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Global Geopolitical Changes and New/Renewable Energy Game

Xuemeng Zhao and Weilun Huang *

School of Finance and Trade, Wenzhou Business College, Wenzhou 325035, China; 20219066@wzbc.edu.cn
* Correspondence: huangwl@wzbc.edu.cn

Abstract: This study analyzes the impact of global geopolitical changes on new/renewable energy (NRE) policies and their roles in enhancing national energy security, elevating international stature, and influencing the global energy market. Using game theory, it reveals how NRE policies promote technological innovation, diversify energy supply, and strengthen international collaboration, thus advancing the global energy system towards a low-carbon transition and improving international energy governance. NRE policies significantly enhance national energy security by reducing dependency on single energy sources, facilitate the global shift to low-carbon energy, and intensify international cooperation. The effectiveness of these policies in driving energy transformation is notable, and they are expected to remain crucial for global energy security and sustainable transition. Recommendations include strengthening the stability and security of energy supply chains through enhanced oversight, increasing investment in R&D and innovation to reduce costs, fostering international cooperation for better policy coordination, and implementing diversified energy policies to encourage the adoption of NRE. These measures will address challenges from global geopolitical dynamics and drive the global energy system towards sustainability and efficiency.

Keywords: new/renewable energy policy; renewable energy; global geopolitics; energy security; international cooperation; game theory

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1. Introduction

In the third decade of the 21st century, the global energy sector encountered unparalleled geopolitical challenges, notably the 2022 conflict between Russia and Ukraine [1]. This conflict exacerbated global energy supply instability and necessitated a comprehensive reevaluation and adjustment of energy policies worldwide [2]. From an economic perspective, this reevaluation underscored the importance of reducing reliance on specific energy-exporting countries, thereby accelerating the advancement of clean and renewable energy technologies [3].

The evolving global geopolitical landscape made discussions on new and renewable energy (NRE) policies increasingly relevant. Economic analyses indicate a significant transformation within the global energy market, with the Russia–Ukraine conflict serving as a notable catalyst for this shift [4]. Such conflicts, along with their economic and political repercussions, amplified the unpredictability of global energy supply and demand and drove up international energy prices [2,5]. This situation compels countries to reassess the resilience and diversity of their energy supply chains. Consequently, the formulation and implementation of NRE policies became crucial for national governments and international organizations.

NRE policies are strategic frameworks and measures implemented by governments to promote the research, development, and application of innovative energy technologies. The primary objectives of these policies are to reduce dependency on conventional fossil fuels, combat climate change, improve energy efficiency, and ensure energy security. To achieve these goals, governments introduce various incentives, such as financial subsidies, tax breaks, and support for research and development to stimulate private sector investment and innovation. These policies are designed to accelerate the commercialization and widespread adoption of new energy technologies, fostering a transition towards a more sustainable and resilient energy system [6,7].

A myriad of factors, including climate change, trade tensions, geopolitical disputes, and the COVID-19 pandemic, profoundly impacted the global energy supply chain, presenting unprecedented risks and challenges to China's energy security framework [8,9]. China's high dependence on external energy sources, escalating geopolitical rivalries, and intensifying trade conflicts constrained its energy import channels. These dynamics led to increased energy prices and consumption costs, thereby affecting the high-quality development of the economy and society [10].

In-depth research into NRE policies is essential for fostering a diversified global energy supply and reducing reliance on any single exporter, thereby mitigating geopolitical risks [11]. The construction of a more stable and sustainable energy supply system, catalyzed by the adoption of NRE sources, is imperative [12]. The energy crisis instigated by the Russia–Ukraine conflict propelled the EU to undertake significant revisions to its energy policy, reflecting its endeavors to secure energy supply, bolster renewable energy development, and attain green, low-carbon objectives. Despite the conflict's backdrop, the EU's energy policy adjustments significantly influenced the global energy geopolitical landscape, diminishing Russia's sway over EU energy and instigating a notable shift in the global energy supply and demand dynamics [13].

The purpose of this study is to conduct an exhaustive analysis of the strategic motivations behind state-level formulation of NRE policies and to scrutinize the interactions and strategic behaviors within the current intricate and fluid global geopolitical milieu from an economic vantage point. Faced with the volatility of the global energy market and the intensifying challenges of climate change, the crafting and execution of novel and renewable energy policies became paramount. This endeavor represents a significant challenge for governments and international organizations globally, while simultaneously offering a pivotal opportunity for transitioning towards a sustainable energy paradigm.

Anchored in economic theory, this study provides an in-depth examination of the convoluted nature of the prevailing global geopolitical backdrop and its implications for the shaping of NRE policies. By amalgamating geopolitical insights with energy policy analysis, this paper pioneers a novel theoretical scaffold, research methodologies, profound analytical depth, and instructive policy direction. (1) The study engages in profound deliberation on the strategic impetus and strategic conduct inherent in NRE policies, factoring in the economic, societal, and political dimensions of the energy market and the intricate interplay of international cooperation and rivalry, proposing a multifaceted analytical construct. (2) Utilizing game theoretical tenets and methodologies, this study assesses the strategic interplay among nations, corporations, and other stakeholders in the policy formulation process for NRE, aiming to enrich theoretical inquiry and to offer pragmatic guidance for the creation of viable and adaptable energy policies.

(3) The creation of mathematical models delves into the decision-making processes of energy system conversion by manufacturers and their implications for energy security under the aegis of NRE policies, enhancing research precision through methodological innovation and unveiling new perspectives on the economic catalysts within the energy transition process. (4) This study accentuates the pivotal attributes of the energy system, such as diminishing marginal costs and indirect network externalities, scrutinizing their significance in policy motivation and impact analysis, thereby furnishing theoretical substantiation for energy policy formulation. (5) Through the construction and analysis of game models, this study offers theoretical and practical guidance on mitigating policy discord and fostering international collaboration, extending existing research and proposing innovative strategies within the domain of global energy governance [14].

This paper is well-structured and logically organized. It begins by outlining the geopolitical challenges confronting the global energy market and emphasizes the critical role of NRE policies. The historical overview of energy transition geopolitics and the review of relevant literature provide insights into the significant transformations and influencing factors shaping the global energy landscape. Utilizing game theory, the analysis delves into strategic interactions among stakeholders, employing mathematical models to evaluate the impact of NRE policies on energy security. The research findings are summarized, followed by policy recommendations aimed at enhancing energy governance.

2. Literature Review

Against the backdrop of the 21st century, the global energy political and economic landscape underwent profound transformations and developments. These shifts are propelled by a multitude of factors, including technological innovation, the ebb and flow of international political relations, fluctuations in market supply and demand dynamics, and policy responses to climate change [15]. As globalization deepens, the international mobility of energy markets is amplified, yet this concurrently heightened the vulnerability of energy supply to geopolitical influences [16]. The United States, capitalizing on its longstanding strategic advantages, not only safeguarded its domestic energy security, but also took an active role in international energy crises, emerging as a paragon of energy security.

The subsequent sections provide a comprehensive examination of the literature concerning the historical, geopolitical, and economic dimensions of energy. The analysis emphasizes key events that shaped the trajectory of energy politics and economics. The literature review substantiates the strategic advantages of new and renewable energy (NRE) policies, including the reduction in marginal costs within energy systems and the significant role of indirect network externalities. These findings serve as critical assumptions underpinning the NRE policy game model proposed in this study.

2.1. Historical Overview of Energy Transition Geopolitics

Since the mid-20th century, global energy politics and economics (as illustrated in Figure 1) underwent numerous pivotal shifts [17]. These transformations recalibrated the energy market's supply–demand equilibrium and significantly impacted international political and economic interactions.

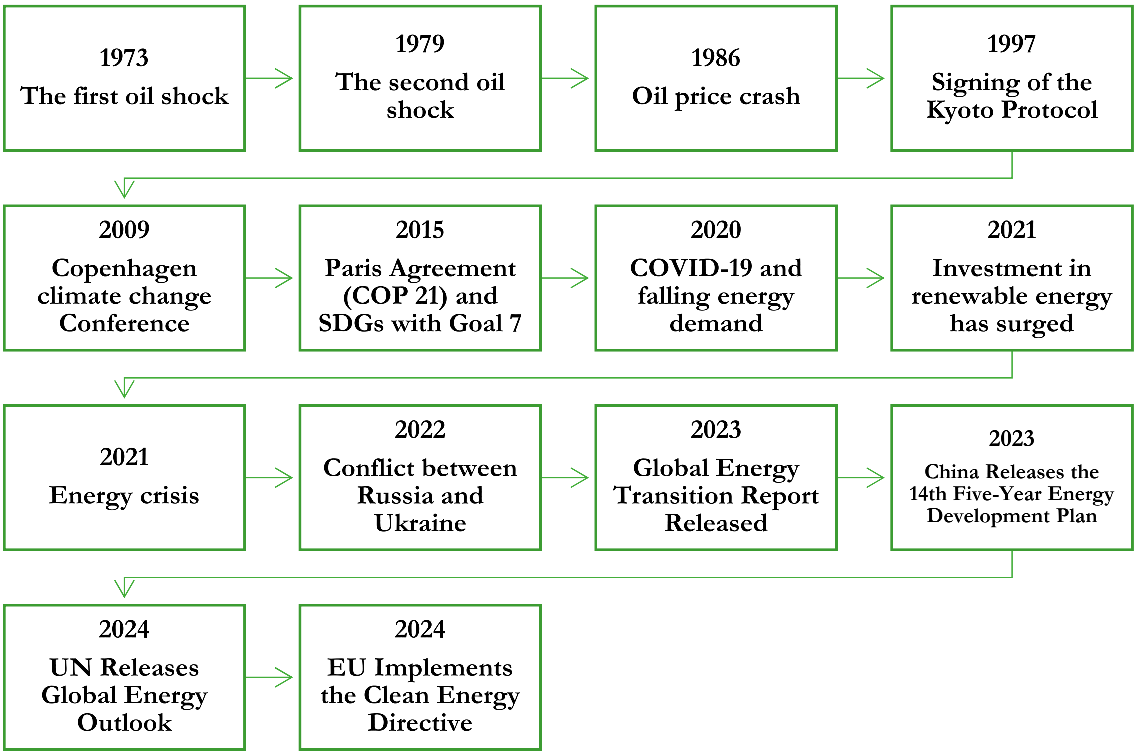

Figure 1. Important Historical Events in the Geopolitical and Economic Development of Energy.

Patidar et al. [18] demonstrate that geopolitical uncertainties and the ongoing threat of global pandemics exert a substantial influence on crude oil price trends. Their study delineates the development of the oil industry into four distinct epochs. The first epoch (1860–1900), characterized by the nascent oil boom, was marked by rapid price oscillations stemming from supply–demand imbalances. The second epoch (1901–1945), an era of global upheaval, delved into the burgeoning oil economic conflicts fomented by rapid industrialization and geopolitical maneuverings. The third epoch (1946–2000), a period of industrial expansion and OPEC's ascendancy, scrutinized the interplay among the global economy, oil prices, and the geopolitical dominance of developed nations, a time when oil prices were subject to extreme volatility [19]. The fourth epoch (2001–2023), the post-K20 period, discusses the advent of the digital economy, process automation, and the predominant control over oil prices by producers [9,20,21]. During this phase, major oil-consuming nations such as India and China grapple with the challenge of aligning economic growth with the volatility of oil prices [22,23].

This paper provides a comprehensive review of the historical development of the global energy market and the geopolitical factors influencing it. From the mid-20th century to the present, the global energy market underwent significant transformations that deeply impacted international political and economic interactions. The literature analyzes the drivers of political and economic changes in the energy sector from multiple dimensions, including technological innovation [24], environmental sustainability [25], market supply and demand dynamics [26], and new energy industry policies [27–29]. It also examines the influence of geopolitics on the energy market [30] and the importance of environmental sustainability in addressing global concerns such as energy security and climate change [30]. This comprehensive perspective fills gaps in previous research and aids in understanding the evolution of the global energy market.

These influencing factors serve as evidence supporting the strategic benefits of NRE policy games. Geopolitical events illustrate the interplay and competition among various political, economic, and social forces [31]. These events often revolve around the control of natural resources, especially energy resources. The formulation of NRE policies is frequently tied to the extraction, distribution, and usage rights of these resources, with stakeholders engaging in strategic games to gain or maintain control.

2.2. The Factors of Energy Politics and Economy

The literature review (as depicted in Figure 2) indicates that key determinants of energy politics and economy span from geopolitical dynamics and technological progress to market and trade shifts, alongside global environmental and sustainability concerns. These multifaceted factors converge to form an intricate system of influence within the realm of energy politics and economy. This paper endeavors to offer a holistic perspective by thoroughly examining these pivotal factors, thereby further elucidating the trajectory of the energy political and economic paradigm amidst global geopolitical shifts.

International collaboration becomes especially critical, with collective action becoming increasingly evident in addressing global concerns such as energy security and climate change [32]. The ongoing reconfiguration of the global energy market and the rejuvenation of energy policies in response to geopolitical provocations represent more than just a reactionary measure to current global instabilities. They offer a strategic pathway for the sustainable and low-carbon evolution of the world economy [33]. The Ukrainian crisis shifted the international community's focus from economic ties and market supply to more pressing matters of security and values. Although this led to temporary price escalations, it also hastened Europe's transition away from Russian energy dependencies, exemplifying a strategic realignment in the Western energy export market [34].

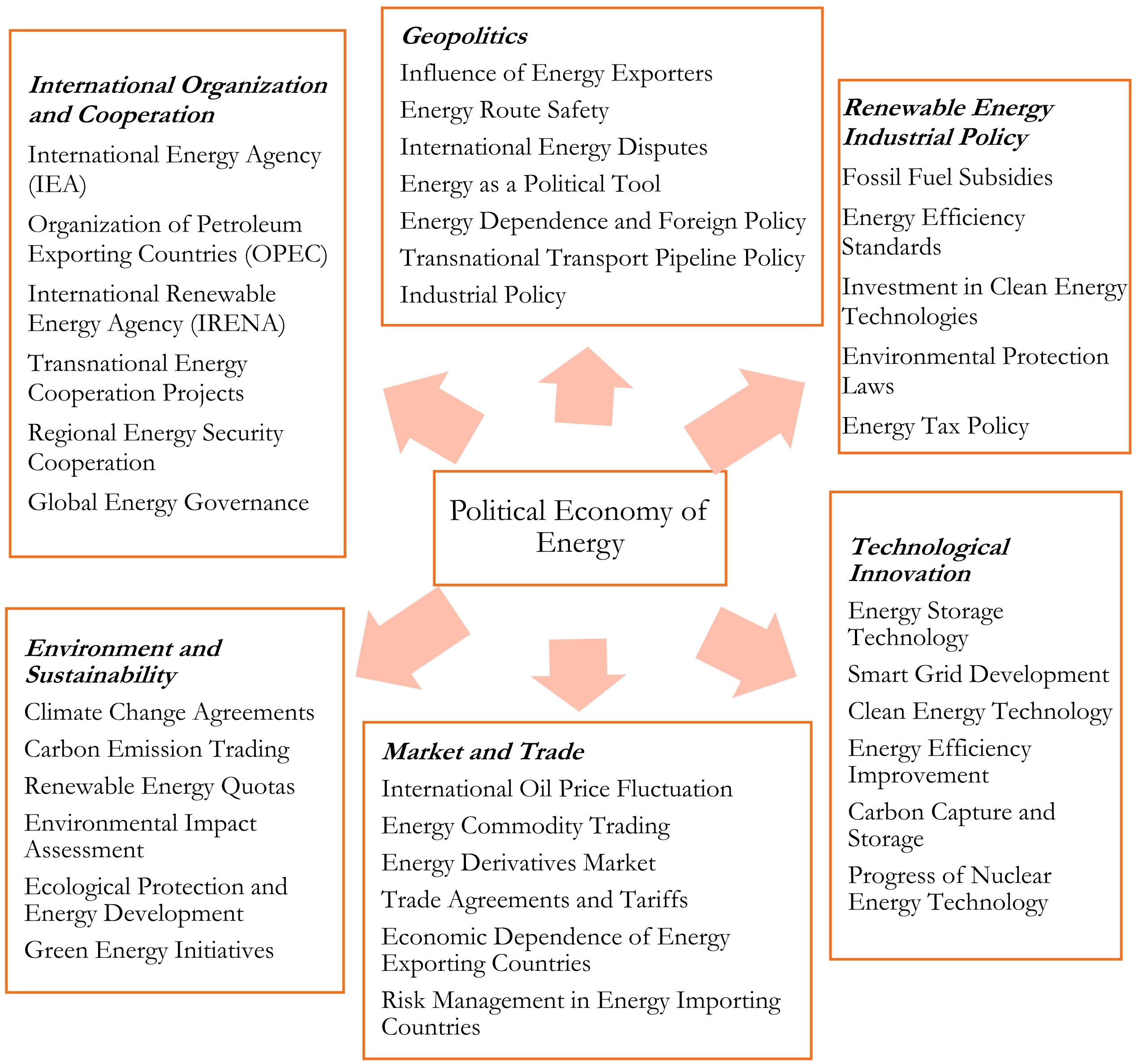

Figure 2. The Factors of Energy Politics and Economy.

Environmental and sustainability considerations are gaining prominence in modern energy politics and economics. Global climate change accords, carbon emission trading mechanisms, and renewable energy quotas are collectively propelling the energy market towards a greener and more carbon-efficient future [22,23]. The European Union's aggressive emission reduction targets are instigating a seismic shift in worldwide energy production and consumption paradigms. International organizations and collaborative efforts are increasingly pivotal in shaping global energy governance. Entities such as the International Energy Agency (IEA), the OPEC, and the International Renewable Energy Agency (IRENA) are fostering stability and growth within the global energy market through the advancement of transnational energy cooperation initiatives and regional energy security alliances.

The influence of geopolitics on the energy market is profound, manifesting not only in the control exerted by energy-exporting nations over global energy pricing and supply through their resource endowments, but also in the security of energy transit routes, international energy disputes, and the escalating utilization of energy as an instrument of political negotiation [35]. These elements dictate a nation's energy dependency patterns and the crafting of its foreign policy. For instance, the EU's strategic "decoupling" from Russian energy resources bolstered the diversification of its energy supply chain and significantly impacted the global energy market.

In assessing the evolution of the global energy market and its geopolitical ramifications, it is imperative to acknowledge the market's inherent complexity and variability. Global energy governance is transitioning from models of unilateral or bilateral cooperation to those of multilateral collaboration and regional alliances. Confronted with the challenges and opportunities presented by energy transformation, nations must balance ensuring their own energy security and engaging proactively in global energy governance, pushing collectively towards a more sustainable and clean energy system. The United States continues to consolidate its leading position in traditional energy sectors while also focusing on enhancing the overall resilience of Western energy supply chains. It endeavors to establish a hub-and-spoke geo-energy alliance centered around its supply chain and a multilateral assistance consortium for developing countries, thereby facilitating the expansion of its energy hegemony and neutralizing major competitors to achieve standard-setting leadership.

NRE industrial policy is pivotal in facilitating energy transformation and sustainable development. Governments have fostered a shift from fossil fuels to renewable energy sources through the implementation of energy efficiency standards, targeted investments in clean energy technologies, and stringent environmental protection regulations. For instance, China's substantial investments in wind and solar energy not only accelerated the restructuring of its domestic energy sector, but also contributed to a reduction in the global costs of clean energy technologies. Emerging sectors within the new energy landscape, such as electric vehicles and photovoltaics, have become focal policy areas for the world's major economies in their quests to achieve economic transformation and green growth. Following his inauguration, the Biden administration dedicated itself to enhancing the United States' competitiveness and leadership in international economic and climate policy realms by aggressively promoting the new energy sector, providing robust support through industrial policies, and leveraging alliances to advance its international new energy industry agenda.

Technological innovation stands as a fundamental catalyst for the political and economic metamorphosis of energy. Progress in energy storage solutions, smart grid technologies, clean energy innovations, and carbon capture and storage not only bolstered energy efficiency, but also unveiled new avenues for market expansion [17]. The swift evolution of electric vehicles, for example, is reshaping global petroleum demand and intensifying the contest for critical mineral resources, such as rare earth elements. Market and trade dynamics exert a profound and immediate influence on energy pricing and security of supply. Volatility in international oil prices, the trading of energy commodities, and the energy derivatives market are central to the functioning of the global energy economy. Shifts in trade agreements and tariff policies, exemplified by the trade tensions between the United States and China, also had indirect yet significant repercussions on the energy sector.

These influencing factors serve as evidence supporting the strategic benefits of NRE policy games. The development and implementation of NRE technologies open new markets and economic opportunities [36,37]. Countries, regions, or companies may push for or oppose certain NRE policies based on their pursuit of these potential economic benefits. A key factor in geopolitical events is the competition for technological superiority. Nations or companies with advanced renewable energy technologies may leverage these advancements to enhance their geopolitical influence, seeking to maximize their benefits in policy-making processes. Participants in geopolitical events, including countries, international organizations, and NGOs, might use NRE policies as tools to increase their political influence and bargaining power. Energy security is also a crucial consideration for many countries when crafting NRE policies. Geopolitical events can affect the stability of energy supplies, prompting nations to consider how to ensure energy security within their policy frameworks, leading to strategic maneuvering in the realm of energy security.

2.3. Important Events in the Political and Economic Development of Energy

As shown in Figure 1, the decline in oil prices in 1986 marked a pivotal shift, diminishing OPEC's influence over oil pricing and significantly impacting the global energy market and political economy. The Kyoto Protocol in 1997, the Copenhagen Climate Change Conference in 2009, and the Paris Agreement in 2015 collectively underscored the international commitment to addressing the environmental impacts of energy consumption and advancing renewable energy development. The COVID-19 pandemic in 2020 highlighted vulnerabilities in the global energy supply chain, while the subsequent surge in renewable energy investment signaled a shift towards sustainable energy sources. The 2022 Russian–Ukrainian conflict further exposed energy security concerns, prompting accelerated efforts for energy diversification. Recent initiatives, including the IRENA's "Global Energy Transition Report", China's 14th Five-Year Plan, the United Nations' "Global Energy Outlook", and the European Union's "Clean Energy Directive", reflect the global focus on renewable energy development, technological innovation, and sustainable energy policies.

From the results of the literature review, it is clear that the phenomenon of diminishing marginal costs in energy systems is particularly significant amidst global geopolitical shifts, especially regarding the evolution of NRE systems. This characteristic implies that the per-unit energy output cost progressively diminishes as the energy system's scale expands, fostering economies of scale essential for NRE systems, which are characterized by higher initial investments and lower operational expenses. This study incorporates the profound research of Nilssen [38], Markvart and Bogus [39], World Energy Council [40], Klemperer [41], Sharpe [42], Shy [43,44], and other scholars, aiming to unravel the multifaceted intricacies of energy system costs and construct a comprehensive framework for the economic appraisal of energy projects. While recognizing that not all costs within an energy system may adhere to a marginal cost decline, this paper adopts the marginal cost decline as a primary assumption for analytical simplicity. Decreasing marginal costs suggest that as production scales up, the cost per additional unit of output decreases, a phenomenon particularly prevalent in production processes that achieve economies of scale [45].

Indirect network externalities within energy systems play a pivotal role in their valuation, increasingly incorporating the impact of complementary products and services. These systems are not solely evaluated on intrinsic performance metrics, but are significantly influenced by the prevalence and variety of complementary products and services, such as smart grids and electric vehicle charging infrastructures. These externalities enhance the attractiveness of an energy system and the robustness and completeness of the technological ecosystem within which it operates. Indirect network externalities suggest that the utility derived from a product or service by consumers or businesses is contingent upon the volume and quality of complementary products or ancillary services available. For instance, the practical value of a computer depends as much on its hardware as on the breadth and nature of the software options accessible. Similarly, the utility of automobiles is inextricably linked to the availability and quality of maintenance services.

Existing literature, including works by Shy [43], Clements [46], Farrell and Saloner [47], Katz and Shapiro [48], and Cabral et al. [49], delineates a bifurcation of network externalities into direct and indirect forms. While direct network externalities pertain to the increased utility as the user base of a product expands, this paper focuses on the indirect network externalities and their influence on the selection of energy systems. This study places special emphasis on the demand function of enterprises as decision-makers in adopting energy systems. Within this analytical construct, the demand for energy systems is shaped not only by product pricing and marginal output, but also significantly by indirect network externalities. The demand for an energy system bifurcates into two components: one anchored in the fundamental demand for energy production capacity and efficiency, the other stemming from the augmented external demand due to an increase in complementary products and services [50,51]. Fundamental demand encapsulates the core value proposition of an energy system concerning its ability to satisfy the requisites of production and operation. Typically, its demand curve exhibits a negative slope, indicating that the marginal value of an energy unit diminishes as its aggregate consumption rises. Conversely, external demand stems from the influence of indirect network externalities. As the array of complementary products and services expands, the marginal value of the energy system may escalate, enhancing the system's resilience in the face of exigencies, such as power outages, and amplifying overall production efficiency.

2.4. Summary

The characteristics of the NRE policy game model in this paper highlight the strategic benefits of NRE policies, the diminishing marginal costs of energy systems, and the indirect network externalities of energy systems. This paper innovatively applies game theory to analyze interactions not only at the national level, but also among businesses and other stakeholders, uncovering the complex dynamics among different players in the formulation of NRE policies. This approach provides a robust tool for predicting how policy changes may impact the global energy market. Particular attention is paid to the indirect network externalities and decreasing marginal costs within energy systems, exploring how these characteristics drive the expansion of new energy markets and the acceptance of new technologies. Furthermore, it proposes innovative strategies for global energy governance, especially in terms of technology sharing and the development of transnational energy infrastructure. By analyzing international energy cooperation and competition, the paper offers strategic recommendations to enhance global energy security. These recommendations provide novel solutions for the global energy governance framework.

From the results of the literature review, governments implement NRE policies to achieve several strategic objectives, including bolstering energy security and elevating international stature. These policies are essential for the sustainable development of the global energy system, providing numerous economic, strategic, and technological benefits (see Table 1). NRE policies aim to decrease reliance on conventional fossil fuels by promoting alternative energy sources, thereby reducing economic risks associated with volatile fossil fuel prices and supply disruptions [52]. They facilitate economies of scale in NRE systems, leading to a decrease in the per-unit cost of energy production, which is particularly significant for technologies requiring high initial investments but lower operational costs over time [53]. By offering financial incentives such as subsidies, tax breaks, and support for research and development, governments can stimulate private sector investment and innovation, accelerating the commercialization and market penetration of new energy technologies and fostering economic growth and job creation [6,7].

NRE policies enhance the diversity and resilience of energy supply chains, reducing dependence on a single energy source or supplier, thus mitigating geopolitical risks and improving energy security [8,9]. They also enable countries to assert leadership on global energy issues, enhancing their international reputation. For instance, the United States' advocacy for new energy technologies and Japan's focus on solar energy research and development illustrate how nations use NRE policies to project soft power and influence the global energy political landscape [52]. Moreover, the implementation of NRE policies involves strategic interactions and rivalries among nations, with countries competing for technological leadership and market dominance in the global energy sector, driving further innovation and improvements in energy technologies [13].

Technologically, NRE policies promote the development and deployment of cutting-edge energy technologies, with governments supporting research and development initiatives that lead to breakthroughs in energy efficiency, storage, and generation technologies [12]. The adoption of NRE systems generates positive externalities by fostering the development of complementary technologies and infrastructures, such as smart grids and electric vehicle charging networks, enhancing the overall utility and attractiveness of NRE systems and encouraging wider adoption [53]. Additionally, NRE policies parallel product innovation strategies, helping enterprises seize a first-mover advantage in the marketplace, shape consumer decision-making processes, and influence the strategic choices of competitors. Effective communication of policy goals and technological advancements serves as a vital instrument for value chain communication, fostering a more competitive market environment [54].

Table 1. Aspects of the New and Renewable Energy (NRE) Policy Game Model.

Aspect	Strategic Benefits	Diminishing Marginal Costs	Indirect Network Externalities
Core Focus	Policy advantages for energy security and stature.	Cost reduction at scale for initial high-investment technologies.	Value increase from complementary products and services.
Market Impact	Spurs sector innovation and competitiveness.	Encourages investment and scale for cost-effectiveness.	Boosts system attractiveness and adoption.
Policy Strategy	Maximize benefits in policy design.	Incentivize scale expansion and technology adoption.	Develop synergistic technologies and infrastructure.
Economic Outcome	Stimulates economic growth and jobs.	Makes NRE more financially viable over time.	Enhances system economic viability through externalities.
Technological Impact	Supports R&D for new energy technologies.	Scale leads to technological improvements.	Complementary tech development such as smart grids.
Global Standing	Enhances international influence in energy.	Facilitates shared benefits through global cooperation.	Nations compete/collaborate on complementary tech advancement.
Sustainability Goal	Leads in low-carbon transition.	Ensures long-term cost-effective sustainable systems.	Establishes robust tech ecosystem for energy systems.

NRE policies also serve as mechanisms for international communication and representation, conveying pivotal messages to businesses and the international community, influencing the strategic energy planning of both domestic and foreign entities. Policy formulation and implementation profoundly impact decision-making processes, bolstering energy security and garnering voter support. Given the intrinsic disparities in the transportation, storage, and utilization of equipment and systems between NRE sources and established fossil fuels, transitioning energy systems by enterprises is imperative [55–59]. By effectively implementing NRE policies, governments can achieve significant economic, strategic, and technological benefits, contributing to a more sustainable and resilient global energy system. These policies not only address immediate energy security concerns, but also position nations as leaders in the transition to a low-carbon economy, enhancing their international standing and influence.

Based on the literature review, significant marginal contributions of this study are identified by integrating the impacts of geopolitical dynamics and technological advancements on the energy market, providing a comprehensive understanding of NRE policy formulation and implementation. Unlike previous studies that analyzed these aspects separately, this approach synthesizes these perspectives to offer a holistic view of the factors influencing energy policy. Employing game theory, this study models the strategic interactions among nations, businesses, and other stakeholders within the NRE policy landscape. This analytical framework provides a novel method for examining the complexities inherent in international energy cooperation and competition. Emphasizing the role of indirect network externalities in the adoption and diffusion of NRE technologies, this research highlights the importance of complementary products and services, illuminating the broader economic and technological ecosystem influencing NRE policy outcomes. From theoretical and empirical analysis, specific policy recommendations are proposed to enhance energy security, drive technological innovation, and foster international collaboration in the NRE sector. These recommendations, supported by a comprehensive game-theoretic model and extensive literature review, address key challenges and leverage opportunities identified through an integrated analytical approach. This framework assists policymakers and stakeholders in navigating the complexities of the energy market and promoting sustainable energy solutions.

3. Theoretical Framework and Research Methods

In this section, each subsection is closely interconnected, forming a comprehensive analysis of the strategic impacts of new and renewable energy (NRE) policies within the global geopolitical context. The section begins by establishing a theoretical framework, where game theory is introduced as the primary tool for analyzing the strategic interactions between various stakeholders involved in NRE policy formulation and implementation. This theoretical foundation sets the stage for the subsequent economic models, which explore how these strategic interactions influence energy system choices. The economic models focus on factors such as network externalities and diminishing marginal costs, providing a quantitative analysis of how manufacturers decide between fossil fuel systems and NRE systems. Building on these models, the section then examines the impact of NRE policies on national energy security, analyzing how strategic decisions affect market equilibrium and contribute to broader energy security goals. The final subsection extends the analysis to the international level, discussing the geopolitical implications of NRE policies and the role of international cooperation in enhancing global energy market stability. Together, these sections provide a cohesive and detailed examination of how NRE policies are shaped by and, in turn, shape global geopolitical dynamics, emphasizing the importance of strategic interactions and international collaboration in achieving energy security and sustainability.

3.1. Theoretical Framework and Hypotheses

The global energy market is undergoing significant changes driven by geopolitical dynamics, technological advancements, and the imperative to address climate change. In this complex environment, formulating and implementing NRE policies are essential for national energy security, technological innovation, and international cooperation. Understanding the strategic interactions among stakeholders, including governments, energy corporations, and international organizations, is crucial. Traditional methods often fall short in capturing these interactions, necessitating a robust theoretical framework such as game theory. Game theory analyzes the strategic behavior of stakeholders, evaluating economic incentives such as subsidies and carbon taxes, and simulating policy scenarios to identify optimal strategies. It also considers indirect network externalities vital for NRE technology adoption. This comprehensive approach provides insights into mitigating geopolitical risks and market volatility, supporting the development of effective and adaptive energy policies [12].

Non-cooperative games highlight scenarios where entities make decisions based on maximizing their self-interest without a definitive cooperative framework. In the realm of NRE policies, this means that nations or firms might prioritize their own energy policies and technological growth unilaterally, avoiding collective solutions. The study of non-cooperative games can reveal underlying conflicts and opportunities for cooperation within policy-making processes, offering strategic decision-making support to policymakers. Game theory serves as a powerful theoretical tool for illuminating the intricate strategic interactions inherent in the formulation of NRE policies, thereby guiding the development of more effective and adaptable policy frameworks. By leveraging the concepts and models of game theory, policymakers can deeply analyze the dynamics among countries, businesses, and other stakeholders, providing both theoretical and practical support for global energy transformation and the achievement of sustainable development objectives.

The model is based on precise assumptions, clear variable definitions, and rigorous analytical methods, aiming to offer a theoretical framework for predicting and elucidating the behavioral patterns and interactive dynamics among nations in the sphere of new energy policies.

The foundational assumptions of the model are as follows: (1) Bounded rationality: all decision-makers aim to maximize their interests yet are constrained by information and computational capabilities. (2) Strategic interaction: each decision-maker's choice is contingent upon expectations of others' potential choices. (3) Repeated games: policy formulation and implementation are iterative processes rather than one-time events. (4) Multi-level games: reflecting the complex interactions of new energy policies across international and national levels. (5) Incomplete information: full comprehension of other participants' preferences, strategic options, and information is unattainable. (The detailed model hypotheses can be found in the Supplementary Materials.)

Variable definitions encompass: (1) Participants (P_i): includes national governments, private firms, and international organizations as actors within the new energy policy game. (2) Strategic space (S_i): the array of strategies available to each participant, such as investing in new energy technologies, devising subsidy policies, or imposing trade restrictions. (3) Strategy selection function ($C_i(S_{-i})$): illustrates the optimal strategy selection for participant i, contingent upon the strategies of others. (4) Payoff function ($U_i(C_i(S_{-i}), S_{-i})$): delineates the utility or benefits accruing to each participant under specific strategy combinations, contingent upon the collective strategic choices. (5) Equilibrium conditions: identifying the Nash equilibrium, wherein no participant can achieve superior benefits by unilaterally altering their strategy.

Analytical methods include: (1) Nash equilibrium analysis, which seeks combinations of strategies that render no participant better off by unilaterally changing their strategy given the strategies of all others. (2) Dynamic game analysis: examines the impact of time-variant strategy choices on game outcomes, potentially employing evolutionary game theory and other techniques. (3) Policy simulation: utilizes computational models to simulate game outcomes under diverse policy scenarios, assessing the impact and efficacy of different policy choices. (4) Sensitivity analysis: evaluates the model outcomes' responsiveness to key assumptions and parameters, gauging the model's robustness.

In an in-depth discussion of the NRE policy game model, this paper aims to elucidate the benefits of NRE policies on the dual governmental objectives of bolstering energy security and elevating international stature. Two pivotal attributes of the energy system are emphasized: diminishing marginal costs and indirect network externalities, which are crucial for dissecting policy motivations and impacts. NRE policies reduce reliance on fossil fuels, promote strategic international interactions, and enhance technological innovation. NRE policies facilitate diverse national strategies, as exemplified by the United States' advocacy for new energy technologies, Japan's solar energy research, and advancements in energy conservation in South Korea and the Netherlands [52]. These policies serve as mechanisms for international communication, aiming to curate a favorable global image, assert leadership on pertinent issues, and influence the global energy political and economic landscape. They play a pivotal role in strategic energy planning and decision-making processes, significantly impacting both domestic and international entities. By addressing intrinsic disparities in energy system infrastructure, NRE policies contribute to transitioning towards more sustainable and resilient energy systems, thereby bolstering energy security and enhancing a nation's global leadership in sustainable energy development [53,54].

The phenomenon of diminishing marginal costs in energy systems, particularly significant amid global geopolitical shifts, is crucial for the evolution of NRE systems. This implies that the per-unit energy output cost decreases as the system's scale expands, fostering economies of scale essential for NRE systems characterized by high initial investments and low operational expenses. Integrating research from Nilssen [38], and others, this study constructs a comprehensive framework for energy project appraisal, highlighting that as production scales up, the cost per additional unit of output decreases [45]. Analyzing various costs—construction, interconnection, learning, risk, environmental, operation, and market volatility—this study underscores the importance of economies of scale and effective management strategies in reducing costs and promoting sustainable energy development. This framework aids in formulating energy policies and investments towards a more economical and sustainable global energy supply system.

3.2. Establishment of the Game Theory Model

On the premise that marginal costs are on a downward trajectory and are correlated with the number of manufacturers, this paper establishes the supply functions for both fossil energy and NRE systems. This approach captures the phenomenon where the per-unit production cost of energy diminishes as the number of manufacturers producing complementary products and services grows. This is instrumental in more precisely gauging the influence of technological advancements and market expansion on energy supply. Fossil energy typically confronts challenges such as resource depletion and extraction difficulties, which limit the scope for cost reduction. To streamline the discussion, this paper posits a negative correlation between the marginal costs of fossil energy systems and the number of manufacturers. This reflects the notion that, to a certain extent, market expansion and economies of scale can yield cost benefits for fossil energy systems, albeit to a lesser extent than for NRE sources. The supply function for the fossil energy system (S_F) is represented as follows:

$$S_F = a_F + b_F p_F - c_F N_F. \tag{1}$$

a_F, b_F, c_F, is a constant. p_F represents the price of energy and N_F represents the number of manufacturers that are compatible or complementary to fossil energy systems.

The benefits of NRE systems from technological advances and economies of scale are more pronounced, and the marginal cost decrease is more significant as the number of complementary product and service manufacturers compatible with NRE systems increases. The NRE system supply function (S_{NR}) is:

$$S_{NR} = a_{NR} + b_{NR} p_{NR} - c_{NR} N_{NR} - d_{NR} T. \tag{2}$$

a_{NR}, b_{NR}, c_{NR}, d_{NR} is a constant. N_{NR} represents the number of manufacturers that are compatible or complementary to the NRE system. T represents technological progress, taking into account that NRE systems may result in lower unit costs due to technological progress. c_F and c_{NR} are parameters that reflect the impact of the number of manufacturers of complementary products and services on the marginal cost. For NRE, c_{NR} has a higher value indicating that its marginal cost decreases more significantly as N_{NR} increases.

Indirect network externalities within energy systems significantly influence their valuation by incorporating the impact of complementary products and services. These systems depend not only on intrinsic performance metrics, but also on the prevalence and variety of complementary products, such as smart grids and electric vehicle charging infrastructures. Indirect network externalities suggest that the utility derived from a product or service by consumers or businesses is contingent upon the volume and quality of these complementary products. For instance, the value of a computer relies on both its hardware and the software options available. Similarly, the utility of automobiles depends on the availability and quality of maintenance services. Existing literature, including works by Shy [43], Clements [46], Farrell and Saloner [47], Katz and Shapiro [48], and Cabral et al. [49] emphasizes the importance of indirect network externalities in energy system selection. This study highlights that demand for energy systems is shaped by product pricing, marginal output, and indirect network externalities, which enhance resilience and overall production efficiency.

In the energy market, the indirect network externalities for both fossil (F) and NRE systems (NR) can be empirically gauged by the count of manufacturers with which they share compatibility or complementarity. This metric not only reflects the market's demand for these energy systems, but also elucidates how technological advancements and policy shifts impact the choice and evolution of energy systems. The cohort of compatible or complementary manufacturers for fossil energy systems is sizable and relatively stable, indicating the mature status of the technology and market in this sector. The demand function for the fossil energy system (D_F) can be expressed as:

$$D_F = \alpha_F - \beta_F p_F + \gamma_F \log(N_F). \tag{3}$$

α_F, β_F, and γ_F are constants. p_F represents the price of fossil energy and N_F represents the number of manufacturers that are compatible or complementary to fossil energy systems. The logarithmic form of the number of vendors is used to capture the nonlinear effects of indirect network externalities. This indicates that as the number of compatible or complementary manufacturers increases, the demand will also increase, but the growth rate will gradually slow down.

The number of manufacturers of NRE systems (N_{NR}) is likely to grow rapidly as technology advances and market acceptance increases. This growth reinforces the impact of indirect network externalities and further enhances the attractiveness of NRE systems. The demand function for the NRE system (D_{NR}) can be expressed as:

$$D_{NR} = \alpha_{NR} - \beta_{NR} p_{NR} + \gamma_{NR} \log(N_{NR}). \tag{4}$$

α_{NR}, β_{NR}, and γ_{NR} are constants. p_{NR} represents the price of NRE and N_{NR} represents the number of manufacturers that are compatible or complementary to the NRE system. With the rapid progress of renewable energy technologies and policy support, consumers and enterprises may be more inclined to adopt NRE solutions, which will be reflected through $\gamma_2 > \gamma_1$, thus strengthening the external demand for NRE systems.

By solving the supply Equations (1) and (2) and the demand Equations (3) and (4), the market equilibrium price of fossil energy system ($S_F = D_F$) is

$$p_F = [N_F c_F - a_F + \alpha_F + \gamma_F \log(N_F)] / (b_F + \beta_F). \tag{5}$$

The market equilibrium price of the NRE system ($S_{NR} = D_{NR}$) is:

$$p_{NR} = [N_{NR} c_{NR} + T d_{NR} - a_{NR} + \alpha_{NR} + \gamma_{NR} \log(N_{NR})] / (b_{NR} + \beta_{NR}). \tag{6}$$

From Equation (5), it is evident that the market equilibrium price of the fossil fuel system is predominantly influenced by supply and demand parameters. The concept of diminishing marginal costs suggests that as the number of manufacturers in the market increases, the per-unit production cost declines. This dynamic shifts the supply curve to the right, leading to a decrease in market prices. Indirect network externalities reveal that an increase in the number of complementary products and services enhances demand for fossil fuels, significantly influencing the market equilibrium price of fossil fuel systems.

Equation (6) illustrates that the market equilibrium prices of NRE systems are influenced by factors such as the number of producers on the supply side, indirect network externalities on the demand side, and technological advancement. Technological progress enhances the supply capacity of NRE by reducing production costs and improving energy system efficiency. As technologies evolve and complementary products and services increase, the appeal of the NRE market grows, boosting demand and impacting the market equilibrium price. This finding is corroborated by the works of Katz and Shapiro [48,60], Bensen and Farrell [61], David [62], Farrell and Saloner [47,63,64], and others who researched equilibrium solutions and the path dependence of unstable markets, including Liebowitz and Margolis [65].

3.3. Analysis of the Game Theory Model

In the expansive arena of the global energy market, energy supply and pricing result from intricate factors intertwined with the energy security and economic advancement of nations and global environmental conservation. The disparity in pricing between fossil fuels and NRE systems significantly affects energy market dynamics, environmental policy formulation, and decisions of consumers and producers. In the short term, the transition to clean energy may be hindered if the market equilibrium price of fossil fuel systems is lower than that of NRE systems. The long-term implications depend on the interplay of technological innovation, policy interventions, and market forces.

Energy pricing significantly influences consumer choices. The relatively low cost of fossil fuels may perpetuate reliance on traditional energy sources, impeding the adoption of NRE solutions and delaying energy transformation. Price discrepancies can sway investor preferences, as lower fossil fuel prices may divert capital towards fossil fuel projects at the expense of NRE sectors, affecting the latter's capacity for research, development, and advancement.

Persistently low fossil fuel prices challenge environmental policies. Governments may need to intervene by reducing NRE costs through subsidies, tax incentives, and other mechanisms, or by increasing fossil fuel costs through measures such as carbon taxes. These interventions aim to incentivize the transition to cleaner energy sources [2,66]. Over the long term, sustained low fossil fuel prices could exacerbate global dependency and intensify greenhouse gas emissions challenges [67]. However, advancements in NRE technologies and economies of scale are anticipated to progressively decrease NRE costs, potentially narrowing or reversing the current price gap.

The prospective shift in energy pricing trends indicates that NRE costs are poised to decrease further with technological progress, leveraging economies of scale, and strengthening environmental policies. Concurrently, escalating fossil fuel costs, driven by resource depletion, environmental regulations, and policy constraints, suggest that in the long run, the market equilibrium price of NRE systems may fall below that of fossil fuel systems. This development could catalyze a structural transformation within the energy market, steering it towards greater sustainability and efficiency.

Table 2 provides a structured synthesis of the New and Renewable Energy (NRE) policy game model, detailing the multifaceted engagement of stakeholders, the theoretical underpinnings of game theory, and the strategic variables at play. It outlines the analytical methods used for understanding the complex interactions and decision-making processes within the NRE policy landscape. Furthermore, it highlights the market dynamics influenced by these policies, emphasizing the role of technological advancement, international relations, and the pursuit of energy security and sustainable development goals. Each aspect is intricately linked, illustrating how non-cooperative strategies and bounded rationality shape the iterative and multi-level policy formulation processes, ultimately impacting the global energy market equilibrium and the transition towards sustainable energy systems. By employing game theory, the model captures the strategic interactions among national governments, energy corporations, and other stakeholders, elucidating the influence of indirect network externalities and diminishing marginal costs on energy market dynamics. This comprehensive framework underscores the importance of integrated policy approaches, technological innovation, and international cooperation in achieving a resilient and sustainable global energy system.

Table 2. New and Renewable Energy (NRE) Policy Game Model Overview.

Aspect	Description	Theoretical Foundation	Market Dynamics
Stakeholders	National governments, energy corporations, consumers, international organizations	Game Theory, Non-cooperative game models	Strategic interactions, Rivalry, Collaboration
Decision Making	Entities prioritize self-interest without a cooperative framework	Bounded Rationality, Strategic Interaction	Policy Simulation, Sensitivity Analysis
Policy Formulation	Iterative processes, multi-level and multi-stakeholder interactions	Repeated Games, Multi-level Games	Influence of indirect network externalities
Economic Framework	Construction of a comprehensive framework for energy project appraisal	Incomplete Information	Equilibrium price analysis
Technological Advancement	NRE policies driving tech innovation and strategic international interactions		Technological progress reducing costs
International Relations	Policies as mechanisms for global image curation and leadership		Pricing trends affecting market dynamics
Energy Security and Sustainable Development	Transitioning towards sustainable energy systems		Consumer choices, Investment preferences

4. Results and Discussions

This section systematically examines the impact of NRE policies on energy security, technological innovation, and international cooperation by developing and analyzing a game theory model. The section begins with an economic and mathematical model to explore how NRE systems are chosen in the market, elucidating how NRE policies influence corporate decision-making to enhance national energy security. It then delves into the strategic behavior of firms in selecting energy systems, investigating how companies optimize resource allocation to maximize profits under the influence of NRE policies. The final part of the section addresses the geopolitical implications of NRE policies on international cooperation by constructing a two-country model, demonstrating how cooperative strategies can enhance global energy market stability and drive technological progress.

This section builds on the existing literature that explores the role of NRE policies in the energy market [1,2] by incorporating a game theory approach to deepen the understanding of how these policies influence cooperation and competition among nations in the context of international relations. The contribution of this section lies in providing a structured analytical framework that explains how nations and corporations make strategic energy system choices in a complex global geopolitical environment, thereby enhancing global energy security [5,16]. Additionally, this section advances the literature by offering insights into the role of indirect network externalities and economies of scale in NRE systems, providing empirical support for policymakers on how to leverage policy incentives to foster technological innovation and facilitate energy market transitions [66,67].

4.1. Economic Models and Energy System Selection

This study presents an in-depth analysis of how NRE policies enhance energy security. It establishes a mathematical model to examine how manufacturers make decisions regarding energy system conversion under the influence of these policies. The purpose of this model is to explore the economic drivers behind energy system choices and their contribution to overall energy security.

The model is set as (1) energy type and system: the model considers two types of energy sources: fossil fuel (E_F) and NRE (E_{NR}), along with their corresponding energy systems: fossil fuel system (S_F) and NRE system (S_{NR}). (2) Factors of production: the factors of production include energy (E), energy system (S), and other production factors (O). (3) Number of firms and network externalities: Assuming there are nnn homogeneous firms, the number of firms using fossil energy systems is N_F and those using NRE systems is N_{NR}. The choice of each system affects the manufacturer's output, represented by network externalities $f(N_F)$ and $f(N_{NR})$. These are non-decreasing concave functions, f(.), reflecting the positive impact of the increase in network size on the manufacturer's output.

The production function is defined as $Y_i = f(N_i)F(E_i, O_i)$, where i can be a fossil energy system or a NRE system. Here, N_i represents the number of manufacturers using the corresponding energy system, E_i is the energy input, and O_i represents other factors of production. To simplify the model, this paper assumes that the consumption of the energy system S_i is directly proportional to the consumption of energy E_i, rather than treating it as a separate variable. This simplification allows for a more direct analysis of the impact of energy system selection on production efficiency. Although the basic form of the production function does not change with different energy systems, the selection of different energy systems will affect the marginal output of production through the network scale effect introduced by the externality function $f(N_i)$.

Suppose the consumption of the energy system (S_i) is proportional to the consumption of energy (E_i), i.e., $S_i = G(E_i)$, where $G' > 0$ and $G'' < 0$. This means that as energy use increases, the corresponding energy system use also increases at a decreasing rate. In this model, the prices of fossil energy and NRE are considered as p_F and p_{NR}, respectively, and the prices of other factors of production are denoted as p_O. For simplicity, the price of the energy system is also denoted as p_O. Assuming that the energy system has diminishing marginal costs, the corresponding cost function is given by: $p_O G(E_i)/H(N_i)$. Here, $H(N_i)$ indicates the cost reduction effect caused by network externalities, and H(.) is a non-diminishing concave function, reflecting the negative impact of the increase in network scale on the manufacturer's cost.

The profit function for manufacturers using fossil energy systems (P_F) and NRE systems (P_{NR}) is defined as the total revenue earned from production activities minus production costs.

$$P_F = p_Y f(N_F)F(E_F, O_F) - p_F E_F - p_O G(E_F)/H(N_F) - p_O O_F;$$

$$P_{NR} = p_Y NR(N_{NR})NR(E_{NR}, O_{NR}) - p_{NR} E_{NR} - p_O G(E_{NR})/H(N_{NR}) - p_O O_{NR};$$

where p_Y: output price; $f(N_F)$: Network externalities function for fossil energy systems; $F(E_F, O_F)$: production function for fossil energy systems; p_F: price of fossil energy; and E_F: energy input for fossil energy production. p_O: price of other production factors; $G(E_F)$: energy system consumption function for fossil energy; $H(N_F)$: cost reduction effect from network externalities for fossil energy; and O_F: other production factors for fossil energy production. $f(N_{NR})$: network externalities function for NRE systems; $F(E_{NR}, O_{NR})$: production function for NRE systems; p_{NR}: price of NRE; and E_{NR}: energy input for NRE production. $G(E_{NR})$: energy system consumption function for NRE systems; $H(N_{NR})$: cost reduction effect from network externalities for NRE systems; and O_{NR}: other production factors for NRE systems.

Given the output price (p_Y), energy prices, and other factor prices, the profit functions are as follows: (1) profit function for fossil energy system:

$$P_F = p_Y f(N_F)F(E_F, O_F) - p_F E_F - p_O G(E_F)/H(N_F) - p_O O_F, \tag{7}$$

(2) profit function for NRE system:

$$P_{NR} = p_Y f(N_{NR})F(E_{NR}, O_{NR}) - p_{NR} E_{NR} - p_O G(E_{NR})/H(N_{NR}) - p_O O_{NR}. \tag{8}$$

4.2. Profit Maximization and Strategic Behavior of Firms

This study employs a phased analysis framework to explore the decision-making process by which firms maximize their profits by adjusting the allocation of energy and other production factors under specific assumptions. In the first stage of the analysis, the hypothetical scenario assumes that only fossil energy exists in the market. Under this background, all enterprises focus on deciding how to allocate fossil energy and other production factors to maximize profits. Optimization of energy allocation: Enterprises determine the optimal amount of fossil energy to use, balancing the cost of energy with the revenue generated from its use, while considering the impact of network externalities. Firms also decide on the optimal allocation of other production factors to maximize overall production efficiency and profitability.

The profit maximization problem faced by manufacturers is modeled as an optimization problem: $\mathrm{Max}_{E_F,O_F}P_F$. The objective is to optimize the use of fossil energy and other production factors to maximize profits. This optimization process is influenced by output prices, energy prices, prices of other production factors, and the differences between output and cost introduced by network externalities. The first-order condition for the firm's decision states that for the input of fossil energy, the marginal value of the output (the product of the output price and the marginal output) should equal its marginal cost.

The first-order derivatives of the production functions with respect to the energy input (E_i) and other production factors (O_i) are given as follows: (1) For fossil energy system: $\partial Y_F/\partial E_F = f(N_F)\cdot\partial F(E_F,O_F)/\partial E_F$; $\partial Y_F/\partial O_F = f(N_F)\cdot\partial F(E_F,O_F)/\partial O_F$. (2) For NRE system: $\partial Y_{NR}/\partial E_{NR} = f(N_{NR})\cdot\partial F(E_{NR},O_{NR})/\partial E_{NR}$; $\partial Y_{NR}/\partial O_{NR} = f(N_{NR})\cdot\partial F(E_{NR},O_{NR})/\partial O_{NR}$. To optimize the production process, this paper set the marginal value of the output (the product of the output price and the marginal output) equal to its marginal cost. These conditions can be expressed as: $p_Y f(N_F)dF(E_F,O_F)/dE_F = p_F$, $p_Y f(N_F)dF(E_F,O_F)/dO_F = p_O$.

These conditions reveal an important economic principle: the marginal output ratio of fossil energy to other production factors is influenced not only by the price ratio but also significantly by the network size of the fossil energy system, i.e., the network externalities. The consideration of network externalities highlights the critical role of energy system choice in improving production efficiency and cost structure. It reveals the potential economic drivers of NRE policies for firms' energy system switching decisions. By optimizing the allocation of energy and other production factors, firms can maximize their profits while contributing to overall energy security and efficiency.

In the second stage, after learning that NRE is available, enterprises must select the optimal production function and then decide the amount of energy and other factors to input. The optimization problem is expressed as: $\mathrm{Max}\{P_F(E_F,O_F),P_{NR}(E_{NR},O_{NR})\}$.

Assume the following functions: $f(N_F) = H(N_F) = \ln(N_F)$, $G(E_F) = E_F$ and the production function $F(E_F,O_F) = E_F^{\theta}(G(E_F)O_F)^{1-\theta} = E_F O_F^{1-\theta}$ (Cobb–Douglas function). The profit maximization problem for fossil energy is expressed as:

$$P_F(E_F,O_F)= p_Y\ln N_F E_F O_F^{1-\theta} - p_F E_F - p_O E_F/\ln N_F - p_O O_F \tag{9}$$

According to the first-order condition of Equation (9), the optimal input of fossil energy and other production factors is:

$$\left(E_F^*,\ O_F^*\right) = \left(\left[\frac{p_O(p_O + p_F\ln N_F)}{P_Y(\ln N_F)^2}\right]^{\frac{\theta}{1-\theta}}\frac{1}{P_Y(1-\theta)\ln N_F},\left[\frac{p_O + p_F\ln N_F}{P_Y(\ln N_F)^2}\right]^{\theta-1}\right).$$

Similarly, the optimal input for NRE and other production factors is:

$$\left(E_{NR}^*,\ O_{NR}^*\right) = \left(\left[\frac{p_O(p_O + p_F\ln N_{NR})}{P_Y(\ln N_{NR})^2}\right]^{\frac{\theta}{1-\theta}}\frac{1}{P_Y(1-\theta)\ln N_{NR}},\left[\frac{p_O + p_F\ln N_{NR}}{P_Y(\ln N_{NR})^2}\right]^{\theta-1}\right)$$

These equations demonstrate that the optimal inputs of fossil and NRE are related to the inputs of other production factors, the price factor, and the logarithm of the number of manufacturers. The optimal inputs for other factors of production are similarly influenced by the inputs of energy, price factors, and the logarithm of the number of firms.

When contemplating the optimal allocation of energy and other production factors, the economic significance primarily manifests in resource allocation efficiency, network externalities, and the influence of pricing and cost structures on production decisions. Enterprises can minimize costs and maximize production efficiency by utilizing fossil energy and complementary production factors. This approach embodies the quintessential economic principle of efficient resource allocation. The concept of network externalities reveals the synergistic effects within enterprise production activities. As the number of enterprises adopting a particular energy system grows, individual enterprises benefit from the expanded network scale, thereby augmenting the marginal output of their production. Pricing and cost structures are pivotal in determining the optimal production scale. The costs associated with energy and other production factors directly impact production costs, positioning enterprises within market competition, and determining their profitability.

Employing a game-theoretic perspective, this paper meticulously examines the strategic behaviors of firms in their selection of energy systems and subsequent interactions. Game theory provides a sophisticated analytical framework for scrutinizing the decision-making processes among entities with competing and potentially conflicting interests. Within this framework, fossil energy and NRE systems are conceptualized as rival players in the market, vying for resources and the favor of manufacturers. This competitive landscape is encapsulated as a strategic game, where the primary objective for each energy system is to attract a larger number of manufacturers to utilize its energy source. By doing so, each system aims to expand its market share and enhance its profitability.

In this strategic game, indirect network externalities wield significant influence. As an energy system gains adoption by an increasing number of manufacturers, its overall attractiveness is amplified due to the proliferation of network effects, such as enhanced services and infrastructure. Consequently, each manufacturer must consider not only the pricing of energy (P_F and P_{NR}) and the costs associated with production factors but also the decisions of their peers, specifically the repercussions of network externalities, when choosing an energy system.

The strategic behavior of a manufacturer in selecting an energy system is encapsulated by an optimal response function, illustrating the most advantageous decision considering the choices made by others within the market [67]. Within this dynamic game, manufacturers continually recalibrate their strategies to adapt to market fluctuations, technological advancements, and the strategic maneuvers of competitors [11]. The progression of NRE technologies and the intensification of policy interventions—such as subsidies for NRE projects and carbon taxes—have made these systems increasingly attractive, inciting a strategic shift in the market [68]. This shift prompted companies to re-evaluate the comparative merits and drawbacks of traditional energy systems versus new/renewable ones, guiding their selection toward the energy system that best aligns with their interests.

Mutual observation and emulation among enterprises may precipitate a collective action effect. Once enough enterprises have embraced NRE systems, others are likely to follow, thereby accelerating the overall energy transition. As the market selects an energy system, a Nash equilibrium may emerge, wherein no enterprise can achieve superior profits by unilaterally altering its energy system selection [47]. This equilibrium is shaped by energy prices, technological progress, and indirect network externalities, reflecting the influence of the availability of complementary products and services on firms' energy system choices [14,51].

In the drive towards carbon neutrality, refining the construction of production, supply, storage, and marketing systems and expediting the growth of clean energy sectors, including natural gas, is essential [67]. Scientific and technological innovation, coupled with policy support, are indispensable in this transformative process. When dissecting the game behavior between fossil energy systems and NRE systems, this paper constructs a simplified game matrix that clearly delineates the impact of the number of manufacturers and the pricing dynamics of the two energy systems [33]. This approach provides a clear representation of the interplay between these critical variables, offering valuable insights into the strategic decision-making processes within the energy market (see Table 3).

Table 3. Game Behavior Analysis Between Fossil Energy and New/Renewable Energy Systems.

	High Prices for NRE Systems ($p_F > p_{NR}$)	**Low Prices for NRE Systems** ($p_F < p_{NR}$)
High Number of Manufacturers of NRE Systems ($N_F > N_{NR}$)	The attractiveness of NRE systems increased, but fossil energy systems remain somewhat attractive due to the high number of manufacturers.	Fossil energy systems are more attractive, and manufacturers tend to use fossil energy.
Low Number of Manufacturers of NRE Systems ($N_F < N_{NR}$)	NRE systems are significantly more attractive, with manufacturers turning heavily to NRE.	High prices for NRE systems may inhibit conversion, but network effects may promote some conversion.

The methodology and process for estimating and constructing Table 3 involve utilizing a Python-based simulation to model the strategic interactions among manufacturers choosing between fossil energy systems and NRE systems. This simulation applies game theory to analyze optimal response functions and Nash equilibrium. Key factors, such as the number of manufacturers, pricing dynamics, indirect network externalities, and policy interventions including subsidies and carbon taxes, are integrated into the model. The Python 3.11.8 simulation permits dynamic adjustments based on market and technological changes, yielding insights into the equilibrium outcomes and strategic decisions of manufacturers (The Python code for the simulations involved in estimating and constructing the methods and procedures outlined in Table 3 can be found in the Supplementary Materials). The version of the Python software currently in use is 3.11.8.

This table encapsulates the complexities of real-world scenarios by capturing the following core concepts: interplay between price and network externalities, influence of price levels on vendor selection, and the double-edged sword of network externalities. When the pricing of an NRE system is more competitive than that of a fossil fuel-based system, its appeal intensifies, especially when a substantial number of manufacturers have adopted the NRE system [48]. This demonstrates how market dynamics are influenced by both competitive pricing and robust network externalities [47]. If the pricing of NRE systems exceeds that of fossil fuels, fossil fuel systems may retain their appeal due to their cost advantage and extensive vendor network, particularly in scenarios where network externalities are not strong enough to offset higher prices. A high number of manufacturers can enhance the attractiveness of an energy system due to network externalities. However, if this is coupled with higher prices, the advantage may diminish [46]. Conversely, competitive pricing can compensate for a smaller manufacturer base, making the system more attractive.

4.3. The Impact of New and Renewable Energy (NRE) Policies on Energy Security

Within the framework of game theory, the impact of NRE policies on energy security is assessed by examining shifts in strategic decisions and optimization behaviors of energy market participants [19]. These policies influence enterprise decisions and market equilibrium, significantly affecting national energy security (see Table 4). Through economic incentives such as subsidies and tax benefits, or constraints such as carbon taxes and environmental regulations, NRE policies can shift corporate and consumer preferences towards sustainable energy systems [67]. This shift is reflected in the game model, altering payoff structures and promoting NRE systems as a strategic choice.

Table 4. Impact of New and Renewable Energy (NRE) Policies on Energy Security.

Aspect of NRE Policies	Description of Impact	Influence on Market Participants	Game Theory Implications
Economic Incentives	Subsidies, tax incentives	Alter corporate and consumer preferences towards NRE	Changes payoff functions, incentivizes NRE
Constraints	Carbon taxes, environmental regulations	Shifts cost structure away from fossil fuels	Dominant strategy for NRE emerges
Cost Reduction	Subsidies for NRE projects	Lowers effective cost of NRE systems	Makes "low price for NRE" more prevalent
Market Transition	Carbon tax on fossil fuels	Increases cost of fossil energy systems	Accelerates shift towards NRE systems
Innovation and Demand Shift	Policy adjustments	Stimulates original innovation and consumer demand	Catalyst for market transformation
Network Externalities	Positive feedback loop	Increases adoption of NRE technologies	Elevates NRE as optimal response
Infrastructure Investment	Charging stations, smart grids	Enhances market competitiveness of NRE systems	Amplifies attractiveness and network effects
Public Awareness	Education and awareness campaigns	Increases social acceptance and demand	Indirectly amplifies network externalities
Diversity and Adaptability	Broadens energy supply options	Increases market's strategic landscape	Enhances stability and resilience
Flexibility in Supply	Diversified energy sources	Enables market stabilization and resistance to shocks	Swift reconfiguration in supply constraints

As market strategies evolve, NRE systems can become dominant, reducing fossil fuel dependence, diversifying energy supply, and enhancing energy security. Governments can lower the costs of NRE systems through subsidies or tax incentives, making them more competitive against fossil fuel systems. These policies increase the likelihood of NRE systems being priced competitively, thereby boosting their adoption. Conversely, carbon taxes or environmental levies on fossil fuels can raise their costs, prompting a shift towards NRE systems. Such measures can reduce fossil fuel consumption while encouraging a transition to sustainable energy. Policy adjustments in the NRE sector are crucial for driving innovation and shifting market demand [45].

Network externalities play a crucial role in amplifying market scale effects under NRE policies, creating a positive feedback loop that accelerates technology adoption [48]. From a game theory perspective, these policies enhance the relative benefits of adopting NRE strategies, making them the optimal choice for market participants. As the adoption of NRE systems spreads, intensified network effects further drive the dissemination of these technologies, strengthening the overall energy security network by reducing dependency on single-source energy [47].

Government investments in related infrastructure, such as charging stations and smart grids, can enhance these network externalities, thereby increasing the market competitiveness of NRE systems [46]. This approach can attract more manufacturers to adopt NRE technologies, creating a more favorable market environment. Additionally, public awareness campaigns can elevate social acceptance and demand for NRE systems, further strengthening network externalities. These efforts collectively shift market dynamics, positioning NRE systems as a dominant strategy within the energy market.

The proactive development of NRE policies diversifies and stabilizes the global energy supply, reducing reliance on single energy sources and mitigating risks associated with geopolitical tensions and price volatility. This diversification enhances the system's resilience to external shocks, ensuring the continuity of national energy security [14].

The vendor payment function for the use of fossil energy systems is defined as $P_F(N_F, N_{NR})$, and the vendor payment function for the use of NRE systems is $P_{NR}(N_F, N_{NR})$. Without considering NRE policies, manufacturers make energy system choices based on current costs and benefits, reaching an equilibrium (N_F^*,N_{NR}^*) in which no firm has incentives to change its choices unilaterally. The inclusion of the explanation regarding the vendor payment function and equilibrium shift is essential to elucidate how manufacturers make decisions regarding their energy systems. This analysis is foundational in understanding the economic behavior and strategic choices of firms in the energy market, particularly when comparing fossil energy systems and NRE systems. By defining the vendor payment function for both fossil and NRE systems and identifying the initial equilibrium, the groundwork is laid to explore the impact of NRE policies on these choices.

After the introduction of NRE policies, which reduce the cost of NRE through subsidies and other means, the payment function changes, resulting in a new equilibrium (N_F^{**},N_{NR}^{**}). Under this new equilibrium, more manufacturers choose NRE systems, increasing N_{NR}. Consequently, the energy supply system becomes more diversified, manufacturers rely more on NRE, and the market becomes less sensitive to external shocks such as price fluctuations and supply disruptions, thus improving the system's resistance to external shocks. Explaining the impact of NRE policies on equilibrium is crucial because it demonstrates the direct effect of policy interventions on manufacturers' behavior. NRE policies such as subsidies reduce the cost of NRE systems, shifting the equilibrium towards greater adoption of these systems. This shift is significant as it leads to a more diversified and resilient energy supply system, reducing dependency on fossil fuels and increasing the market's stability against external shocks. This analysis helps in understanding the policy's effectiveness in achieving energy security and sustainability goals.

To simplify the stability analysis under the new equilibrium, the stability of the system at (N_F^{**},N_{NR}^{**}) can be analyzed using the Jacobian matrix:

$$J = \begin{bmatrix} \partial^2 P_F / \partial N_F^2 & \partial^2 P_F / (\partial N_F \partial N_{NR}) \\ \partial^2 P_{NR} / (\partial N_F \partial N_{NR}) & \partial^2 P_{NR} / \partial N_{NR}^2 \end{bmatrix} \quad (10)$$

The stability of the system requires that the eigenvalue of j is negative. The stability analysis using the Jacobian matrix is included to provide a rigorous mathematical framework for assessing the stability of the new equilibrium. This is a critical step in verifying whether the new equilibrium, resulting from the introduction of NRE policies, is stable or if it might lead to further adjustments in the market. Ensuring that the system's eigenvalues are negative is a standard method in dynamic systems to confirm stability, thus validating the long-term effectiveness of NRE policies.

4.4. The Geopolitical Implications of NRE Policies and International Cooperation

The impetus for NRE policies extends to the realm of international relations, catalyzing both cooperation and competition, effectively setting the stage for a cooperative game. By engaging in the exchange of NRE technologies and the development of transnational energy infrastructure, nations can bolster global energy security [5,69]. Concurrently, these policies invigorate international competition, driving technological advancements and cost reductions, thereby revitalizing the global energy market [16]. Discussing NRE policies within the context of international relations illustrates their broader geopolitical and economic implications [5], highlighting how international collaboration and competition can enhance technological progress and market vitality [16].

To assess the international impact of NRE policies, a streamlined model of international relations is employed. This model dissects nations' decision-making processes regarding NRE investments and explores the influence of these decisions on international cooperation and competition [66]. It features two principal actors, Country A and Country B, each considering independent investment (I) or international cooperation (C), with strategies aimed at maximizing economic and security benefits, such as technological innovation and energy supply security [67]. This analysis illustrates how cooperation can lead to better outcomes, reinforcing the importance of international partnerships in global energy security [70–73].

The two-country payment function is defined as $P_A(S_A, S_B)$ and $P_B(S_A, S_B)$, with S_A and S_B representing the strategic choices of the two countries, respectively. The analysis shows that if both countries cooperate (C, C), they can achieve higher returns $(P_A(C, C) > P_A(I, I))$ and $(P_B(C, C) > P_B(I, I))$ than if they act independently (I, I), thus achieving a better Nash equilibrium state. Including the analysis of cooperative and non-cooperative states helps compare the benefits of different strategic approaches. By showing that cooperative strategies yield higher returns than non-cooperative ones, the discussion emphasizes the advantages of international cooperation in NRE policies. This analysis is crucial for policymakers to understand the potential gains from collaborative efforts and to design incentive mechanisms that foster cooperation.

The stability of cooperation is further analyzed by comparing the payment function in cooperative and non-cooperative states. It is confirmed that the benefits provided by cooperation are superior to those in the non-cooperative state. The introduction of incentive mechanisms Λ, such as technology transfer agreements and joint research and development funds, can increase the attractiveness of cooperation, namely $P_A(C, C, \Lambda) > P_A(C, C)$ and $P_B(C, C, \Lambda) > P_B(C, C)$, thereby consolidating and promoting international partnerships. The stability of cooperation section is vital to confirm that cooperative strategies are not only beneficial but also sustainable over the long term. By comparing the payment functions in cooperative and non-cooperative states and introducing incentive mechanisms, the analysis demonstrates how stable and attractive cooperative arrangements can be maintained. This provides practical insights into how international partnerships can be strengthened and sustained.

5. Conclusions and Policy Recommendations

This paper examines the strategic motivations and behavioral models underpinning NRE policies amidst fluctuating global geopolitics. It systematically assesses the impact of geopolitical shifts on the global energy market and NRE policies. Utilizing mathematical modeling and game theory, the paper evaluates the influence of manufacturers' decisions to convert energy systems under these policies on energy security. It elucidates the strategic rationale behind nations' policy formulations, discusses the competitive dynamics among countries in the realm of NRE, and proposes strategies to address prevalent challenges and opportunities.

Key findings underscore (1) the critical role of NRE policies in bolstering energy security and facilitating the transition to a low-carbon energy system [74]. These policies enhance energy security by diversifying energy sources and reducing dependence on single-source supplies, a necessity in the context of global geopolitical instability and energy market volatility [12]. Strategic implementation, international collaboration, and technological advancements are pivotal in maximizing the effectiveness of these policies. The European Union's adoption of NRE policies significantly reduced reliance on imported fossil fuels, bolstering resilience against energy supply disruptions, while China's extensive investments in solar and wind energy have diversified its energy portfolio and strengthened its energy infrastructure against external shocks [75]. The IEA confirms that NRE policies not only diversify energy supplies but also mitigate geopolitical risks associated with fossil fuel dependence, contributing to greater resilience against supply disruptions due to political instability or natural disasters.

(2) NRE policies are instrumental in advancing the global transition to a low-carbon energy paradigm by accelerating the development and deployment of clean energy technologies [6,7]. Germany's Energiewende policy has been particularly effective in expanding renewable energy capacity, especially in wind and solar, leading to substantial reductions in CO_2 emissions and dependence on fossil fuels. Denmark's investments in wind energy

also positioned it as a leader in renewable energy, resulting in significant cuts in carbon emissions and enhanced energy security [76].

(3) International collaboration through NRE policies significantly advanced the global energy governance framework, elevating energy security and providing effective strategies for navigating global energy market uncertainties and climate change challenges [77]. Collaborative efforts, such as those led by the International Renewable Energy Agency (IRENA), played a crucial role in coordinating global energy policies, promoting technology transfer, and harmonizing standards, thus contributing to a more resilient and sustainable global energy system.

(4) The effectiveness of NRE policies in driving energy transformation is well-documented and expected to remain pivotal in the evolving global energy governance system [78]. In the European Union, these policies significantly increased the share of renewables in total energy consumption, thereby reducing CO_2 emissions and enhancing energy security by decreasing reliance on fossil fuels. Similar policies in Turkey reduced the country's dependence on imported energy, increased the share of renewables in its energy mix, and supported compliance with international emission reduction commitments.

The study provides an in-depth analysis of strategic interactions and collaborations among nations and stakeholders in the formulation and implementation of NRE policies. Using game theory, it explores the dynamics of international cooperation and competition in the realm of NRE policies, highlighting how these interactions shape policy outcomes and contribute to the stability and resilience of the global energy system [79]. Actionable policy recommendations are clearly provided, suggesting measures such as strengthening oversight of energy supply chains, increasing investment in R&D, and fostering international cooperation. These recommendations aim to enhance energy security, drive technological innovation, and improve global energy governance.

Policy suggestions: (1) Reinforce Stability and Security of Energy Supply Chains: Enhanced oversight and protection are crucial to ensuring the integrity of energy transportation and distribution [80]. Establishing emergency plans enhances the energy market's capacity to withstand external shocks and safeguards national and regional energy security [81].

(2) Increase Investment in R&D and Innovation: Governments and agencies must amplify financial backing and policy incentives to expedite technological advancements and reduce costs. This approach enhances the competitiveness of NRE sources through private sector engagement and market-driven innovation mechanisms [82].

(3) Foster International Cooperation: To collectively overcome energy market challenges, nations should bolster collaboration, disseminate NRE technologies, and synergize efforts to develop and operate transnational energy infrastructure. Leveraging international cooperation platforms enhances information exchange and policy coordination, fortifying the stability and resilience of the global energy system [83]. Nations should actively participate in international energy governance mechanisms and advocate for the establishment of unified energy policies and standards to nurture the stability and sustainable evolution of the global energy market [84].

(4) Implement Agile and Diversified Energy Policies: To reduce reliance on single or imported energy sources, countries should advocate for supply diversification through policy incentives. [82] This includes the development of indigenous energy resources and extensive adoption of NRE. Emphasis should also be placed on enhancing energy efficiency and refining energy consumption structures to reduce waste and increase energy utilization efficiency [85].

Future research should focus on applying the multi-level NRE Policy game model to explore energy security, technological evolution, and market access, offering insights into the strategic behavior of stakeholders at national, regional, and corporate levels. System dynamics modeling is crucial for simulating the impact of NRE policies, incorporating variables such as energy production and technological advancement. For instance, Loh and Bellam [86] used such modeling to advocate for Singapore's Energy 2050 Plan, emphasizing renewable energy and reduced consumption. Agent-based modeling (ABM) is recommended to simulate interactions of market participants, aligning with the model's focus on micro-level interactions to inform macro-level policy. Big data analytics and AI are essential for assessing policy impacts and forecasting risks, providing a scientific basis for refining policies. Interdisciplinary approaches are vital for addressing NRE policy challenges, integrating economics, political science, and environmental science to promote innovative energy policy research. Empirical testing across diverse geopolitical contexts is necessary to validate the theoretical models and ensure they translate into effective energy security strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17164115/s1. Supplementary material contains model hypotheses and python which simulations involved in estimating and building Table 3's methods and procedures.

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References

1. Lin, B.; Shi, L. Do environmental quality and policy changes affect the evolution of consumers' intentions to buy new energy vehicles. *Appl. Energy* **2022**, *310*, 118582. [CrossRef]
2. Wang, Y.; Yu, L. Can the current environmental tax rate promote green technology innovation?—Evidence from China's resource-based industries. *J. Clean. Prod.* **2021**, *278*, 123443. [CrossRef]
3. Qin, B.; Wang, H.; Liao, Y.; Liu, D.; Wang, Z.; Li, F. Liquid hydrogen superconducting transmission based super energy pipeline for Pacific Rim in the context of global energy sustainable development. *Int. J. Hydrogen Energy* **2024**, *56*, 1391–1396. [CrossRef]
4. Wang, C.; Yan, C.; Li, G.; Liu, S.; Bie, Z. Risk assessment of integrated electricity and heat system with independent energy operators based on Stackelberg game. *Energy* **2020**, *198*, 117349. [CrossRef]
5. Jerzyniak, T.; Herranz-Surrallés, A. EU Geoeconomic Power in the Clean Energy Transition. *JCMS J. Common Mark. Stud.* **2024**, *62*, 1028–1045. [CrossRef]
6. Wu, Z.; Fan, X.; Zhu, B.; Xia, J.; Zhang, L.; Wang, P. Do government subsidies improve innovation investment for new energy firms: A quasi-natural experiment of China's listed companies. *Technol. Forecast. Soc. Chang.* **2022**, *175*, 121418. [CrossRef]
7. Wu, H.; Hu, S. The impact of synergy effect between government subsidies and slack resources on green technology innovation. *J. Clean. Prod.* **2020**, *274*, 122682. [CrossRef]
8. Bai, X.; Chen, H.; Oliver, B.G. The health effects of traffic-related air pollution: A review focused the health effects of going green. *Chemosphere* **2022**, *289*, 133082. [CrossRef]
9. Isik, M.; Dodder, R.; Kaplan, P.O. Transportation emissions scenarios for New York City under different carbon intensities of electricity and electric vehicle adoption rates. *Nat. Energy* **2021**, *6*, 92–104. [CrossRef] [PubMed]
10. Qi, G.; Jia, Y.; Zou, H. Is institutional pressure the mother of green innovation? Examining the moderating effect of absorptive capacity. *J. Clean. Prod.* **2021**, *278*, 123957. [CrossRef]
11. Chen, Y.; Ni, L.; Liu, K. Innovation efficiency and technology heterogeneity within China's new energy vehicle industry: A two-stage NSBM approach embedded in a three-hierarchy meta-frontier framework. *Energy Policy* **2022**, *161*, 112708. [CrossRef]
12. Ma, S.; He, Y.; Gu, R.; Li, S. Sustainable supply chain management considering technology investments and government intervention. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *149*, 102290. [CrossRef]
13. Tan, R.; Tang, D.; Lin, B. Policy impact of new energy vehicles promotion on air quality in Chinese cities. *Energy Policy* **2018**, *118*, 33–40. [CrossRef]
14. Ge, T.; Cai, X.; Song, X. How does renewable energy technology innovation affect the upgrading of industrial structure? The moderating effect of green finance. *Renew. Energy* **2022**, *197*, 1106–1114. [CrossRef]
15. Sovacool, B.K.; Newell, P.; Carley, S.; Fanzo, J. Equity, technological innovation and sustainable behaviour in a low-carbon future. *Nat. Hum. Behav.* **2022**, *6*, 326–337. [CrossRef] [PubMed]
16. Blondeel, M.; Price, J.; Bradshaw, M.; Pye, S.; Dodds, P.; Kuzemko, C.; Bridge, G. Global energy scenarios: A geopolitical reality check. *Glob. Environ. Chang.* **2024**, *84*, 102781. [CrossRef]
17. Jin, J.; McKelvey, M. Building a sectoral innovation system for new energy vehicles in Hangzhou, China: Insights from evolutionary economics and strategic niche management. *J. Clean. Prod.* **2019**, *224*, 1–9. [CrossRef]

18. Patidar, A.K.; Jain, P.; Dhasmana, P.; Choudhury, T. Impact of global events on crude oil economy: A comprehensive review of the geopolitics of energy and economic polarization. *GeoJournal* **2024**, *89*, 50. [CrossRef]
19. Liu, J.; Chen, J.; Wang, C.; Chen, Z.; Liu, X. Market Trading Model of Urban Energy Internet Based on Tripartite Game Theory. *Energies* **2020**, *13*, 1834. [CrossRef]
20. Miao, C.; Fang, D.; Sun, L.; Luo, Q. Natural resources utilization efficiency under the influence of green technological innovation. *Resour. Conserv. Recycl.* **2017**, *126*, 153–161. [CrossRef]
21. Gong, M.; Dai, A. Multiparty Evolutionary Game Strategy for Green Technology Innovation Under Market Orientation and Pandemics. *Front. Public Heal.* **2022**, *9*, 821172. [CrossRef] [PubMed]
22. Lin, B.; Ma, R. Green technology innovations, urban innovation environment and CO_2 emission reduction in China: Fresh evidence from a partially linear functional-coefficient panel model. *Technol. Forecast. Soc. Chang.* **2022**, *176*, 121434. [CrossRef]
23. Zhao, M.; Sun, T.; Feng, Q. Capital allocation efficiency, technological innovation and vehicle carbon emissions: Evidence from a panel threshold model of Chinese new energy vehicles enterprises. *Sci. Total. Environ.* **2021**, *784*, 147104. [CrossRef] [PubMed]
24. Cao, Y.; Li, L.; Zhang, Y.; Liu, Z.; Wang, L.; Wu, F.; You, J. Co-products recovery does not necessarily mitigate environmental and economic tradeoffs in lithium-ion battery recycling. *Resour. Conserv. Recycl.* **2023**, *188*, 106689.
25. Wu, G.; Xu, Q.; Niu, X.; Tao, L. How Does Government Policy Improve Green Technology Innovation: An Empirical Study in China. *Front. Environ. Sci.* **2022**, *9*, 799794. [CrossRef]
26. Hammad, M.A.; Elgazzar, S.; Jereb, B.; Sternad, M. Requirements for Establishing Energy Hubs: Practical Perspective. *Amfiteatru Econ.* **2023**, *25*, 798–812. [CrossRef] [PubMed]
27. Idowu, A.; Ohikhuare, O.M.; Chowdhury, M.A. Does industrialization trigger carbon emissions through energy consumption? Evidence from OPEC countries and high industrialised countries. *Math. Biosci. Eng.* **2023**, *7*, 165–186. [CrossRef]
28. Awada, M.; Mestre, R. Revisiting the Energy-Growth nexus with debt channel. A wavelet time-frequency analysis for a panel of Eurozone-OECD countries. *Data Sci. Financ. Econ.* **2023**, *3*, 133–151. [CrossRef]
29. Li, Z.; Huang, Z.; Su, Y. New media environment, environmental regulation and corporate green technology innovation: Evidence from China. *Energy Econ.* **2023**, *119*, 106545. [CrossRef]
30. Wang, Z.; Li, X.; Xue, X.; Liu, Y. More government subsidies, more green innovation? The evidence from Chinese new energy vehicle enterprises. *Renew. Energy* **2022**, *197*, 11–21. [CrossRef]
31. Dingbang, C.; Cang, C.; Qing, C.; Lili, S.; Caiyun, C. Does new energy consumption conducive to controlling fossil energy consumption and carbon emissions?-Evidence from China. *Resour. Policy* **2021**, *74*, 102427. [CrossRef]
32. Novikau, A.; Muhasilović, J. Turkey's quest to become a regional energy hub: Challenges and opportunities. *Heliyon* **2023**, *9*, e21535. [CrossRef] [PubMed]
33. Mao, Y.; Li, P.; Li, Y. Exploring the promotion of green technology innovation in the new energy vehicle industry: An evolutionary game analysis. *Environ. Sci. Pollut. Res.* **2023**, *30*, 81038–81054. [CrossRef]
34. Ren, G.; Ma, G.; Cong, N. Review of electrical energy storage system for vehicular applications. *Renew. Sustain. Energy Rev.* **2015**, *41*, 225–236. [CrossRef]
35. Bian, X.; Chen, P.; Gao, Z.; Fang, G. How to promote the energy transition?—An analysis based on the size and technology effect in new energy industry. *Front. Energy Res.* **2023**, *10*, 1082368. [CrossRef]
36. Wang, Y.; Wang, Y.; Huang, Y.; Li, F.; Zeng, M.; Li, J.; Wang, X.; Zhang, F. Planning and operation method of the regional integrated energy system considering economy and environment. *Energy* **2019**, *171*, 731–750. [CrossRef]
37. Zuo, W.; Li, Y.; Wang, Y. Research on the optimization of new energy vehicle industry research and development subsidy about generic technology based on the three-way decisions. *J. Clean. Prod.* **2019**, *212*, 46–55. [CrossRef]
38. Nilssen, T. Two Kinds of Consumer Switching Costs. *RAND J. Econ.* **1992**, *23*, 579. [CrossRef]
39. Markvart, T.; Bogus, K. *Solar Electricity*; Wiley: New York, NY, USA, 1994.
40. World Energy Council. *New Renewable Energy Resources: A Guide to the Future*; Kogan Page: London, UK, 1994.
41. Klemperer, P. Competition when Consumers have Switching Costs: An Overview with Applications to Industrial Organization, Macroeconomics, and International Trade. *Rev. Econ. Stud.* **1995**, *62*, 515–539. [CrossRef]
42. Sharpe, S.A. The Effect of Consumer Switching Costs on Prices: A Theory and its Application to the Bank Deposit Market. *Rev. Ind. Organ.* **1997**, *12*, 79–94. [CrossRef]
43. Shy, O. *The Economics of Network Industries*; Cambridge University Press (CUP): Cambridge, UK, 2000.
44. Shy, O. A quick-and-easy method for estimating switching costs. *Int. J. Ind. Organ.* **2002**, *20*, 71–87. [CrossRef]
45. Shan, H.; Yang, J. Promoting the implementation of extended producer responsibility systems in China: A behavioral game perspective. *J. Clean. Prod.* **2020**, *250*, 119446. [CrossRef]
46. Clements, M.T. Direct and indirect network effects: Are they equivalent? *Int. J. Ind. Organ.* **2004**, *22*, 633–645. [CrossRef]
47. Farrell, J.; Saloner, G. Standardization, compatibility, and innovation. *Rand J. Econ.* **1985**, *16*, 70–83. [CrossRef]
48. Katz, M.L.; Shapiro, C. Network externalities, competition, and compatibility. *Am. Econ. Rev.* **1985**, *75*, 424–440.
49. Cabral, L.M.; Salant, D.J.; A Woroch, G. Monopoly pricing with network externalities. *Int. J. Ind. Organ.* **1999**, *17*, 199–214. [CrossRef]
50. Rohlfs, J. A Theory of Interdependent Demand for a Communications Service. *Bell J. Econ. Manag. Sci.* **1974**, *5*, 16. [CrossRef]
51. Economides, N. The economics of networks. *Int. J. Ind. Organ.* **1996**, *14*, 673–699. [CrossRef]

52. Su, D.; Gu, Y.; Du, Q.; Zhou, W.; Huang, Y. Factors affecting user satisfaction with new energy vehicles: A field survey in Shanghai and Nanjing. *J. Environ. Manag.* **2020**, *270*, 110857. [CrossRef]
53. Willis, H.; Scott, W. *Distributed Power Generation*; Taylor & Francis: London, UK, 2000; ISBN 9780824703363.
54. Henard, D.H.; Szymanski, D.M. Why Some New Products are More Successful than Others. *J. Mark. Res.* **2001**, *38*, 362–375. [CrossRef]
55. Heil, O.P.; Walters, R.G. Explaining Competitive Reactions to New Products: An Empirical Signaling Study. *J. Prod. Innov. Manag.* **1993**, *10*, 53–65. [CrossRef]
56. Lilly, B.; Walters, R. Toward a model of new product preannouncement timing. *J. Prod. Innov. Manag.* **1997**, *14*, 4–20. [CrossRef]
57. Calantone, R.J.; Schatzel, K.E. Strategic Foretelling: Communication-Based Antecedents of a Firm's Propensity to Preannounce. *J. Mark.* **2000**, *64*, 17–30. [CrossRef]
58. Boonea, D.S.; Lemonb, K.N.; Staelin, R. The impact of firm introductory strategies on consumers' perceptions of future product introductions and purchase decisions. *J. Prod. Innov. Manag.* **2001**, *18*, 96–109. [CrossRef]
59. Schatzel, K. Beyond the firm's initial declaration: Are preannouncements of new product introductions and withdrawals alike? *J. Prod. Innov. Manag.* **2001**, *18*, 82–95. [CrossRef]
60. Katz, M.L.; Shapiro, C. Systems Competition and Network Effects. *J. Econ. Perspect.* **1994**, *8*, 93–115. [CrossRef]
61. Besen, S.M.; Farrell, J. Choosing How to Compete: Strategies and Tactics in Standardization. *J. Econ. Perspect.* **1994**, *8*, 117–131. [CrossRef]
62. David, P.A. Clio and the economics of QWERTY. *Am. Econ. Rev.* **1985**, *75*, 332–337.
63. Farrell, J.; Saloner, G. Installed base and compatibility: Innovation, product preannouncements, and predation. *Am. Econ. Rev.* **1986**, *76*, 940–955.
64. Farrell, J.; Saloner, G. Standardization and variety. *Econ. Lett.* **1986**, *20*, 71–74. [CrossRef]
65. Liebowitz, S.J.; Margolis, S.E. Path dependence, lock-in, and history. *J. Law Econ. Organ.* **1995**, *11*, 205–226. [CrossRef]
66. Han, J.; Guo, J.-E.; Cai, X.; Lv, C.; Lev, B. An analysis on strategy evolution of research & development in cooperative innovation network of new energy vehicle within policy transition period. *Omega* **2022**, *112*, 102686. [CrossRef]
67. Hussain, J.; Lee, C. A green path towards sustainable development: Optimal behavior of the duopoly game model with carbon neutrality instruments. *Sustain. Dev.* **2022**, *30*, 1523–1541. [CrossRef]
68. Yang, T.; Yuan, Z.; Xing, C. Research on China's fiscal and taxation policy of new energy vehicle industry technological innovation. *Econ. Res. Istraz.* **2022**, *36*, 2108100. [CrossRef]
69. Carlson, E.L.; Pickford, K.; Nyga-Łukaszewska, H. Green hydrogen and an evolving concept of energy security: Challenges and comparisons. *Renew. Energy* **2023**, *219*, 119410. [CrossRef]
70. Lee, C.-C.; Hussain, J. Optimal behavior of environmental regulations to reduce carbon emissions: A simulation-based dual green gaming model. *Environ. Sci. Pollut. Res.* **2022**, *29*, 56037–56054. [CrossRef] [PubMed]
71. Yu, Z.; Wan, Y.J.; Jun, C.Y. Research on the factors influencing the competitiveness of Chinese NEVs: A study from the perspective of GVC. *J. Bus. Res.* **2021**, *36*, 53–71. [CrossRef]
72. Yue, W.; Liu, Y.; Tong, Y.; Song, Z. Role of government subsidies in the new energy vehicle charging infrastructure industry: A three-party game perspective. *Chin. J. Popul. Resour. Environ.* **2021**, *19*, 143–150. [CrossRef]
73. Zhang, Y.; Hu, H.; Zhu, G.; You, D. The impact of environmental regulation on enterprises' green innovation under the constraint of external financing: Evidence from China's industrial firms. *Environ. Sci. Pollut. Res.* **2022**, *30*, 42943–42964. [CrossRef] [PubMed]
74. Jember, A.G.; Xu, W.; Pan, C.; Zhao, X.; Ren, X.-C. Game and Contract Theory-Based Energy Transaction Management for Internet of Electric Vehicle. *IEEE Access* **2020**, *8*, 203478–203487. [CrossRef]
75. Hussain, J.; Lee, C.-C.; Chen, Y. Optimal green technology investment and emission reduction in emissions generating companies under the support of green bond and subsidy. *Technol. Forecast. Soc. Chang.* **2022**, *183*, 121952. [CrossRef]
76. Dubský, Z.; Tichý, L. The role of narratives in the discourse on energy security of the European Commission: The EU's transition in energy relations with Russia. *Extr. Ind. Soc.* **2024**, *17*, 101392. [CrossRef]
77. Ghorbani, Y.; Zhang, S.E.; Nwaila, G.T.; Bourdeau, J.E.; Rose, D.H. Embracing a diverse approach to a globally inclusive green energy transition: Moving beyond decarbonisation and recognising realistic carbon reduction strategies. *J. Clean. Prod.* **2023**, *434*, 140414. [CrossRef]
78. Tan, R.; Lin, B. Public perception of new energy vehicles: Evidence from willingness to pay for new energy bus fares in China. *Energy Policy* **2019**, *130*, 347–354. [CrossRef]
79. Deng, Y.; You, D.; Wang, J. Research on the nonlinear mechanism underlying the effect of tax competition on green technology innovation—An analysis based on the dynamic spatial Durbin model and the threshold panel model. *Resour. Policy* **2022**, *76*, 102545. [CrossRef]
80. Cai, X.; Zhu, B.; Zhang, H.; Li, L.; Xie, M. Can direct environmental regulation promote green technology innovation in heavily polluting industries? Evidence from Chinese listed companies. *Sci. Total. Environ.* **2020**, *746*, 140810. [CrossRef]
81. Cabral, L.M.B. *Introduction to Industrial Organization*; MIT Press: Cambridge, MA, USA, 2000; ISBN 9780262032865.
82. Sun, X.; Liu, X.; Wang, Y.; Yuan, F. The effects of public subsidies on emerging industry: An agent-based model of the electric vehicle industry. *Technol. Forecast. Soc. Chang.* **2019**, *140*, 281–295. [CrossRef]

83. Aswani, R.S.; Sajith, S.; Kumar, A. Can offshore wind energy bridge geopolitical asymmetries through cooperative sustainable development in the South China Sea? *Asian J. Political Sci.* **2023**, *31*, 140–160. [CrossRef]
84. Chen, Z.; Wang, T.; Mao, Y. Strategies of stakeholders to promote distributed photovoltaics in China: An evolutionary game study. *Energy Rep.* **2022**, *8*, 11039–11051. [CrossRef]
85. Schuetze, B.; Hussein, H. The geopolitical economy of an undermined energy transition: The case of Jordan. *Energy Policy* **2023**, *180*, 113655. [CrossRef]
86. Loh, J.R.; Bellam, S. Towards net zero: Evaluating energy security in Singapore using system dynamics modelling. *Appl. Energy* **2024**, *358*, 122537. [CrossRef]