Policy Contagion, Financial Contagion, and Energy Innovation: A Survey

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Abstract

This survey paper explores the complex interplay of policy contagion, financial contagion, and energy innovation, which collectively influence the transition toward sustainable energy systems. The study highlights how policy contagion, through the diffusion of regulatory frameworks, can either facilitate or hinder energy innovation, as exemplified by renewable energy policies impacting solar photovoltaic advancements. Financial contagion, marked by the spread of financial shocks, affects energy market stability and green finance, necessitating integrated policy approaches to manage climate-related risks. The paper emphasizes the critical role of energy innovation in reducing reliance on non-renewable sources, with technology diffusion being crucial for energy efficiency and low-carbon transitions. It underscores the interconnectedness of renewable energy consumption, trade, and environmental sustainability, as posited by the Environmental Kuznets Curve hypothesis. The survey structures its analysis by examining policy and financial contagion mechanisms, the role of new and renewable energy innovations, and technology diffusion's impact on energy policy. It further explores sustainable technology adoption, emphasizing the significance of government and private sector initiatives. The paper concludes by synthesizing key findings and recommending future research directions to support sustainable energy transitions, highlighting the need for robust policy frameworks and strategic interventions to mitigate financial contagion risks and promote energy innovation.

1 Introduction

1.1 Interconnected Processes in Energy Transition

The transition to a sustainable energy system is characterized by a complex interplay among policy contagion, financial contagion, and energy innovation. Policy contagion, which involves the diffusion of regulatory initiatives across jurisdictions, plays a crucial role in shaping energy innovation by establishing frameworks that can either promote or hinder technological advancements. For example, renewable energy support policies significantly influence innovation in solar photovoltaics, illustrating the interconnectedness of policy and energy innovation [1]. Furthermore, the concept of energy justice highlights the necessity of aligning policy-making with broader societal objectives during the energy transition [2].

Financial contagion, defined by the transmission of financial shocks across borders, impacts the stability of energy markets and investment landscapes for energy innovation. The promotion of green finance through systemic financial governance policies underscores the interconnected nature of policy contagion, financial contagion, and energy innovation [3]. Central banks and financial regulators are essential in managing climate-related financial risks, emphasizing the need for integrated approaches in policy and financial governance to facilitate a low-carbon economy [4].

Energy innovation serves as a vital driver of the energy transition, encompassing the development and deployment of technologies that reduce dependence on non-renewable energy sources. The

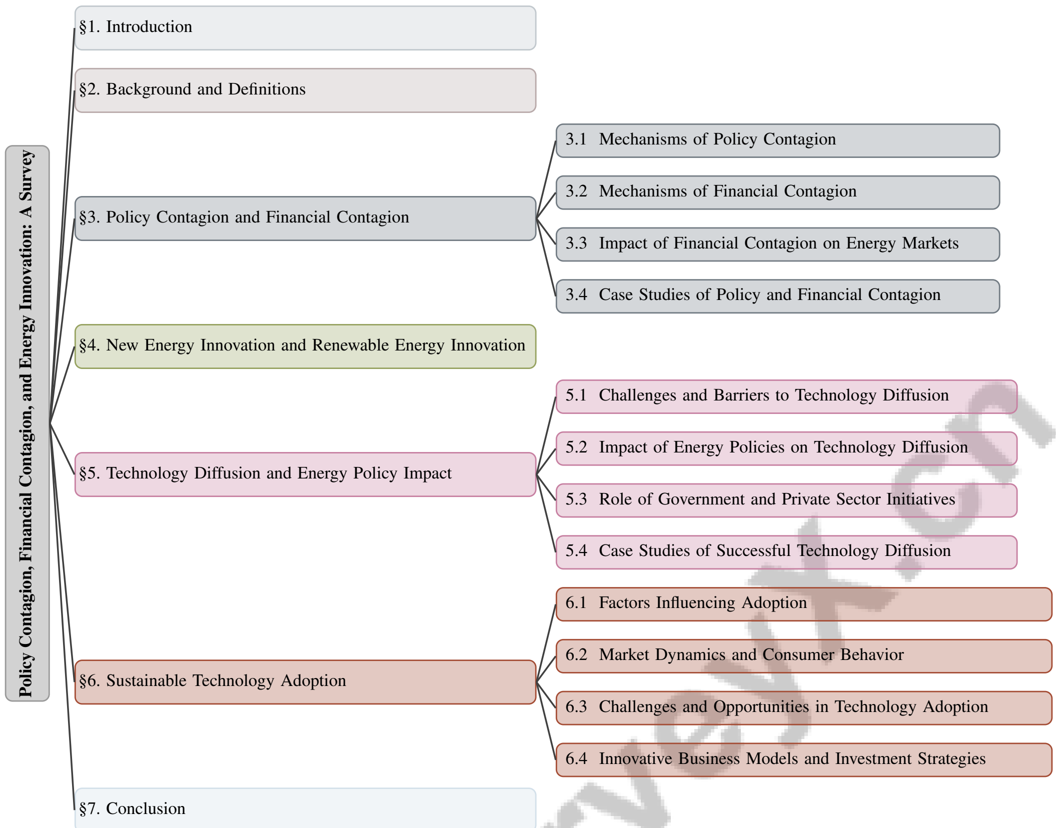


Figure 1: chapter structure

diffusion of energy efficiency technologies (EETs) among small and medium-sized enterprises is critical for achieving energy savings and reducing carbon emissions; however, this process often encounters barriers such as insufficient motivation for information sharing and low visibility of EETs [5]. Additionally, the dynamics of technology diffusion in the electricity sector, influenced by investor decision-making, further illustrate the interconnected processes of policy and technology diffusion that are essential for transitioning to low-carbon technologies [6].

The relationship between renewable energy consumption, energy innovation, total trade, and environmental sustainability is evident through the Environmental Kuznets Curve hypothesis, which underscores the interconnectedness of these elements in achieving sustainable energy transitions [7]. Moreover, the macroeconomic implications of stranded fossil-fuel assets (SFFA) highlight the influence of low-carbon technology diffusion and climate policies on global energy markets [8].

The interplay between technology adoption policies and urban development necessitates a bottom-up approach to the energy transition, emphasizing the importance of integrated strategies in promoting sustainable energy systems [9]. Grasping these dynamics is crucial for formulating strategies that leverage policy and financial instruments to bolster sustainable energy innovations, ultimately facilitating a transition towards a more sustainable energy system.

1.2 Importance of Understanding Contagion and Innovation

Grasping the dynamics of policy and financial contagion alongside energy innovation is vital for cultivating sustainable energy systems. Transitioning to renewable energy sources necessitates a holistic approach that addresses environmental, economic, and social challenges. Increased investments in renewable energy and energy efficiency are crucial for mitigating environmental degradation and underscore the significance of innovation in the energy sector [10].

The political structures that shape emission reduction strategies are pivotal, as they determine the effectiveness and pace of policy implementation aimed at carbon emissions reduction [11]. This understanding is particularly relevant in the context of transformative innovation policies, which should extend beyond economic growth to encompass social and environmental objectives [12].

Energy policy shifts among major global players, such as China and the EU, are essential for enhancing bilateral cooperation and investment flows required for a successful energy transition [13]. Additionally, understanding the response of renewable energy technological innovation to CO2 emissions constraints is crucial for developing resilient and sustainable energy systems [14].

The risk of fossil fuel assets becoming stranded due to a global transition towards low-carbon energy and stringent climate policies highlights the importance of comprehending these dynamics [8]. Such awareness can inform the development of policies and financial strategies that support the renewable energy transition while mitigating potential economic disruptions. Innovation within the energy sector is imperative to tackle the pressing challenges posed by climate change and fossil fuel depletion, necessitating a concerted effort to transition to renewable energy sources [15].

1.3 Structure of the Survey

The survey systematically explores the multifaceted interactions among policy contagion, financial contagion, and energy innovation, and their collective impact on the transition to sustainable energy systems. The paper begins with an **Introduction** that elucidates the interconnected processes integral to the energy transition, emphasizing the importance of understanding these processes for fostering sustainable energy systems.

Following the introduction, the survey delves into the , providing an in-depth analysis of essential concepts such as policy contagion, which examines how policies in one region influence others; financial contagion, which highlights the interconnectedness of financial markets; new energy innovation and renewable energy innovation, focusing on advancements in sustainable technologies; technology diffusion, discussing the spread of innovations across sectors; energy policy impact, assessing the effects of various policies on energy markets and technologies; and sustainable technology adoption, emphasizing the integration of eco-friendly technologies into everyday practices. This comprehensive framework lays the groundwork for understanding the dynamics of green finance and its role in promoting renewable energy innovation, particularly in the context of varying economic development levels and governmental stability [16, 17].

The next section, **Policy Contagion and Financial Contagion**, examines the mechanisms through which policies and financial crises propagate across regions or sectors, analyzing their implications for global financial stability and energy markets. This section is further divided into subsections that explore the specific mechanisms of policy and financial contagion, their impacts on energy markets, and illustrative case studies.

The survey then shifts focus to **New Energy Innovation and Renewable Energy Innovation**, exploring the development and dissemination of innovative energy technologies. This section discusses the role of technological advancements in renewable energy and their transformative potential for energy systems.

Subsequently, **Technology Diffusion and Energy Policy Impact** analyzes the process of technology diffusion within the energy sector and the influence of energy policies on this process. This section includes discussions on challenges and barriers to diffusion, the impact of energy policies, and the roles of government and private sector initiatives, supported by case studies of successful technology diffusion.

The penultimate section, **Sustainable Technology Adoption**, investigates the factors influencing the adoption of sustainable technologies, addressing the challenges and opportunities in integrating these technologies into existing energy systems. This section also explores innovative business models and investment strategies that facilitate sustainable technology adoption.

Finally, the **Conclusion** synthesizes the key findings of the survey, discussing the implications of policy and financial contagion on energy innovation and sustainable technology adoption. The document offers comprehensive recommendations for future research and policy development aimed at facilitating the transition to a sustainable energy system, emphasizing the importance of interdisciplinary approaches and the integration of energy justice principles to effectively address the complexities of energy policy formulation and evaluation in diverse metropolitan contexts [2, 18]. The survey concludes with insights into **Future Research Directions**, providing guidance for future studies aimed at advancing sustainable energy transitions.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Theoretical Frameworks and Models

The study of contagion and innovation in energy transitions is supported by diverse theoretical models that illuminate underlying mechanisms. Central to this is the technology diffusion model, which examines the adoption decision-making process, highlighting economic and environmental incentives while acknowledging costs and uncertainties as barriers, necessitating robust policy frameworks for effective diffusion [19]. The Environmental Kuznets Curve (EKC) hypothesis, suggesting an inverted U-shaped relationship between economic growth and environmental degradation, informs strategies for sustainable development, complemented by econometric models that analyze regional variations in renewable energy technological innovation (RETI) under CO2 constraints [14].

Financial econometrics, through models like the Capital Asset Pricing Model (CAPM), provides insights into the relationship between expected returns and systematic risk, pertinent to financial contagion's impact on energy markets [20]. The adaptation of the Ising model from statistical physics to simulate technology adoption underscores the role of individual perceptions and social influence in innovation diffusion [21]. Network theory, employing spectral analysis, explores how network structures influence diffusion-like processes such as innovation spread and financial shocks [22]. Financial networks, characterized by structural properties and node relationships like ownership and credit, offer strategic insights for managing contagion [23].

Models integrating macroeconomic principles with environmental dynamics assess technology diffusion's implications on fossil fuel markets, exemplified by the IMPACT model, which merges technology adoption policies with zoning regulations to understand urban emissions [9]. The adaptation of the Eisenberg-Noe model to include contingent payments enhances the understanding of financial contagion dynamics by focusing on the conditions for the existence and uniqueness of clearing payments [24].

Agent-Based Modeling (ABM) simulates the diffusion of energy efficiency technologies (EETs) by modeling agent interactions within a network [5], augmented by webAI, which analyzes textual data from company websites for a comprehensive understanding of technology engagement [25]. Machine learning integration with technology diffusion modeling provides a framework for evaluating energy transition policies, offering predictive insights into future developments [18]. Central banks and financial regulators are pivotal in fostering climate risk awareness and aligning financial regulations with climate objectives.

Addressing innovation, investment, and policy framework challenges is crucial for advancing green energy transitions, as uncertainties and low cost-competitiveness of renewable technologies pose significant obstacles. Effective policy interventions and strategic resource allocations are necessary for sustainable technology adoption and diffusion. Extending organizational behavior theories to technology diffusion, particularly with open data, enhances understanding of these processes [26].

2.2 Policy and Regulatory Frameworks

Policy and regulatory frameworks are essential for facilitating contagion and innovation in the energy sector, focusing on mitigating systemic risks while fostering technological advancements. Emphasizing regulatory policies that address systemic risks across financial networks rather than individual entities is crucial for maintaining financial stability and promoting green finance initiatives [24]. Such policies align financial systems with sustainable development goals, increasingly reflected in central banks' regulatory agendas [3].

In non-OECD and low-income economies, transitioning to green finance drives significant renewable energy technology advancements [16]. This transition requires a paradigm shift in innovation policy to address complex societal challenges and foster an environment conducive to sustainable technological innovations [12]. Regulatory frameworks must consider geographical factors influencing technology diffusion, as these external elements significantly affect technological adoption rates and directions [27].

Incorporating advanced methodologies like webAI into policy frameworks allows for a nuanced understanding of technology diffusion by capturing contributions from various actors often overlooked by traditional methods [25]. This comprehensive approach is essential for responsive policies addressing the multifaceted nature of technology adoption and diffusion.

Understanding financial network dynamics, including financial contagion mechanisms, is critical for developing regulatory frameworks that mitigate systemic risks and enhance financial stability [23]. Challenges such as high upfront costs, economic and regulatory uncertainties, and lack of tailored information necessitate policies providing targeted support and incentives for technology adoption, particularly in sectors like agriculture [28].

In low- and middle-income countries (LMICs), the slow AI diffusion pace, potential job losses from automation, and limited policy response resources underscore the need for adaptable and inclusive regulatory frameworks [29]. These frameworks must address specific regional needs and constraints, ensuring technological advancements contribute to broader socio-economic development.

The limitations of traditional forecasting models, such as those utilizing sigmoids, highlight the necessity for flexible regulatory frameworks informed by a comprehensive understanding of future trends and uncertainties [30]. By integrating robust analytical tools and fostering collaborative approaches, policy and regulatory frameworks can effectively support contagion and innovation processes, facilitating the transition towards sustainable energy systems.

3 Policy Contagion and Financial Contagion

3.1 Mechanisms of Policy Contagion

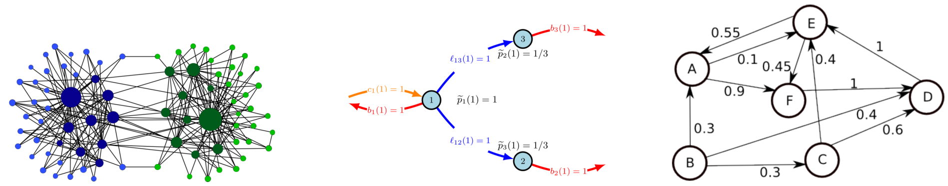
Policy contagion is integral to the global energy transition, facilitating the cross-jurisdictional transmission of regulatory frameworks influenced by interconnected economic, social, and environmental factors. This process is vital for the widespread adoption of renewable energy policies, promoting a collective shift towards sustainable systems amidst significant environmental challenges from fossil fuel dependency [10]. Key mechanisms include the diffusion of regulatory innovations addressing systemic risks in financial networks, crucial for financial stability and advancing green finance [31]. Policy changes in one region can trigger adaptations elsewhere, amplifying contagion's impact. The redistribution of stranded fossil-fuel assets elevates financial contagion risks, particularly in OECD countries, necessitating coordinated international policy responses [32].

Empirical evidence, such as patent applications, underscores the relationship between policy measures and innovation output, highlighting policy's role in fostering innovation essential for sustainable energy technology diffusion [1]. The Environmental Kuznets Curve (EKC) hypothesis further illustrates policy impacts on renewable energy and innovation, aiding sustainable transitions [7]. A causal network framework captures volatility and spillover effects among financial assets, identifying causal relationships crucial for understanding sectoral policy influences and enabling targeted interventions to mitigate financial contagion [33, 31].

Financial contagion complexity is exemplified by systemic risk propagation through interbank networks, where mutual exposures lead to insolvency [34]. Correlated bank exposures and interbank dynamics complicate these interactions [35]. Reverse stress testing reveals vulnerabilities, identifying minimal shocks capable of causing significant losses due to contagion [36].

In renewable energy, increased consumption positively influences economic growth, promoting similar policy adoption across regions [37]. Innovation enhances energy efficiency, underscoring policy contagion's role in advancing sustainable practices [38]. Integrated global economy-environment simulation models assess macroeconomic impacts of stranded fossil-fuel assets, providing insights into broader policy contagion implications in the energy sector [8].

As shown in Figure 3, understanding policy and financial contagion dynamics is essential for effective economic policy formulation and crisis management strategies. The figures illustrate various contagion mechanisms through network structures, emphasizing their importance in economic policy development.



(a) The image depicts a complex network of interconnected nodes and edges, with a focus on two distinct clusters of nodes.[39]

(b) The image depicts a network of nodes and arrows representing a directed acyclic graph (DAG).[40]

(c) The image represents a directed graph with nodes labeled A, B, C, D, E, and F, and edges connecting them with weights.[41]

Figure 2: Examples of Mechanisms of Policy Contagion. This figure illustrates the mechanisms of policy contagion, focusing on three primary categories: Regulatory Frameworks, Innovation and Technology, and Financial Contagion. Each category highlights specific aspects such as renewable energy policies, patent applications, and systemic risk propagation, emphasizing their roles and interconnections in facilitating policy contagion.

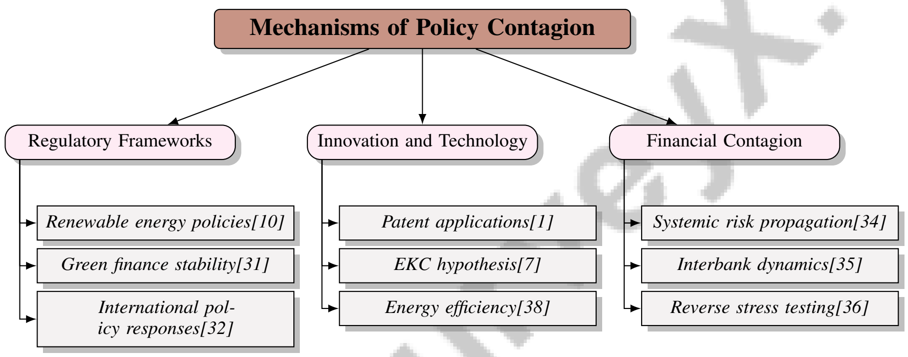


Figure 3: This figure illustrates the mechanisms of policy contagion, focusing on three primary categories: Regulatory Frameworks, Innovation and Technology, and Financial Contagion. Each category highlights specific aspects such as renewable energy policies, patent applications, and systemic risk propagation, emphasizing their roles and interconnections in facilitating policy contagion.

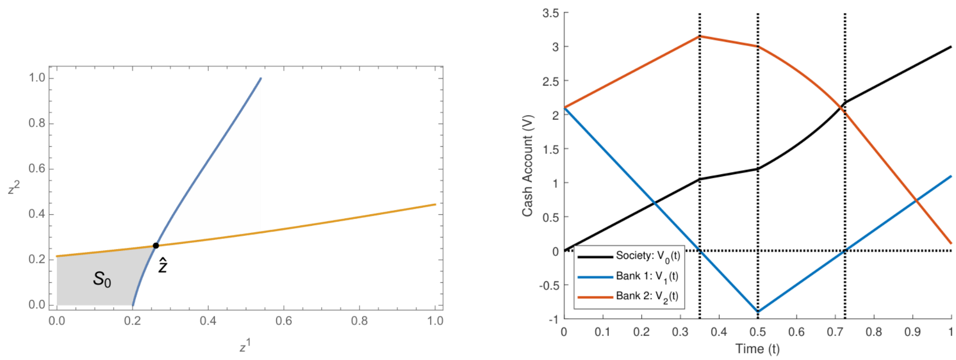
3.2 Mechanisms of Financial Contagion

Financial contagion significantly threatens global financial stability, particularly in energy markets, by disrupting investment flows and exacerbating systemic risks [42]. A primary contagion mechanism is asset liquidation, where initial shocks cause cascading failures across financial networks. Overlapping portfolios and leverage further complicate these interactions, amplifying disturbances [43].

The dynamics of financial contagion are intricately linked to asset liquidation and institutional interconnectedness. The ANWSER model quantifies contagion risk by assessing banks' portfolio diversity and interbank credit network structures [44]. A dual neural network approach predicts asset liquidations from initial shocks, enhancing contagion dynamics understanding [45]. Reverse stress testing reveals systemic vulnerabilities by identifying minimal shocks causing significant financial distress [36]. Quantile Graphical Models (QGMs) characterize nonlinear dependencies among financial variables, enhancing systemic risk and contagion comprehension [46].

Integrating fire sales and borrowing capabilities into contagion models provides a comprehensive systemic risk view, highlighting asset liquidation and credit dynamics interplay [47]. Network theory is crucial in analyzing systemic risk propagation, particularly through scale-free networks with highly connected nodes facilitating contagion [34]. Financial network stability is influenced by interbank connections and portfolio similarities, contributing to systemic risk by facilitating shock propagation [35]. Random Matrix Theory (RMT) insights from global banking network structures enhance contagion understanding [48]. Extending financial network models to define global stability measures allows evaluating various network combinations to identify vulnerabilities [49].

Understanding these mechanisms is crucial for developing strategies to mitigate financial contagion's impact on energy markets, ensuring a stable transition to sustainable energy systems. Sophisticated modeling techniques, such as network analysis and dynamic interventions, enable policymakers and financial institutions to address contagion intricacies effectively, promoting resilience in market structures and responsible investment practices [42, 50].



(a) The image is a graph with two lines and a shaded area.[39]

(b) The image depicts a graph showing the evolution of cash accounts over time for three entities: the society, Bank 1, and Bank 2.[51]

Figure 4: Examples of Mechanisms of Financial Contagion

As depicted in Figure 4, financial contagion dynamics are crucial for understanding shock propagation through interconnected networks. The first graph illustrates the relationship between two variables, z^1 and z^2, emphasizing divergent outcomes based on initial conditions. The second graph shows cash account evolution for three entities, highlighting financial institutions' interconnectedness and the broader economy. Together, these examples provide valuable insights into risk assessment and management strategies [39, 51].

3.3 Impact of Financial Contagion on Energy Markets

Financial contagion significantly impacts energy markets by disrupting investment flows and destabilizing conditions through systemic shock transmission across interconnected networks. Direct connections, such as cross-holdings, and indirect connections, like common asset holdings, facilitate rapid contagion spread, necessitating comprehensive systemic risk assessments [41]. Financial system stability is sensitive to factors like diversification and leverage, with critical thresholds identified for maintaining systemic stability [42].

The dynamics of financial contagion, characterized by asset liquidation and institutional interconnectedness, profoundly influence energy market stability. The ANWSER model indicates that banks' investment portfolio diversity and risk exposure significantly affect contagion risk, underscoring the need for robust portfolio management strategies [44]. Incorporating borrowing capabilities into financial models alters contagion dynamics, emphasizing liquidity and confidence as crucial for systemic stability [47]. Additionally, heterogeneity in bank characteristics affects contagion dynamics, with specialized banks being more susceptible to triggering systemic risk [52].

The potential for stranded fossil-fuel assets to incur financial losses exceeding $1 trillion, especially in OECD countries, highlights energy markets' vulnerability to financial shocks$[32]$.Climatemitig$ $NECOVaR) method provides robust risk predictions essential for understanding energy market impacts$[33].

Empirical evidence of significant contagion among G20 equity markets during the COVID-19 pandemic illustrates energy markets' susceptibility to unpriced risk factors [54]. This contagion was evident in both developed and emerging markets, emphasizing the need to recognize pandemics as potential sources of financial instability affecting energy investments [55]. Furthermore, the dynamic intervention framework proposed by Papachristou et al. effectively mitigates defaults in financial networks, suggesting targeted interventions can stabilize energy markets by preventing significant losses [40].

AI-generated, for reference only.

Stochastic models reveal the resilience of different network structures against systemic shocks, providing critical insights into energy market stability within the broader financial system [39]. The multi-step control model reduces financial contagion risk through targeted cash injections, emphasizing strategic interventions to maintain network stability and protect energy market integrity [31]. Understanding these dynamics is essential for developing strategies to mitigate financial contagion's impact on energy markets, ensuring a resilient transition to sustainable energy systems.

3.4 Case Studies of Policy and Financial Contagion

Analyzing policy and financial contagion through case studies provides valuable insights into energy market dynamics and broader economic systems. A notable example is the comparative study of energy policy frameworks in China and the European Union (EU), illustrating how policy contagion can drive investment flows and shape strategic priorities in the energy sector [13].

In financial contagion, a stylized model of a financial system comprising N banks and M assets elucidates contagion dynamics initiated by shocks like toxic assets or bank failures. This model demonstrates how average diversification and leverage within networks affect systemic stability, offering insights for regulatory frameworks aimed at mitigating contagion risks [42]. The approach proposed by Maeno et al. enriches this understanding by incorporating investment portfolio characteristics and interbank relationships, providing nuanced regulatory insights into financial contagion mechanisms [44].

The financial contagion among investment funds, captured by Pinheiro et al., highlights the importance of assessing systemic risks to guide investment decisions, ensuring resilient financial systems [41]. Similarly, analyzing fiscal decentralization and technological innovation in China reveals their negative effects on CO2 emissions, while globalization continues to drive environmental degradation, illustrating the complex interplay between policy decisions and environmental outcomes [11].

The systemic risk and potential contagion in financial networks are exemplified by Greece's counterfactual scenario of reinstating the drachma, assessing equilibrium prices and systemic risks, providing insights into the repercussions of significant policy shifts on financial stability [56]. Additionally, macroprudential regulation and identifying systemic institutions are key strategies for mitigating contagion, despite moral hazard concerns [57].

The identities of banking systems, shaped by individual characteristics and global network interactions, illustrate financial contagion complexities [48]. Empirical applications of Bayesian covariance graphical latent models to financial time series data from the US and Europe provide evidence of intricate contagion dynamics [58]. Utilizing vector copulas to characterize dependence between random vectors offers a robust framework for financial contagion analysis, significantly impacting understanding shock transmission across systems [59].

These case studies underscore the interconnected nature of policy and financial contagion within energy markets, revealing how systemic risks propagate through overlapping portfolios and interbank relationships. This highlights the critical need for robust regulatory frameworks and strategic interventions to enhance market stability and facilitate the transition to sustainable energy systems. Findings indicate that while diversification may benefit individual institutions, it can inadvertently exacerbate systemic vulnerabilities, necessitating a nuanced regulatory approach that considers the "robust yet fragile" characteristics of financial networks. Furthermore, the positive impact of green finance on renewable energy innovation, particularly in non-OECD and lower-income economies, emphasizes the need for targeted policies aligning financial mechanisms with sustainability goals [57, 42, 43, 16].

In recent years, the field of energy innovation has witnessed significant advancements, particularly in the realm of new and renewable energy technologies. Understanding the complexities of this field necessitates a clear depiction of its underlying structures and relationships. Figure 5 illustrates the hierarchical structure of key concepts in new energy innovation and renewable energy innovation, categorizing technological advancements, dissemination strategies, and impacts on energy systems. This figure highlights the influential factors, strategic frameworks, and tools that drive technological advancements, as well as the strategic interventions and facilitators that promote the dissemination of innovative energy technologies. Furthermore, it emphasizes the transformation and assessment strategies that enhance the efficiency and sustainability of energy systems. By analyzing these components, we can better comprehend the multifaceted nature of energy innovation and its implications for future developments in the sector.

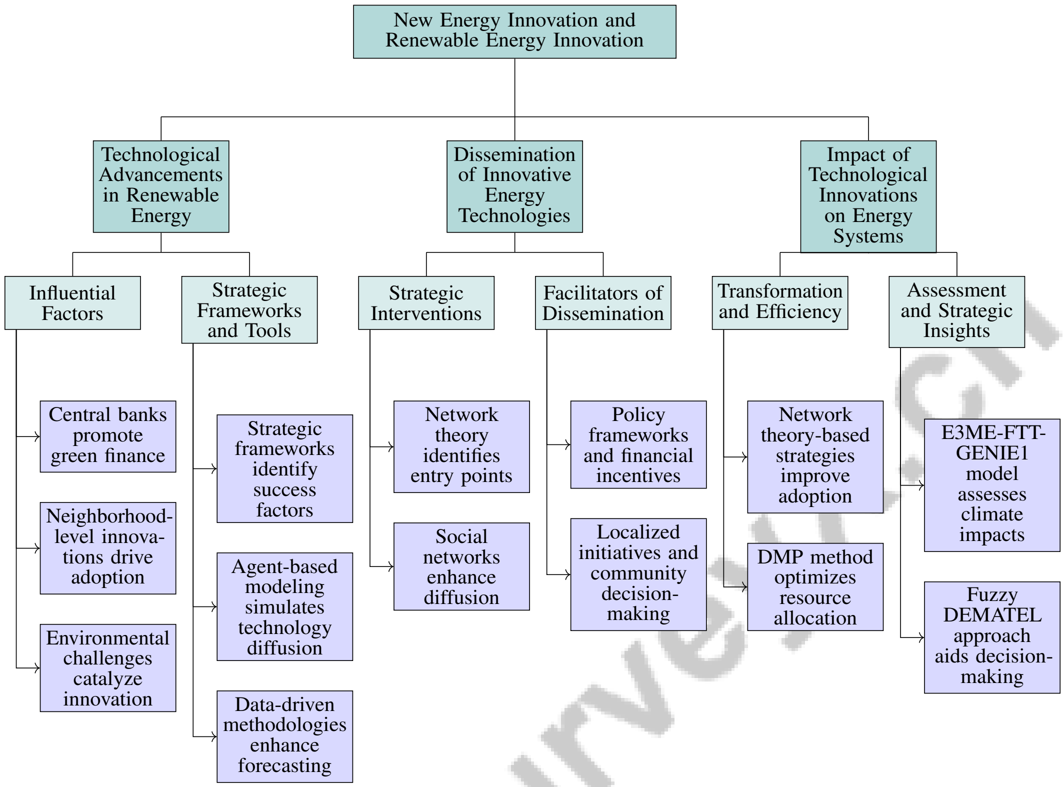


Figure 5: This figure illustrates the hierarchical structure of key concepts in new energy innovation and renewable energy innovation, categorizing technological advancements, dissemination strategies, and impacts on energy systems. It highlights the influential factors, strategic frameworks, and tools that drive technological advancements, the strategic interventions and facilitators that promote the dissemination of innovative energy technologies, and the transformation and assessment strategies that enhance energy systems' efficiency and sustainability.

4 New Energy Innovation and Renewable Energy Innovation

4.1 Technological Advancements in Renewable Energy

Method Name	Technological Approaches	Policy and Regulation	Environmental Drivers
IBTDM[21]	Agent-based Modeling	Strategic Frameworks	Co2 Emissions
FDEMATEL[60]	Fuzzy Dematel	-	-

Table 1: Overview of technological approaches, policy frameworks, and environmental drivers associated with renewable energy technology diffusion methods. The table highlights the use of agent-based modeling and fuzzy DEMATEL in understanding technology adoption influenced by strategic frameworks and CO2 emissions.

Technological advancements are central to advancing sustainable energy systems, enhancing efficiency while reducing environmental impacts. Central banks play a pivotal role in this transition by promoting green finance through regulatory frameworks, which facilitates the adoption of renewable technologies [3]. The IMPACT model illustrates how neighborhood-level innovations drive renewable energy adoption through localized decision-making and community initiatives [9]. Environmental challenges, particularly CO2 emissions, act as catalysts for renewable energy technological innovation (RETI), thereby accelerating sustainability transitions [14]. Agent-based modeling, especially the Ising-like

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model, provides insights into technology diffusion by simulating adoption influenced by individual perceptions and social interactions [21].

Table 1 presents a comparative analysis of methods employed in the diffusion of renewable energy technologies, emphasizing the roles of technological approaches, policy regulations, and environmental drivers. Strategic frameworks, such as those used for 4G technology in Iran, help identify critical success factors in technology adoption, informing policymakers on enhancing renewable energy technology diffusion [60]. The interplay between policy frameworks, financial stability, and localized initiatives is essential for advancing sustainable energy transitions. This dynamic fosters effective energy transition policy implementation, as seen in metropolitan areas like Singapore, London, and California, aligning with carbon emission reduction and renewable energy promotion. Data-driven methodologies, including artificial neural networks, enable better forecasting of renewable energy capacity and scenario generation, contributing significantly to global carbon neutrality targets [11, 18, 16, 13].

4.2 Dissemination of Innovative Energy Technologies

The widespread adoption and integration of innovative energy technologies require strategic interventions. Network theory identifies optimal entry points for introducing new technologies, as demonstrated by successful agricultural training initiatives that facilitate innovative practice adoption [61]. This highlights the importance of leveraging social networks to enhance energy technology diffusion. Figure 6 illustrates these concepts, emphasizing the roles of network theory, agent-based models, and policy frameworks in the dissemination process.

The dissemination process is further influenced by the interplay between individual decision-making and broader social dynamics. Agent-based models, like the Ising-like model, simulate these interactions, showing how individual perceptions and neighbor influences impact technology adoption [21]. The figure also depicts how agent-based models simulate the effects of these individual perceptions and social influences on adoption, reinforcing the significance of understanding this interplay for mapping energy technology spread pathways.

Policy frameworks and financial incentives are significant facilitators of energy innovation dissemination. By promoting green finance, central banks and financial regulators create an enabling environment for renewable technology adoption, essential for overcoming financial barriers [3]. As highlighted in the figure, localized initiatives, emphasized by the IMPACT model, demonstrate community-level decision-making in technology adoption, showcasing the role of grassroots efforts in driving innovation dissemination and contributing to broader energy transition goals [9].

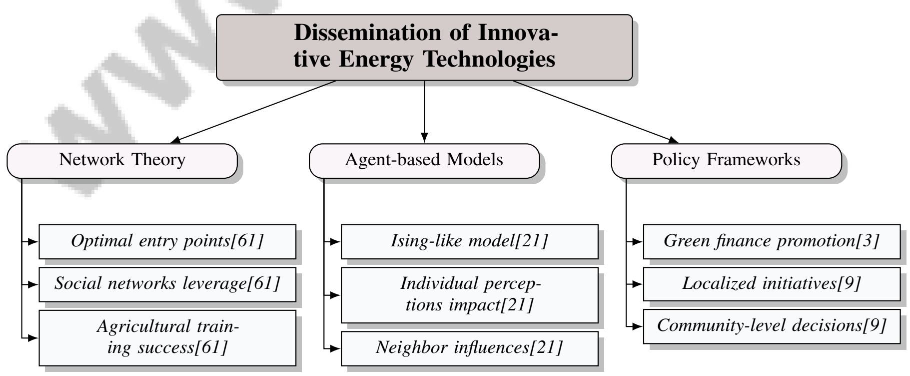

Figure 6: This figure illustrates the dissemination of innovative energy technologies, highlighting the roles of network theory, agent-based models, and policy frameworks. Network theory focuses on leveraging optimal entry points and social networks for technology diffusion. Agent-based models, such as the Ising-like model, simulate the effects of individual perceptions and neighbor influences on adoption. Policy frameworks emphasize the promotion of green finance and localized initiatives to facilitate technology adoption at the community level.

4.3 Impact of Technological Innovations on Energy Systems

Technological innovations are crucial in transforming energy systems by enhancing efficiency, reducing environmental impact, and facilitating a shift to sustainable energy sources. Network theory-based targeting in dissemination strategies significantly improves adoption rates, akin to transformations in agricultural practices [62]. These strategies can similarly accelerate renewable technology adoption within energy systems.

The DMP method, which surpasses traditional approaches in resource allocation, provides a robust framework for optimizing technological innovation spread in energy systems [63]. Its adaptability is vital for managing the dynamic processes involved in widespread new energy technology adoption, ensuring efficient resource allocation for maximum impact.

The E3ME-FTT-GENIE1 model assesses the environmental impacts of various climate policy scenarios, illustrating how technological innovations can shape climate outcomes [64]. By evaluating these scenarios, the model underscores innovations' critical role in facilitating sustainable energy transitions and addressing climate change.

Moreover, the fuzzy DEMATEL approach offers nuanced insights into the complex interrelationships among factors influencing technology adoption, aiding strategic decision-making in the energy sector [60]. This enables policymakers to identify and prioritize key drivers and barriers, supporting targeted strategies for promoting energy innovations.

Recent studies highlight that renewable energy and energy innovation significantly reduce environmental degradation, underscoring the transformative impact of technological advancements on energy systems [7]. These innovations enhance energy systems' efficiency and sustainability, playing a crucial role in achieving broader environmental and economic goals.

5 Technology Diffusion and Energy Policy Impact

5.1 Challenges and Barriers to Technology Diffusion

Technology diffusion in the energy sector faces numerous impediments, chiefly the scarcity of replicable solutions, which stifles the spread of valuable innovations [17]. This challenge is compounded by supply chain complexities, where traceability technologies yield benefits only upon widespread adoption, complicating the identification of initial adopters [65]. Cultural differences further hinder diffusion, as evidenced by the varied adoption of fertilizers in Ethiopian villages [66]. In Malawi, reliance on traditional farming methods and neglect of social networks impede technological uptake [61].

Barriers to green building technologies (GBTs) are systematically categorized, highlighting resistance due to knowledge deficits, high costs, and inadequate legal frameworks [19, 67, 68]. The adoption of smart technologies (SMTs) is hampered by privacy concerns and technological complexity [69], while in the financial sector, understanding interbank networks is crucial for resilience against systemic risks [34].

Cross-country correlations complicate standard estimation methods [27], and reliance on limited databases may exclude critical insights from non-English sources, emphasizing the need for a more inclusive diffusion analysis [15]. WebAI's mapping accuracy depends on online content quality, potentially missing firms without a digital footprint [25]. Addressing these multifaceted challenges is essential for effective technology diffusion, supporting sustainable energy transitions.

5.2 Impact of Energy Policies on Technology Diffusion

Energy policies significantly influence technology diffusion, acting as both facilitators and obstacles. Instruments like carbon pricing and subsidies are crucial for promoting renewable energy technologies by providing financial incentives [6]. However, existing policies often inadequately address diffusion barriers, necessitating more effective frameworks [28]. Central banks' roles in green finance are pivotal yet limited by ambiguous legal mandates, underscoring the need for aligned financial regulations [3]. Government support, particularly in high-emission areas, is vital for fostering renewable energy technological innovation (RETI) through subsidies and mandates [14].

Urban policies, like zoning regulations, integrate energy considerations into planning, aiding emissions reduction and sustainable development [9]. The interplay between trade and sustainability, as illustrated by the Environmental Kuznets Curve, further highlights policy impacts on diffusion [7]. Financial network interconnections pose systemic risks, necessitating robust policy interventions for stability and diffusion promotion [49]. Challenges in forecasting policy impacts on diffusion persist due to limited initial data insights [30].

The inadequacy of traditional information dissemination, particularly within social networks, calls for innovative policy designs. Leveraging social networks is crucial for enhancing technology adoption [61]. Political leadership, institutional pressure, technological advancements, and organizational readiness are key factors influencing open data technology adoption in government, providing insights into broader diffusion contexts [26].

5.3 Role of Government and Private Sector Initiatives

Government and private sector initiatives are critical for advancing technology adoption in the energy sector. Analyzing default conditions based on financial accounts reveals how these initiatives bolster financial stability and technology adoption [51]. Supply chain traceability models (SCTM) address adoption challenges by optimizing technology integration, aiding both government and private sector efforts [65]. Business model enhancements and external support are essential for climate-smart agriculture (CSA) innovation diffusion, emphasizing public-private collaboration [70].

As illustrated in Figure 7, the key initiatives in technology adoption within the energy sector are depicted, emphasizing the interconnectedness of financial stability, technology adoption strategies, and diffusion models. The figure highlights the role of government and private sector efforts through various models, including the Dynamic Eisenberg-Noe Model and Supply Chain Traceability Model, as well as approaches in climate-smart agriculture, social learning networks, and the influence of cultural factors. Additionally, diffusion models, such as agent-based models, and the consideration of social structures are crucial for understanding the dynamics of technology adoption.

Social learning, driven by peer interactions, is a significant adoption driver. Initiatives leveraging social networks can accelerate diffusion, as seen in agricultural contexts [62]. Understanding cultural and social structures, like Ethiopian Peasant Associations, is crucial for crafting tailored initiatives that respect cultural nuances [66]. Agent-based models, such as the Ising model, provide insights into early adopters' spatial dispersion, informing targeted interventions to maximize adoption impact [21].

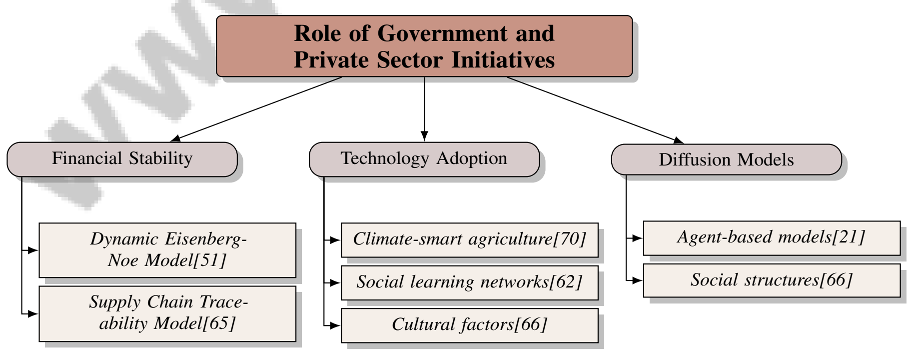

Figure 7: This figure illustrates the key initiatives in technology adoption within the energy sector, emphasizing financial stability, technology adoption strategies, and diffusion models. The role of government and private sector efforts is highlighted through models like the Dynamic Eisenberg-Noe Model and Supply Chain Traceability Model, as well as through approaches in climate-smart agriculture, social learning networks, and cultural factors. Additionally, diffusion models such as agent-based models and the consideration of social structures are crucial for understanding technology adoption dynamics.

5.4 Case Studies of Successful Technology Diffusion

Successful technology diffusion hinges on the strategic interplay of regulatory frameworks, market conditions, and systemic risk management. Quantile Graphical Models (QGMs) applied to financial data elucidate systemic risk and financial contagion, offering insights into technology dissemination across countries [46]. These models quantitatively assess how financial stability influences technology diffusion, particularly in energy systems.

Interbank network systemic risk propagation underscores challenges and opportunities in technology diffusion [34]. Future research should explore simultaneous adverse shocks on multiple institutions, highlighting regulatory measures' role in network stability. Eurozone contagion model testing emphasizes integrating macroeconomic factors to understand volatility and contagion drivers, informing technology diffusion case studies [71]. RD effect estimation methodologies clarify factors driving successful diffusion, providing a framework for evaluating research and development's impact on innovation [27].

Developing models to account for financial networks' temporal evolution and climate-related financial risks is crucial for future research [23]. These models inform adaptive regulatory strategies to mitigate financial network risks, supporting sustainable technology diffusion. Optimizing sales and borrowing strategies in financial networks highlights the importance of quantifying confidence and exploring systemic risk factors [47].

6 Sustainable Technology Adoption

The adoption of sustainable technologies is shaped by a convergence of economic, social, cultural, and policy factors, each playing a critical role in the transition towards sustainable energy systems. These elements collectively influence stakeholders' decision-making processes, highlighting the dynamics of sustainable technology integration.

6.1 Factors Influencing Adoption

Sustainable technology adoption is driven by economic, social, cultural, and policy dynamics. Economically, factors such as real gross fixed capital formation and carbon emissions significantly influence growth and technology adoption [37]. The alignment of energy policies among global powers like China and the EU underscores the need for coherent frameworks to enhance sustainable technology adoption [13]. Cultural diversity necessitates adoption strategies that account for cultural differences, thereby promoting tailored approaches that respect local contexts [66]. Social networks are pivotal in facilitating diffusion, particularly in agriculture, where they enhance the spread of sustainable technologies [62]. Demographic factors, such as income, age, and innovativeness, are positively correlated with adoption, though privacy concerns may impede progress [69].

Policy interventions are more effective when technology-specific, fostering innovation and supporting sustainable technology adoption [1]. Integrating energy justice is crucial for equitable outcomes, requiring policies that address justice and equity in energy transitions [2]. Timely policy adjustments, supported by data-driven platforms, are vital for influencing adoption drivers [18]. The spatial dispersion of early adopters can accelerate product adoption, particularly when advantages over existing options are clear [21]. Understanding subscriber behavior informs strategic frameworks that enhance innovation diffusion [60]. Governance frameworks are essential to manage AI diffusion risks to democracy and political stability in low- and middle-income countries [29]. Addressing these multifaceted influences aids policymakers and stakeholders in promoting sustainable technology diffusion.

6.2 Market Dynamics and Consumer Behavior

Market dynamics and consumer behavior are fundamental in driving sustainable technology adoption. Economic conditions, characterized by competition, regulatory frameworks, and financial incentives, shape consumer decisions and promote technology uptake [10]. Consumer behavior, influenced by social, cultural, and psychological factors, significantly impacts adoption. Social networks and peer influences facilitate knowledge exchange, reducing perceived risks and accelerating diffusion [61].

Social learning, where consumers learn from others, is crucial in sectors with information asymmetry [66].

Cultural factors shape consumer perceptions and technology adoption, necessitating marketing strategies aligned with local values [66]. Demographic characteristics such as income, age, and education affect consumer preferences, with higher income and education levels generally linked to greater adoption propensity [69]. Psychological aspects, including attitudes towards risk and environmental consciousness, also influence adoption decisions. Environmentally conscious consumers are more likely to adopt sustainable technologies, emphasizing the importance of fostering positive attitudes towards sustainability [21]. Perceived benefits like cost savings and environmental impact are significant in shaping consumer choices [60].

Market dynamics, including competitive pressures and technological advancements, drive sustainable technology adoption. Competitive markets stimulate innovation and reduce costs, making sustainable technologies more accessible. Technological advancements enhance performance and appeal, encouraging consumer adoption by offering superior alternatives [14].

6.3 Challenges and Opportunities in Technology Adoption

Integrating sustainable technologies into existing systems presents challenges and opportunities critical for achieving a low-carbon economy. Initial emission increases from energy efficiency improvements necessitate significant renewable energy investments to offset negative impacts [10]. Strategic policy combinations are essential for substantial emissions reductions, as integrating low-carbon technologies can be complex [6].

High upfront costs, market failures, and regional innovation disparities hinder renewable energy development, emphasizing the need for tailored financial incentives and government interventions. Socio-economic impacts of stranded assets, risking $1-4 trillioninglobalwealthloss, highlighttheurgencyofearlydecarbonization[8].Traditionalinformationdissemination$

Opportunities exist in leveraging strategic frameworks and policy analyses for technology adoption. Integrating adoption into urban development frameworks requires nuanced policy analysis to address urban challenges [9]. Technological diffusion's potential to mitigate climate impacts presents significant opportunities, necessitating coordinated global action for sustainable transitions [72]. Future research could explore strategic models' application in various contexts to validate their effectiveness [60]. Challenges and opportunities in renewable energy and innovation integration, particularly in regions like MENA, underscore the need for adaptive policy frameworks responsive to regional specificities [7].

6.4 Innovative Business Models and Investment Strategies

Innovative business models and investment strategies are pivotal for accelerating sustainable technology adoption and ensuring effective integration into energy systems. Developing sustainable energy models requires understanding market dynamics, consumer behavior, and regulatory landscapes, which significantly impact renewable energy solutions' feasibility and scalability. Consumers are evolving into active "prosumers," engaging in innovation within online communities to enhance technology diffusion. Demographic factors such as age, income, and education are crucial in adoption, while green finance is increasingly important for fostering renewable energy innovation, especially in non-OECD and developing economies [15, 16, 69, 17].

Key aspects of innovative business models include leveraging network effects and social learning to enhance adoption. Facilitating peer-to-peer interactions and knowledge exchange can overcome informational barriers and reduce perceived risks associated with new technologies [62]. This approach is effective in sectors where traditional dissemination methods are inadequate, enabling rapid innovation diffusion through social networks [61].

Flexible and adaptive investment strategies are essential for navigating energy sector uncertainties. Adaptive frameworks incorporating scenario analysis and stress testing help investors anticipate and respond to market and regulatory changes, supporting long-term sustainability [51]. Integrating technology adoption into urban development frameworks offers unique opportunities for innovative business models to drive sustainable transitions. Aligning energy policies with urban planning initia-

AI-generated, for reference only.

tives creates synergies, enhancing renewable technology adoption and improving energy efficiency [9].

Strategically aligning business models with government policies and incentives fosters an innovation-conducive environment. Public-private partnerships play a pivotal role by pooling resources and expertise to overcome financial and technical adoption barriers. Collaborating with governmental agencies provides businesses access to funding and policy support, facilitating sustainable technology deployment [3].

7 Conclusion

7.1 Future Research Directions

Future research should focus on developing robust forecasting models that overcome the limitations of traditional sigmoid modeling by incorporating a wider array of data, thereby enhancing the predictive accuracy and reliability of energy transition forecasts [30]. Additionally, refining financial contagion models through the integration of complex dynamics and variations in network structures can deepen our understanding of contagion mechanisms and improve predictive accuracy in financial systems [50].

Further studies must enhance data accuracy regarding technological innovation levels and create comprehensive models that incorporate innovation within the energy system. This holistic approach will elucidate how technological advancements can be effectively integrated into sustainable energy transitions [14]. Moreover, exploring tailored solutions for risk management and strengthening the role of farmers' associations in disseminating relevant information are essential for promoting the diffusion of energy-efficient technologies in agriculture [28].

Investigating the relationships among identified factors and conducting longitudinal studies to assess changes in perception before and after the adoption of open data policies will yield valuable insights into technology adoption dynamics and the role of information transparency in facilitating sustainable energy transitions [26]. Future research should also prioritize the development of sophisticated models that operationalize contagion, addressing dynamic changes in graphical structures to enhance our understanding of contagion dynamics within energy innovation.

Furthermore, examining the interrelationships between barriers and their effects on the adoption of green building technologies (GBTs) will provide critical insights into overcoming obstacles to sustainable technology adoption [19]. Developing dynamic contagion models that utilize real-time data will enhance our comprehension of how interbank connections evolve during crises, offering strategic insights for managing systemic risks in financial networks [35].

Finally, improving discrete choice frameworks to consider additional variables influencing technology adoption and validating these models across various transportation technologies will bolster our capacity to predict and facilitate the diffusion of sustainable innovations [73]. Collectively, these research directions aim to support the transition toward sustainable energy systems by addressing critical gaps in our understanding and promoting the development of innovative solutions.

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