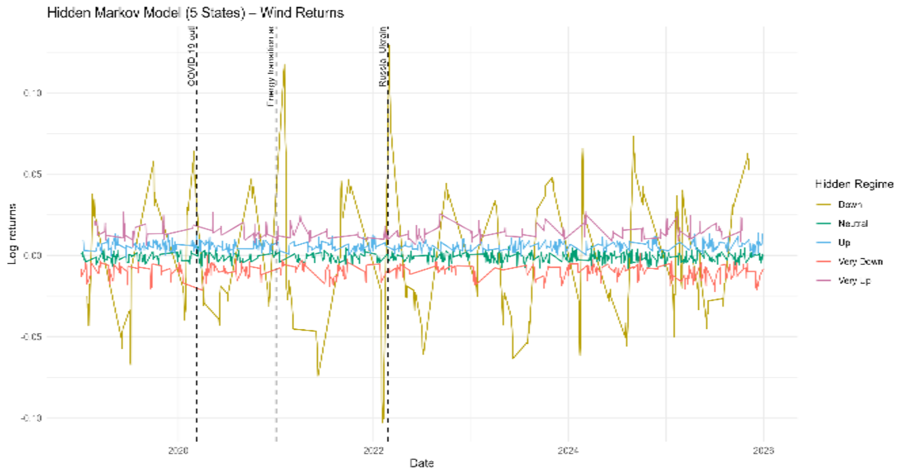

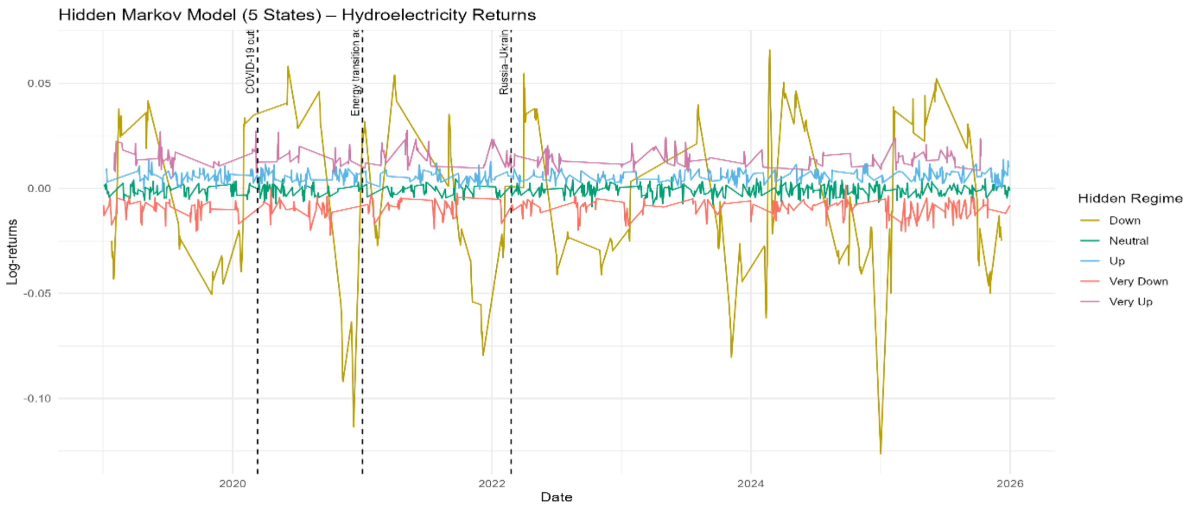

Figure 4 illustrates the estimated five-state Markov chains for fossil and renewable energy returns, as well as for sectoral CO_2 emissions in China. Each panel highlights the temporal evolution of returns across distinct Markov regimes, reflecting differentiated levels of stability and volatility within the Chinese energy and environmental system. The identification of five states allows for a fine-grained characterization of the nonlinear nature of the observed dynamics, distinguishing phases of low volatility; associated with relative structural stability; from regimes of high or extreme instability corresponding to periods of major disruptions.

With respect to sectoral CO_2 emissions, **Figure 4** reveals a marked alternation between stable and unstable regimes, particularly pronounced in the industrial and electricity generation sectors. The industrial sector exhibits prolonged episodes in high-volatility regimes, reflecting its strong exposure to business cycles, energy demand fluctuations, and adjustments in industrial policy. The electricity sector, by contrast, displays frequent transitions across regimes, capturing persistent pressures related to grid balancing, the coexistence of fossil and renewable energy sources, and the gradual reconfiguration of the energy mix. Residential sector emissions, however, appear relatively more fragmented, with dynamics characterized by intermittent shifts toward extreme regimes, often associated with exogenous shocks such as the COVID-19 pandemic or unusually severe climatic events. Regarding fossil energy sources, the returns on coal, oil, and natural gas are characterized by a strong predominance of intermediate and high-volatility regimes, with relatively persistent transitions between these states. This configuration reflects the substantial structural inertia of the Chinese energy system, which remains heavily reliant on fossil fuels, as well as its exposure to fluctuations in international energy markets, supply constraints, and successive adjustments in environmental regulation. Coal exhibits well-defined and relatively persistent regimes, underscoring its central role in China's energy mix despite medium- and long-term decarbonization objectives.

Renewable energy sources; hydropower, solar, and wind; exhibit distinct regime dynamics, yet they are not free from instability. Hydropower displays relatively stable phases, intermittently disrupted by shifts toward high-volatility regimes, primarily driven by hydrological variability and climatic constraints. Solar and wind energy, by contrast, are characterized by more frequent alternations between intermediate and extreme regimes, reflecting their sensitivity to weather conditions, rapid technological change, and adjustments in public support policies. These results suggest that, despite their increasing role in China's energy transition, renewable energy sources remain subject to significant short-term instability.

Figure 4 highlights a Chinese energy system marked by strong regime heterogeneity and frequent transitions between states, thereby confirming the presence of nonlinear behaviors and structural breaks. The coexistence of prolonged phases of stability and episodes of extreme instability underscores the decisive impact of exogenous shocks; health-related, economic, and geopolitical; on energy returns and CO_2 emissions. These findings fully justify the use of a multi-regime Markov model and suggest that China's energy transition remains characterized by a largely gradual dynamic, driven by cyclical adjustments rather than abrupt structural shifts. From a public policy perspective, this regime-based interpretation provides a relevant analytical framework for anticipating periods of heightened vulnerability in the energy system and for adapting low-carbon transition strategies in an environment of persistent uncertainty.

Table 5 (Appendix) reports the estimated transition probability matrices associated with the five-state Markov chain for energy returns; both fossil and renewable; as well as for sectoral CO_2 emissions in the United States. These transition probabilities make it possible to assess the persistence of each regime and to analyze the dynamics of transitions across favorable, unfavorable, and extreme states, thereby highlighting the mechanisms of adjustment and shock propagation within the U.S. energy system. **Table 5** reports the transition probability matrices associated with the five-state Markov chain (Very Down, Down, Normal, Up, Very Up) estimated for sectoral CO_2 emission returns; industry, electricity generation, and residential; as well as for the main fossil and renewable energy sources in the United States. These matrices allow for an in-depth analysis of regime persistence and the dynamics of transitions across favorable, unfavorable, and extreme states, thereby providing valuable insights into the nonlinear behavior of the U.S. energy and environmental system. A key finding emerges from the analysis of the diagonal elements of the matrices: extreme regimes (Very Down and Very Up) exhibit the highest persistence probabilities, particularly for fossil fuels and certain renewable energy sources. For example, the probabilities of remaining in the Very Down or Very Up states for coal, natural gas, oil, hydropower, and solar energy frequently exceed 0.53, reaching up to approximately 0.68 for coal in the Very Down regime and around 0.63 in the

Very Up regime. This strong persistence indicates that when a major shock occurs, its effects tend to be prolonged over time, reflecting the high degree of structural inertia characterizing U.S. energy markets. By contrast, intermediate states (Normal, Down, and Up) display lower persistence probabilities and more frequent transitions toward other regimes. This pattern suggests that these states correspond to transitory adjustment phases during which returns remain particularly sensitive to cyclical changes and macroeconomic signals.

For sectoral CO_2 emissions, notable differences emerge across sectors. The residential sector stands out due to the high persistence of the Normal regime (with probabilities exceeding 0.53), reflecting relatively stable emission dynamics associated with household energy use, more predictable consumption patterns, and gradual improvements in energy efficiency. In contrast, the industrial and electricity generation sectors exhibit greater regime mobility, with significant transition probabilities from Down or Normal states toward extreme regimes. This configuration highlights the strong exposure of these sectors to business cycle fluctuations, adjustments in the energy mix, and exogenous shocks. The transition matrices for coal, natural gas, and oil reveal pronounced persistence in both negative and positive extreme regimes. Transitions from the Very Down state to other regimes remain relatively limited, indicating that periods of crisis or sharp contraction in fossil fuel markets tend to persist. Similarly, Very Up regimes exhibit high stability, corresponding to boom phases characterized by supply constraints, price surges, or geopolitical shocks. These findings underscore the high vulnerability of fossil energy markets to global disruptions and the difficulty of a rapid return to normal conditions following a shock.

Although renewable energy sources; hydropower, solar, and wind; are often perceived as more stable in the long run, the transition matrices show that they are not immune to short-term instability. The Very Down and Very Up regimes also display high persistence probabilities for these sources, exceeding 0.50 in most cases. However, compared with fossil fuels, renewable energies exhibit slightly higher probabilities of transitioning from extreme states toward intermediate regimes, suggesting a greater capacity for adjustment. This responsiveness is likely supported by public policy mechanisms, technological diversification, and the increasing flexibility of electricity grids. Overall, **Table 5** highlights a Markovian dynamic characterized by strong persistence in extreme regimes and greater mobility in intermediate states, thereby confirming the deeply nonlinear nature of energy returns and sectoral CO_2 emissions in the United States. The coexistence of prolonged phases of extreme stability and rapid transitions among intermediate regimes underscores the critical role of exogenous shocks; health-related, geopolitical, and macroeconomic; in shaping energy dynamics. These results fully justify the use of a multi-regime Markov chain model and yield important implications for energy policy. The strong inertia of unfavorable regimes suggests that negative shocks may have long-lasting effects, calling for more responsive stabilization mechanisms and an acceleration of energy diversification policies. Conversely, the persistence of favorable regimes highlights the potential of expansion phases to strengthen investments in low-carbon infrastructure and to consolidate the U.S. energy transition.

Table 6 (Appendix) reports the estimated transition probability matrices associated with the five-state Markov chain for the returns of the various fossil and renewable energy sources, as well as for sectoral CO_2 emissions in China. These transition probabilities allow for an assessment of regime persistence and an analysis of the dynamics governing transitions across favorable, unfavorable, and extreme states, thereby highlighting the mechanisms of adjustment, transmission, and shock propagation within the Chinese energy and environmental system.

Table 6 reports the transition probability matrices associated with the five-state Markov chain estimated for sectoral CO_2 emission returns, as well as for the main fossil and renewable energy sources in China. The analysis of these probabilities makes it possible to assess regime persistence, state mobility, and the dynamics of shock transmission within an energy system characterized by strong integration and a gradual transition process. A first salient finding concerns the **high persistence of extreme regimes**, particularly for fossil energy sources and certain renewables. The probabilities of remaining in the *Very Down* state frequently exceed 0.47 and reach more than 0.57 for residential electricity and hydropower, indicating substantial inertia during phases of contraction or major disruption. Similarly, the probabilities associated with the *Very Up* state are high for the residential sector (approximately 0.69), as well as for coal, oil, hydropower, and wind energy, suggesting that phases of rapid expansion or favorable structural tensions also tend to persist over time. By contrast, the intermediate states (*Down, Normal,* and *Up*) exhibit greater mobility, with significant probabilities of transition toward extreme regimes. This configuration confirms that adjustment phases in China often act as **bridges** between periods of relative stability and states of pronounced instability. For sectoral CO_2 emissions, the results reveal **heterogeneous dynamics** across sectors. The residential sector stands out due to particularly strong persistence in the *Down* and *Very Up* regimes, reflecting high sensitivity to public policies, rapid urbanization, and changes in energy consumption behavior. In contrast, the industrial and electricity generation sectors exhibit more frequent alternations across regimes, indicating heightened exposure to business cycle fluctuations and energy mix adjustments. The relatively high probability of transitions from *Normal* or *Up* states toward extreme regimes highlights the critical role of exogenous shocks;such as the COVID-19 pandemic, geopolitical tensions, and supply constraints;in shaping China's emission dynamics.

The matrices associated with coal, natural gas, and oil reveal strong persistence in extreme regimes, particularly the *Very Down* regime for coal and the *Very Up* regime for oil. This configuration reflects the **structural complementarity of fossil energy sources in China**, where adjustments in the energy mix remain largely coordinated and centrally planned. Transitions from unfavorable to favorable regimes are relatively limited, underscoring the difficulty of achieving rapid readjustment following a negative shock. Renewable energy sources; hydropower, solar, and wind; also display high persistence in extreme regimes, although their transition matrices reveal distinct profiles. Hydropower shows strong persistence in the *Very Down* regime, reflecting its dependence on hydrological and climatic conditions. Solar and wind energy, by contrast, exhibit pronounced transitions toward the *Very Up* regime, capturing rapid deployment supported by ambitious public policies, but also revealing elevated short-term volatility linked to technical and meteorological constraints.

The comparison between the five-state transition probability matrices for the United States and China highlights **major structural differences** in the Markovian dynamics of their energy systems. First, while both countries exhibit strong persistence in extreme regimes, this persistence is more asymmetric in China. Probabilities associated with the *Very Down* and *Very Up* states are generally higher and more concentrated, reflecting a more centralized and inert energy system in which shocks tend to generate prolonged effects. By contrast, in the United States, intermediate states display greater mobility, suggesting a faster adjustment capacity of market mechanisms. Second, sectoral CO_2 emissions appear relatively more stable in the United States, particularly for the residential sector, which is largely dominated by the *Normal* regime. In China, this same sector is characterized by persistent extreme regimes, reflecting more rapid structural transformations linked to urbanization, electrification, and demand-side management policies. Third, with respect to renewable energy sources, the United States exhibits a more **substitutive dynamic** vis-à-vis fossil fuels, with more frequent transitions toward intermediate regimes. In China, by contrast, the transition matrices suggest a still largely **complementary logic**, in which renewables and fossil fuels co-evolve, leading to greater persistence of extreme regimes.

Overall, **Table 6** reveals a Chinese energy system characterized by strong persistence in extreme regimes, limited mobility away from crisis or expansion states, and an energy transition driven more by **addition than substitution**. In comparison, the U.S. energy system appears more flexible, with more frequent transitions across intermediate regimes, reflecting a greater capacity to absorb shocks. These findings confirm the relevance of a multi-regime Markov framework and suggest that, in the case of China, energy transition policies should not only reinforce the deployment of renewable energy sources but also reduce the system's structural inertia to limit the persistence of unfavorable regimes and accelerate the decoupling of energy growth from CO_2 emissions.

Figure 5 illustrates the transition probabilities among the five states of the Markov chain estimated for the different levels of energy returns and sectoral CO_2 emissions in the United States. These probabilities reflect the dynamics governing transitions from one state to another and make it possible to analyze regime persistence as well as structural changes in energy performance and carbon emissions at the sectoral level.

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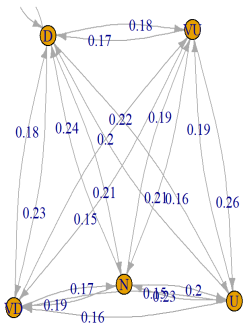
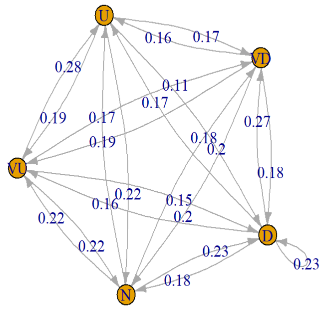
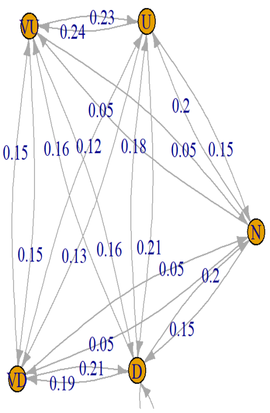
Markov Transition Diagram (5 States) – Industry Returns



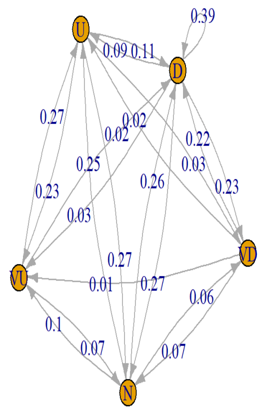
Markov Transition Diagram (5 States) – Power Returns



Markov Transition Diagram (5 States) – Residential Returns



Markov Transition Diagram (5 States) – Coal Returns



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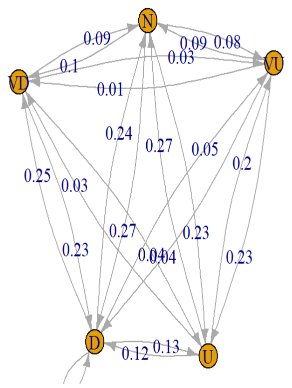
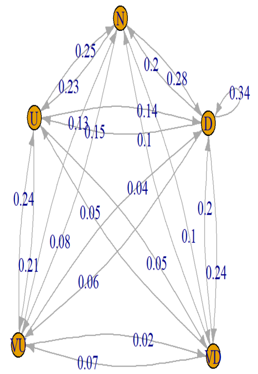
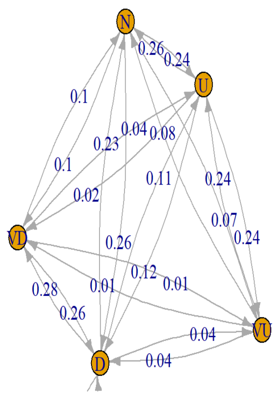
Markov Transition Diagram (5 States) – Gas Returns



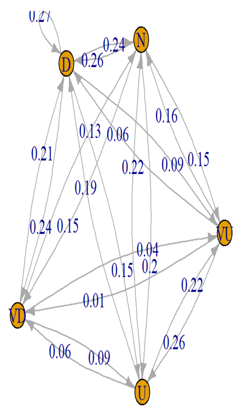
Markov Transition Diagram (5 States) – Oil Returns



Markov Transition Diagram (5 States) – Hydroelectricity Returns



Markov Transition Diagram (5 States) – Wind Returns



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Markov Transition Diagram (5 States) – Solar Returns

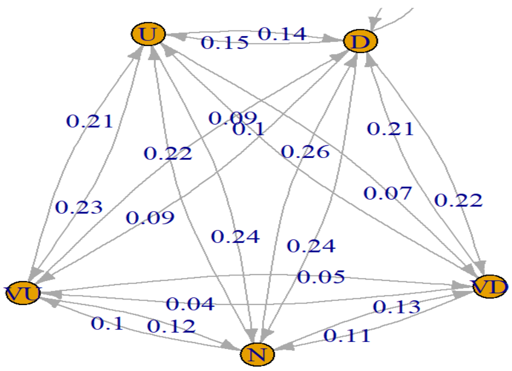


Figure 5 provides a concise illustration of the transition probabilities associated with the five-state Markov chain estimated for fossil and renewable energy returns as well as for sectoral CO_2 emissions in the United States. This graphical representation highlights the inter-regime dynamics of the U.S. energy and environmental system and allows for the identification of mechanisms of regime persistence, mobility, and shock propagation across states.

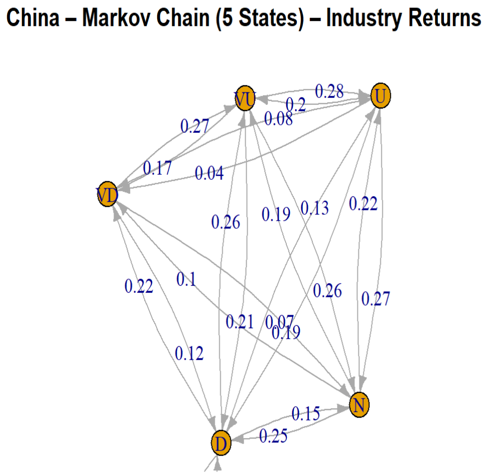
A key insight concerns the **strong persistence of extreme regimes**, particularly the *Very Down* and *Very Up* states, whose self-transition probabilities are consistently high. This configuration indicates that when a large negative or positive shock affects energy returns or sectoral emissions, its effects tend to persist over time. This inertia is especially pronounced for fossil energy sources; coal, natural gas, and oil; reflecting the structural rigidity of U.S. fossil fuel markets, which are highly exposed to geopolitical shocks, supply-side constraints, and fluctuations in international energy markets.

Figure 5 also shows that the intermediate states (*Normal, Down,* and *Up*) play a central role as **transition zones**. The probabilities of moving from these states toward extreme regimes are relatively high, suggesting that phases of apparent equilibrium or moderate adjustment remain fragile and can rapidly shift under the influence of exogenous shocks. These dynamic underscores the inherently unstable nature of energy returns in the short and medium run, even outside periods of major crises. For sectoral CO_2 emissions, **Figure 5** reveals heterogeneous patterns across sectors. The residential sector stands out for its high probability of remaining in the *Normal* state, reflecting relatively stable domestic emission dynamics associated with more predictable consumption behaviors and gradual energy-efficiency policies. By contrast, the industrial and electricity generation sectors exhibit greater regime mobility, with frequent transitions toward extreme states. This instability reflects their strong dependence on business cycles, adjustments in the energy mix, and demand-side shocks.

With respect to renewable energy sources, **Figure 5** indicates that although they are associated with a more favorable long-term decarbonization trajectory, they are not immune to short-term instability. The *Very Down* and *Very Up* regimes also display high persistence probabilities for hydropower, solar, and wind energy. However, compared with fossil fuels, transitions from extreme regimes toward intermediate states occur somewhat more frequently, suggesting a faster adjustment capacity of renewable energy sectors. This responsiveness is likely supported by public policy mechanisms, technological diversification, and the increasing flexibility of the electricity system.

Overall, **Figure 5** highlights a strongly nonlinear Markovian dynamic characterized by the coexistence of high persistence in extreme regimes and greater mobility in intermediate states. This structure confirms that the U.S. energy system is subject to successive phases of relative stability, adjustment, and prolonged disruption. From a public policy perspective, these results suggest that negative shocks tend to generate lasting effects on energy returns and CO_2 emissions, underscoring the need for more responsive stabilization policies and for accelerating the deployment of low-carbon energy sources to reduce the persistence of unfavorable regimes.

Figure 6 highlights the transition probabilities among the five Markov regimes identified for energy source returns and sectoral CO_2 emissions in China. Analyzing these probabilities provides insights into regime persistence, inter-state mobility, and structural adjustments within the Chinese energy system, reflecting the combined influence of economic, energy-related, and environmental dynamics.



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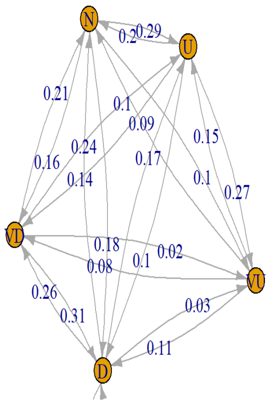
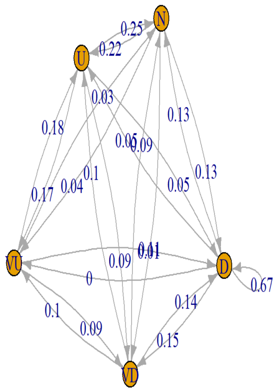
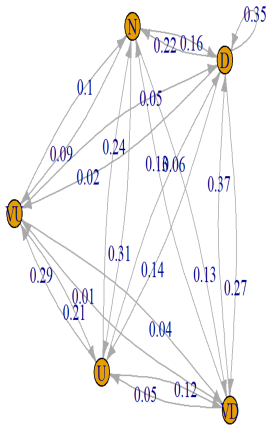
China – Markov Chain (5 States) – Power Returns



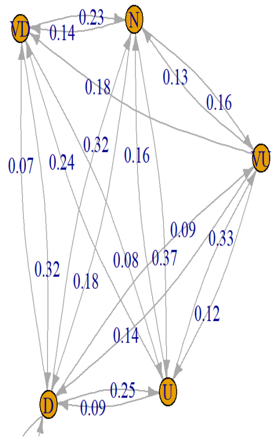
China – Markov Chain (5 States) – Residential Returns



China – Markov Chain (5 States) – Coal Returns



China – Markov Chain (5 States) – Gas Returns



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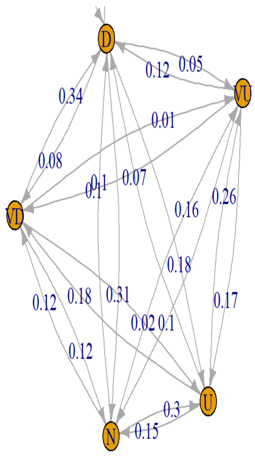
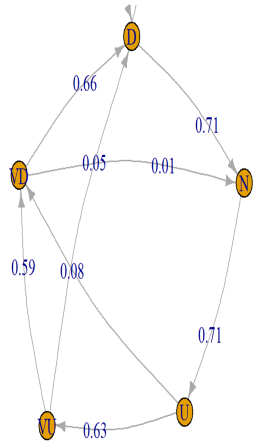
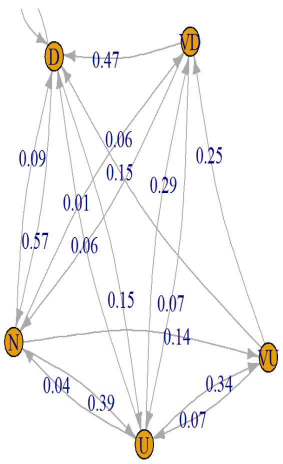
China – Markov Chain (5 States) – Oil Returns



China – Markov Chain (5 States) – Solar Returns



China – Markov Chain (5 States) – Wind Returns



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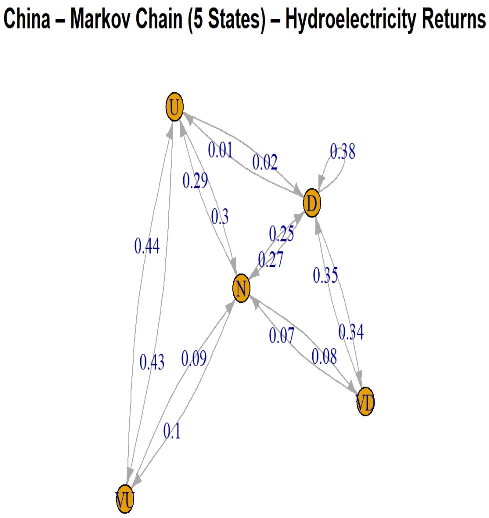

Figure 6 illustrates the transition probabilities associated with the five-state Markov chain estimated for fossil and renewable energy returns, as well as for sectoral CO_2 emissions in China. This representation makes it possible to apprehend the inter-regime dynamics of the Chinese energy system and to highlight the mechanisms of persistence, mobility, and shock propagation affecting energy and environmental performance. A first salient result lies in the strong persistence of **extreme regimes**, particularly the *Very Down* and *Very Up* states, whose self-transition probabilities are high for most of the series considered. This feature reflects pronounced **structural inertia** within the Chinese energy system: when a major negative or positive shock occurs, its effects tend to persist over time. This phenomenon is especially pronounced for fossil energy sources; coal, natural gas, and oil; mirroring their central and still dominant role in China's energy mix, as well as the planned and relatively rigid nature of production adjustments.

Figure 6 also shows that the intermediate states (*Down, Normal,* and *Up*) display higher mobility, acting as **transition regimes** between extreme phases. The probabilities of moving from these states toward the *Very Down* or *Very Up* regimes remain significant, suggesting that phases of normal operation or moderate adjustment in the Chinese energy system are still vulnerable to exogenous shocks. These frequent transitions reflect heightened sensitivity to economic disruptions, energy supply tensions, and adjustments in industrial and environmental policies. With respect to sectoral CO_2 emissions, this **Figure** reveals **heterogeneous dynamics across sectors**. The industrial and electricity generation sectors exhibit a high probability of transitioning toward extreme regimes, underscoring their strong dependence on economic activity, energy demand, and the structure of the electricity mix. This instability reflects the weight of heavy industry in the Chinese economy and the persistence of a largely carbon-intensive power generation system. By contrast, the residential sector shows relatively higher persistence in certain regimes, indicating more regulated emission dynamics, albeit

punctuated by shifts toward extreme states during major shocks, such as the COVID-19 pandemic or atypical climatic events.
Regarding renewable energy sources, **Figure 6** shows that despite their growing role in China's energy transition, these sources remain characterized by high persistence probabilities in extreme regimes. Hydropower displays strong inertia in unfavorable regimes, reflecting its dependence on hydrological and climatic conditions. Solar and wind energy, in turn, exhibit notable persistence in the *Very Up* regime, capturing rapid deployment supported by ambitious public policies, but also revealing increased short-term volatility linked to technical and meteorological constraints. These findings suggest that China's energy transition remains largely **complementary**, with renewable energy sources being added to existing fossil capacities rather than rapidly substituting for them. Overall, **Figure 6** highlights an **asymmetric and highly persistent Markovian dynamic**, characterized by long-lasting extreme regimes and limited mobility away from these states. This configuration contrasts with that observed in more flexible systems and reflects a **gradual energy transition**, marked by strong institutional and structural inertia. From a public policy perspective, these results suggest that achieving a sustained reduction in CO_2 emissions in China will require not only continued expansion of renewable energy sources but also measures aimed at reducing the persistence of unfavorable regimes; particularly by accelerating the effective replacement of fossil fuels and enhancing the flexibility of the energy system.

5. Energy Transition and Sectoral CO_2 Emissions

The analysis of sectoral CO_2 emissions using a five-state Markov chain highlights the complexity of transition dynamics within the context of energy transformation. Distinguishing between the *Very Down, Down, Normal, Up,* and *Very Up* regimes allows for a fine-grained characterization of phases of emission contraction, stability, and expansion, while capturing both regime persistence and inter-regime mobility. The estimated transition probabilities reveal strong inertia in extreme states, reflecting the structural nature of shocks affecting the industrial, electricity generation, and residential sectors, as well as the slow pace of adjustments toward more sustainable emission trajectories. Intermediate regimes appear as unstable transition states, prone to shifting toward either favorable or unfavorable conditions depending on changes in the energy mix and the occurrence of exogenous shocks. Within this framework, the five-state Markov modeling approach provides a relevant analytical tool for evaluating the effectiveness of the energy transition. It underscores that sustained reductions in CO_2 emissions depend not only on the expansion of renewable energy sources but also on the capacity of the energy system to reduce the persistence of unfavorable regimes and to accelerate transitions toward low-carbon states. **Figure 7** illustrates the energy transition dynamics for CO_2 emissions across the industrial, electricity generation, and residential sectors in the United States.

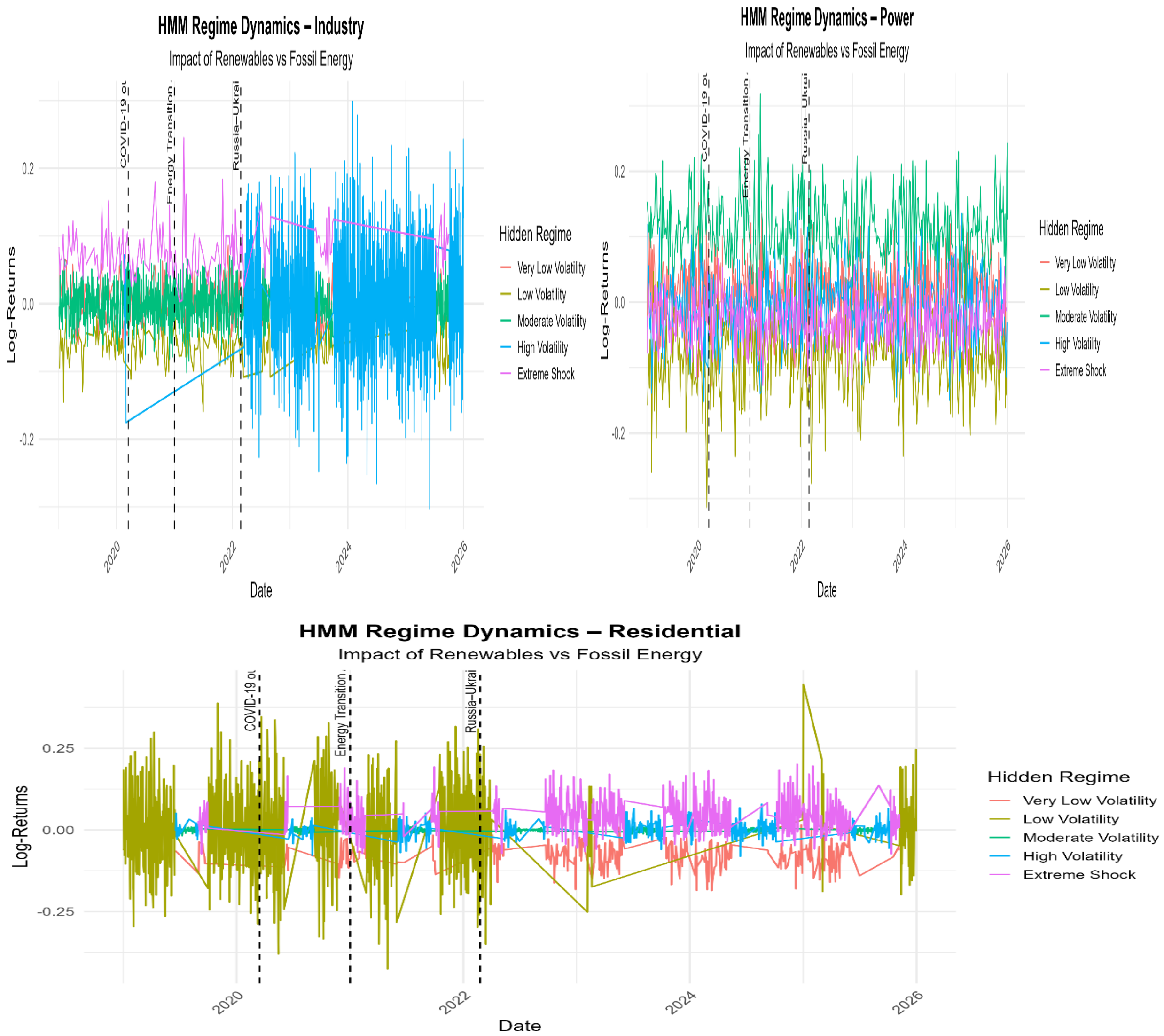

Figure 7 provides an integrated view of the transition dynamics derived from the five-state Markov modeling framework, highlighting the overall structure of regimes associated with energy returns and sectoral CO_2 emissions. This **Figure** enables an examination of how the different states are organized over the medium and long term and allows for an assessment of the relative predominance of regimes in shaping the dynamics of the energy and environmental system. The results suggest a non-negligible concentration of probability mass around extreme regimes, indicating marked persistence in phases of sharp contraction or expansion. This configuration confirms that energy dynamics and CO_2 emissions are largely driven by states characterized by pronounced disequilibria, rather than by a system functioning sustainably around a stable normal regime. Intermediate regimes thus appear as transitory states, playing an adjustment role between more persistent extreme phases.

Figure 7 also reveals structural differences in the distribution of regimes across sectors and energy sources. Emissions originating from the industrial and electricity generation sectors exhibit a stronger predominance of unfavorable or unstable regimes, reflecting their high sensitivity to economic conditions, energy demand, and the structure of the energy mix. By

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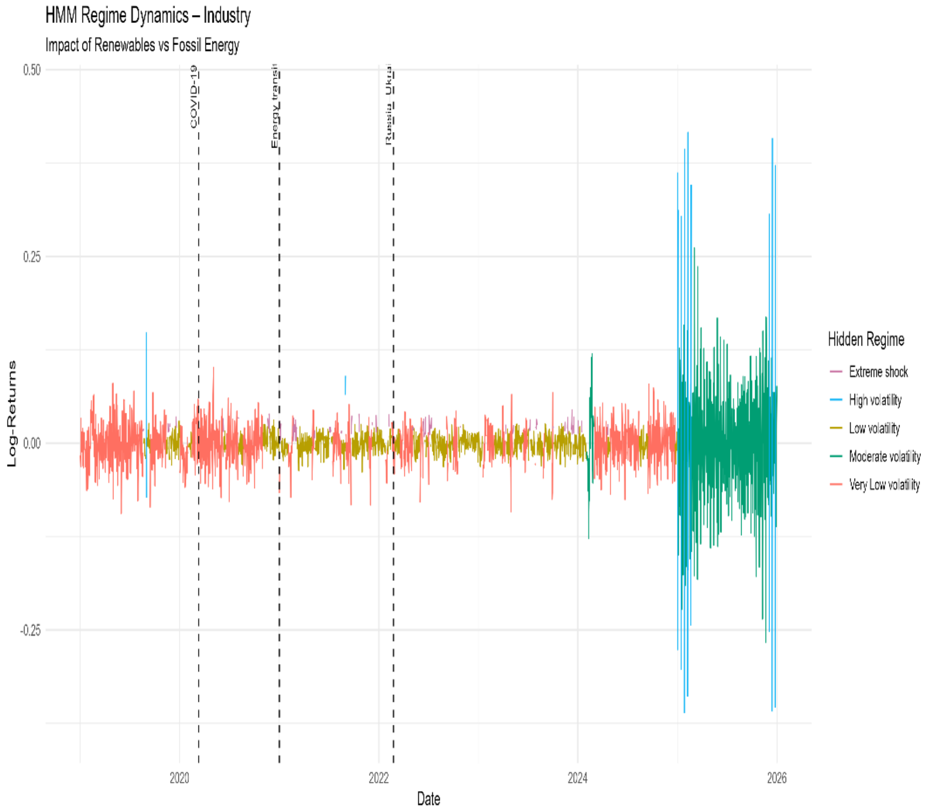
contrast, the residential sector tends to display a distribution more concentrated around intermediate states, indicating relatively more predictable dynamics, albeit occasionally exposed to major exogenous shocks. With respect to energy sources, fossil fuels are characterized by a high probability of occupying extreme regimes, underscoring their heightened sensitivity to geopolitical shocks, international market fluctuations, and regulatory constraints. Renewable energy sources, while associated with a long-term trajectory compatible with decarbonization objectives, also exhibit a significant presence in unstable regimes, reflecting short-term volatility driven by climatic conditions, technical constraints, and adjustments in policy support mechanisms.

Overall, **Figure 7** shows that the energy transition does not follow a linear or monotonic path but instead unfolds through a cyclical and nonlinear dynamic, marked by prolonged phases of instability and high persistence of extreme regimes. These findings emphasize that sustained reductions in CO_2 emissions depend not only on the expansion of renewable energy capacities but also on the ability of energy systems to reduce structural inertia and promote faster transitions toward low-carbon regimes. In this context, the five-state Markov modeling framework emerges as a particularly relevant analytical tool for assessing credibility and the effective pace of energy transition pathways.

Figure 8 highlights the impact of the energy transition on sectoral CO_2 emissions in China. It allows for an examination of how changes in the energy mix; characterized by the gradual integration of renewable energy sources alongside fossil fuels; affect emission dynamics across the main emitting sectors.



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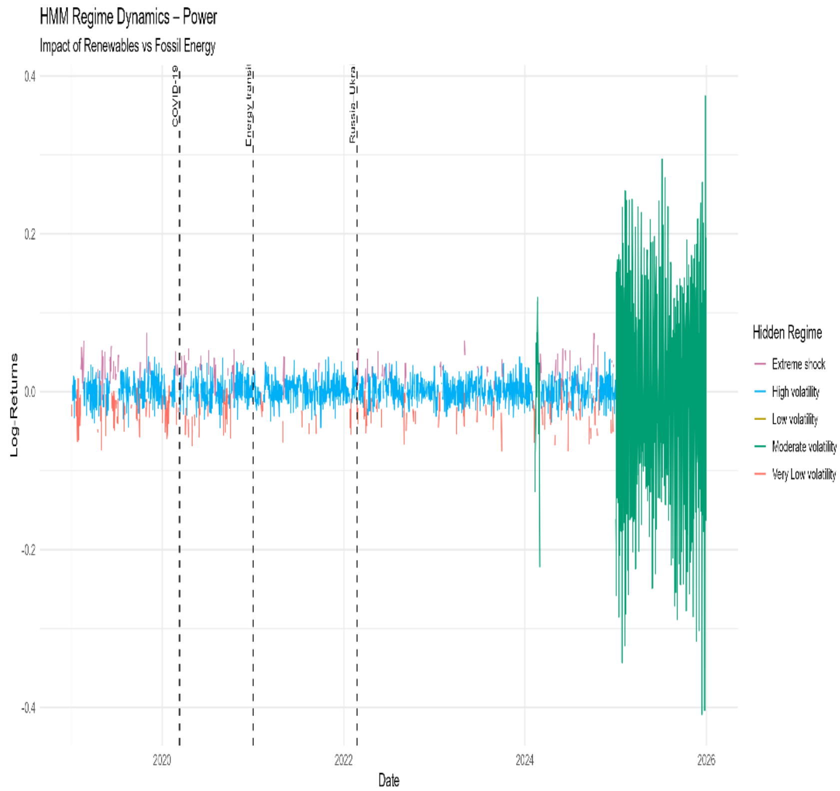

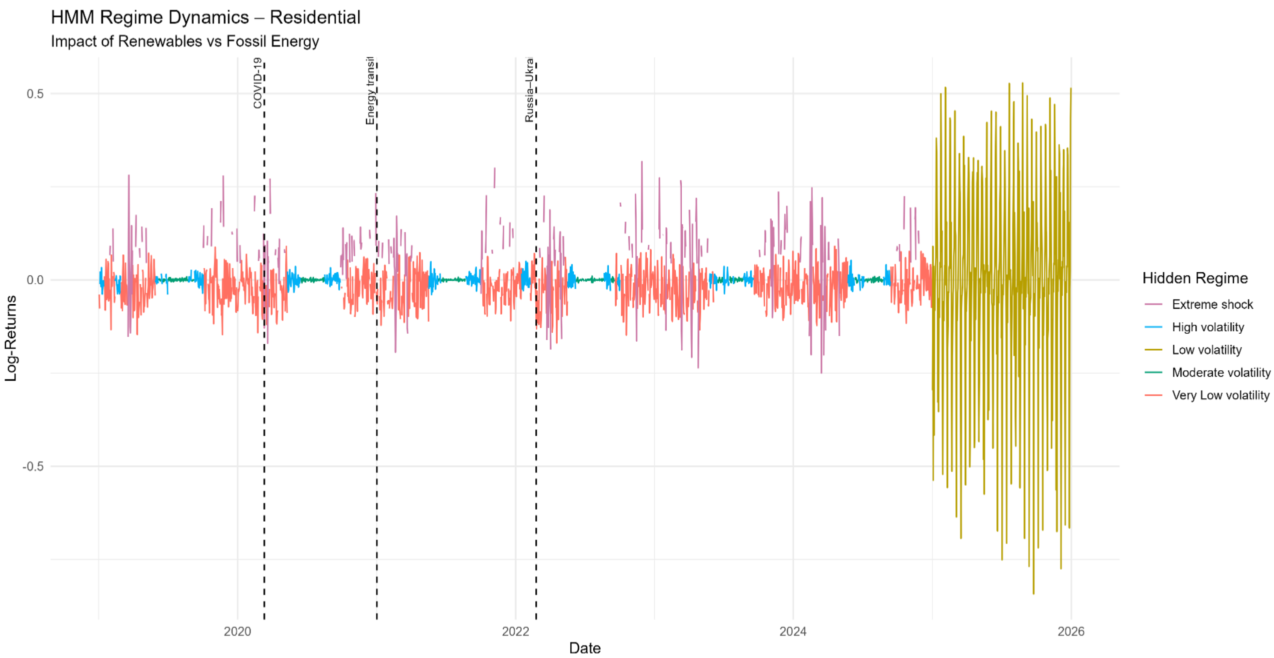

Figure 8 highlights the transition dynamics of sectoral CO_2 emissions in China under the effect of the gradual transformation of the energy mix, analyzed within the five-regime Markov framework. It provides an integrated perspective on how the progressive introduction of renewable energy sources, combined with the continued structural reliance on fossil fuels,

shapes emission trajectories across the main emitting sectors; namely industry, electricity generation, and the residential sector.

Figure 8 underscores the **strong persistence of extreme regimes**, particularly in the industrial and electricity sectors. Both sectors exhibit a non-negligible concentration of probability in the *Very Up* and *Very Down* states, reflecting a high sensitivity to macroeconomic, energy-related, and institutional shocks. This configuration points to the existence of a **carbon lock-in**, widely documented in the literature on highly industrialized economies, and reflects China's continued dependence on an energy-intensive production system still largely based on coal. Despite the rapid expansion of renewable capacity, the energy transition does not translate into an immediate stabilization of emissions, but rather into an alternation between contraction and rebound phases, indicative of an incomplete transformation of productive structures.

Figure 8 further reveals that the **intermediate regimes** (*Down, Normal,* and *Up*) act as **unstable transition zones**, characterized by high mobility toward extreme states. This instability suggests that, in the Chinese context, phases of emission normalization remain fragile and highly vulnerable to exogenous shocks, such as fluctuations in global demand, geopolitical tensions in energy markets, or abrupt adjustments in industrial and climate policies. In other words, the growing presence of renewable energy does not eliminate emission volatility but coexists with cyclical dynamics inherited from the fossil-based energy system.

The residential sector displays a distinct profile, as illustrated in Figure 8. While it also exhibits a certain degree of persistence in both unfavorable and favorable extreme regimes, its dynamics appear more asymmetric and strongly dependent on public policy. Transitions toward the *Very Down* regime can be associated with energy-efficiency policies, electrification of household end uses, and demand-side management measures, whereas *Very Up* phases reflect the impact of structural factors such as rapid urbanization, rising living standards, and growing household energy needs. This duality illustrates the ambivalent nature of the residential energy transition, where technological gains are partially offset by volume effects.

From a systemic perspective, Figure 8 confirms that China's energy transition follows a **predominantly additive rather than substitutive logic**. Renewable energy sources are integrated primarily to meet rising energy demand, without generating a proportional reduction in fossil fuel use. This transition pattern results in a high persistence of extreme emission regimes, limiting the energy system's ability to converge sustainably toward low-carbon states. Consequently, while renewable expansion is necessary, it appears insufficient on its own to induce a profound structural shift in emission trajectories.

From an economic and environmental policy standpoint, the results illustrated in Figure 8 suggest that achieving sustained reductions in sectoral CO_2 emissions in China requires **targeted action to reduce the persistence of unfavorable regimes**, rather than focusing exclusively on expanding renewable capacity. Measures aimed at accelerating the effective substitution of fossil fuels, enhancing power system flexibility, and reducing institutional inertia are essential to shorten the duration of high–carbon-intensity phases. In this sense, Figure 8 highlights that the credibility of China's carbon neutrality pathway depends as much on the qualitative transformation of the energy system as on its quantitative expansion.

Conclusion

Our article set out to analyze the dynamic interactions between energy returns and sectoral CO_2 emissions in the United States and China within the context of the ongoing energy transition, using a multivariate five-state Markov chain framework. By explicitlymodeling nonlinear dynamics, regime persistence, and transition probabilities, the study provides a comprehensive assessment of how fossil and renewable energy sources interact with emission trajectories across key sectors in the world's two largest emitting economies. The empirical results reveal several robust findings. First, across all energy sources and sectoral CO_2 emissions in both countries, a common five-regime structure emerges as the optimal specification, highlighting the fundamentally nonlinear and regime-dependent nature of energy and emission dynamics. Extreme regimes (*Very Down* and *Very Up*) exhibit particularly high persistence, especially fossil energy sources and emission-intensive sectors such as industry and electricity generation. This persistence indicates that major shocks; whether economic, health-related, or geopolitical; tend to produce long-lasting effects, delaying a rapid return to stable emission paths. These findings are consistent with recent global evidence showing that, despite large-scale renewable deployment, fossil fuel consumption and energy-related emissions remain structurally resilient to shocks and policy interventions (Climate TRACE, 2026; World Economic Forum, 2025).

Second, the comparative analysis highlights pronounced cross-country differences in regime dynamics. The United States exhibits higher mobility across intermediate regimes (*Down, Normal,* and *Up*), reflecting greater market flexibility and a more substitutive interaction between renewable and fossil energy sources. In contrast, China displays stronger asymmetry and persistence of extreme regimes, consistent with a transition strategy characterized by gradualism, centralized planning, and complementarities between fossil fuels and renewables. This pattern aligns with recent empirical evidence suggesting that China's energy transition has so far relied more on the **addition** of renewable capacity rather than rapid **substitution** away from fossil fuels, thereby maintaining high structural inertia in emission dynamics.

Placed in the context of recent empirical literature, the findings corroborate and extend existing results. Recent studies emphasize that sectoral emissions respond heterogeneously to renewable energy expansion and remain highly sensitive to macroeconomic cycles and external shocks. The strong persistence of extreme regimes identified in this study echoes evidence that emission declines observed during crisis episodes; such as the COVID-19 pandemic; were largely temporary, followed by rebounds driven by energy demand recovery and continued fossil fuel reliance (Deng et al., 2026). Moreover, the differentiated regime behavior of renewable energy sources; combining long-term decarbonization potential with short-term volatility; is consistent with recent analyses of renewable integration under conditions of climatic variability, grid constraints, and system flexibility challenges (Rahimi and Kardgar (2026)).

Despite its contributions, this study is subject to several limitations. First, the analysis focuses on energy returns and sectoral CO_2 emissions without explicitly incorporating policy variables such as carbon pricing, subsidies, or regulatory stringency, which may directly influence regime transitions. Second, while high-frequency daily data allow for precise identification of regime dynamics, they may obscure longer-term structural trends related to capital stock turnover and technological diffusion. Third, the Markov framework assumes time-invariant transition probabilities within regimes, potentially overlooking gradual changes in adjustment behavior induced by institutional reforms or learning effects.

These limitations open several avenues for future research. Extending the framework to include explicit policy and institutional indicators would allow for a more direct assessment of how targeted interventions affect regime persistence and mobility. Incorporating time-varying transition probabilities or semi-Markov structures could capture evolving adjustment speeds throughout the transition process. Moreover, future studies could investigate cross-country spillovers and interconnected regime dynamics in a multi-country setting, particularly considering the increasing global integration of energy markets and clean-technology supply chains.

From a policy perspective, the findings carry important implications. The strong persistence of unfavorable regimes suggests that renewable energy expansion alone is insufficient to guarantee sustained emission reductions. Authorities should therefore complement renewable deployment with measures explicitly designed to reduce structural inertia, such as accelerating the retirement of fossil fuel assets, strengthening electricity grid flexibility, and expanding energy storage capacity. In the United States, policies that reinforce substitution mechanisms and stabilize investment during volatile phases may help shorten the duration of extreme regimes. In China, reducing institutional rigidity and promoting more effective displacement of fossil fuels will be critical to limiting the persistence of emission-intensive regimes.

Overall, this study demonstrates that the energy transition is better understood as a **nonlinear, regime-dependent process** rather than a smooth adjustment path. By highlighting the persistence of extreme regimes and differentiated dynamics across major economies, the multivariate Markov framework provides a robust analytical basis for evaluating transition credibility and guiding energy and climate policy design in an era of heightened uncertainty.

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Appendix

Table 5. Transition probability matrices associated with the five-state Markov chain of returns referenced to the U. S

Industry	Down	Normal	UP	Very Down	Very Up
Down (D)	0.2152642	0.2133072	0.1643836	0.2270059	0.1800391
Normal (N)	0.2372549	0.1784314	0.2039216	0.1921569	0.1882353
UP (U)	0.2015656	0.2289628	0.2191781	0.1643836	0.1859100
Very Down (VD)	0.1780822	0.1722114	0.1545988	0.2700587	0.2250489
Very Up (VU)	0.1686275	0.2058824	0.2588235	0.1470588	0.2196078
Power	Down	Normal	UP	Very Down	Very Up
Down (D)	0.2309198	0.1780822	0.1682975	0.2661448	0.1565558
Normal (N)	0.2294118	0.1941176	0.1686275	0.1843137	0.2235294
UP (U)	0.2035225	0.2152642	0.2230920	0.1722114	0.1859100
Very Down (VD)	0.1839530	0.1956947	0.1604697	0.2720157	0.1878669
Very Up (VU)	0.1529412	0.2156863	0.2803922	0.1058824	0.2450980
Residential	Down	Normal	UP	Very Down	Very Up
Down (D)	0.2700587	0.19960861	0.1800391	0.19373777	0.15655577
Normal (N)	0.1532417	0.53831041	0.2023576	0.05304519	0.05304519
UP (U)	0.2074364	0.15264188	0.2681018	0.13307241	0.23874755
Very Down (VD)	0.2093933	0.05479452	0.1232877	0.46575342	0.14677104
Very Up (VU)	0.1604697	0.05479452	0.2270059	0.15459883	0.40313112
Coal	Down	Normal	UP	Very Down	Very Up
Down (D)	0.38551859	0.26614481	0.09001957	0.22700587	0.031311155
Normal (N)	0.25686275	0.32941176	0.25294118	0.06274510	0.098039216
UP (U)	0.10958904	0.26810176	0.36399217	0.02739726	0.230919765
Very Down (VD)	0.22504892	0.06653620	0.01956947	0.68297456	0.005870841
Very Up (VU)	0.02352941	0.06862745	0.27450980	0.00000000	0.633333333
Gas	Down	Normal	UP	Very Down	Very Up
Down (D)	0.33463796	0.23679061	0.12915851	0.246575342	0.05283757
Normal (N)	0.27450980	0.30980392	0.22941176	0.101960784	0.08431373
UP (U)	0.12133072	0.26810176	0.37769080	0.031311155	0.20156556
Very Down (VD)	0.22896282	0.09001957	0.03913894	0.614481409	0.02739726
Very Up (VU)	0.04117647	0.09411765	0.22549020	0.005882353	0.63333333
Oil	Down	Normal	UP	Very Down	Very Up
Down (D)	0.3444227	0.2015656	0.14677104	0.24461840	0.06262231
Normal (N)	0.2784314	0.3156863	0.22549020	0.09803922	0.08235294
UP (U)	0.1409002	0.2504892	0.34246575	0.05479452	0.21135029
Very Down (VD)	0.1996086	0.1037182	0.05088063	0.57925636	0.06653620
Very Up (VU)	0.0372549	0.1274510	0.23529412	0.02156863	0.57843137
Hydroelectricity	Down	Normal	UP	Very Down	Very Up
Down (D)	0.3268102	0.23287671	0.11350294	0.283757339	0.043052838

Normal (N)	0.2593320	0.32612967	0.24165029	0.098231827	0.074656189
UP (U)	0.1154599	0.25831703	0.36790607	0.021526419	0.236790607
Very Down (VD)	0.2622309	0.10176125	0.04109589	0.587084149	0.007827789
Very Up (VU)	0.0371820	0.08023483	0.23679061	0.007827789	0.637964775
Solar	Down	Normal	UP	Very Down	Very Up
Down (D)	0.30136986	0.2407045	0.15068493	0.21526419	0.09197652
Normal (N)	0.25882353	0.2941176	0.22156863	0.12549020	0.10000000
UP (U)	0.14090020	0.2367906	0.31898239	0.07436399	0.22896282
Very Down (VD)	0.21330724	0.1076321	0.09980431	0.53620352	0.04305284
Very Up (VU)	0.08627451	0.1196078	0.20980392	0.04901961	0.53529412
Wind	Down	Normal	UP	Very Down	Very Up
Down (D)	0.27397260	0.2446184	0.14872798	0.24266145	0.09001957
Normal (N)	0.26129666	0.2475442	0.20039293	0.14538310	0.14538310
UP (U)	0.19178082	0.2191781	0.30724070	0.06457926	0.21722114
Very Down (VD)	0.21330724	0.1252446	0.08610568	0.53424658	0.04109589
Very Up (VU)	0.06066536	0.1624266	0.25831703	0.01174168	0.50684932

Table 6. Transition probability matrices associated with the five-state Markov chain of returns referenced to the China

Industry	Down	Normal	UP	Very Down	Very Up
Down (D)	0.2387476	0.1467710	0.12915851	0.22113503	0.26418787
Normal (N)	0.2485323	0.2485323	0.21722114	0.09784736	0.18786693
UP (U)	0.1917808	0.2739726	0.29354207	0.04109589	0.19960861
Very Down (VD)	0.1154599	0.0704501	0.07632094	0.46966732	0.26810176
Very Up (VU)	0.2058824	0.2607843	0.28431373	0.16862745	0.08039216
Power	Down	Normal	UP	Very Down	Very Up
Down (D)	0.2974560	0.24461840	0.17416830	0.25636008	0.02739726
Normal (N)	0.1839530	0.26223092	0.28962818	0.16046967	0.10371820
UP (U)	0.1019608	0.19803922	0.29019608	0.13529412	0.27450980
Very Down (VD)	0.3091977	0.20939335	0.09784736	0.36399217	0.01956947
Very Up (VU)	0.1076321	0.08610568	0.14677104	0.08414873	0.57534247
Residential	Down	Normal	UP	Very Down	Very Up
Down (D)	0.673189824	0.12720157	0.04696673	0.14872798	0.003913894
Normal (N)	0.131115460	0.50489237	0.22309198	0.10567515	0.035225049
UP (U)	0.047058824	0.24509804	0.45294118	0.08627451	0.168627451
Very Down (VD)	0.142857143	0.09393346	0.09589041	0.56947162	0.097847358
Very Up (VU)	0.005870841	0.02935421	0.18199609	0.09001957	0.692759295
Coal	Down	Normal	UP	Very Down	Very Up
Down (D)	0.34833659	0.21917808	0.14481409	0.27201566	0.015655577
Normal (N)	0.15851272	0.31115460	0.30724070	0.13111546	0.091976517
UP (U)	0.06470588	0.23921569	0.28627451	0.11764706	0.292156863

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Very Down (VD)	0.37377691	0.13307241	0.04696673	0.43835616	0.007827789
Very Up (VU)	0.05479452	0.09784736	0.21330724	0.04109589	0.592954990
Gas	Down	Normal	UP	Very Down	Very Up
Down (D)	0.27397260	0.3209393	0.25244618	0.0665362	0.08610568
Normal (N)	0.17612524	0.1565558	0.36986301	0.1409002	0.15655577
UP (U)	0.09197652	0.1643836	0.17612524	0.2407045	0.32681018
Very Down (VD)	0.31702544	0.2309198	0.07827789	0.3737769	0.00000000
Very Up (VU)	0.13921569	0.1274510	0.12352941	0.1784314	0.43137255
Oil	Down	Normal	UP	Very Down	Very Up
Down (D)	0.37181996	0.3091977	0.18395303	0.08414873	0.050880626
Normal (N)	0.10392157	0.3196078	0.29607843	0.11960784	0.160784314
UP (U)	0.06849315	0.1526419	0.33855186	0.17808219	0.262230920
Very Down (VD)	0.33659491	0.1174168	0.01565558	0.52054795	0.009784736
Very Up (VU)	0.11937378	0.1017613	0.16634051	0.09784736	0.514677104
Hydroelectricity	Down	Normal	UP	Very Down	Very Up
Down (D)	0.37769080	0.26614481	0.01369863	0.34246575	0.00000000
Normal (N)	0.25048924	0.27201566	0.29354207	0.08414873	0.09980431
UP (U)	0.01565558	0.29941292	0.25636008	0.00000000	0.42857143
Very Down (VD)	0.35420744	0.07240705	0.00000000	0.57338552	0.00000000
Very Up (VU)	0.00000000	0.09019608	0.43725490	0.00000000	0.47254902
Solar	Down	Normal	UP	Very Down	Very Up
Down (D)	0.29158513	0.708414873	0.0000000	0.00000000	0.0000000
Normal (N)	0.00000000	0.285714286	0.7142857	0.00000000	0.0000000
UP (U)	0.00000000	0.000000000	0.2857143	0.08023483	0.6340509
Very Down (VD)	0.66340509	0.005870841	0.0000000	0.33072407	0.0000000
Very Up (VU)	0.04509804	0.000000000	0.0000000	0.58823529	0.3666667
Wind	Down	Normal	UP	Very Down	Very Up
Down (D)	0.281800391	0.56555773	0.15264188	0.00000000	0.0000000
Normal (N)	0.086105675	0.33072407	0.38551859	0.06262231	0.1350294
UP (U)	0.009803922	0.04313725	0.32352941	0.28627451	0.3372549
Very Down (VD)	0.471624266	0.06066536	0.07045010	0.39726027	0.0000000
Very Up (VU)	0.150684932	0.00000000	0.06849315	0.25244618	0.5283757