Renewable Energy Technology Innovation and Policy: A Survey

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Abstract

This survey paper provides a comprehensive examination of renewable energy technology innovation (RETI), policy dynamics, and sustainability, emphasizing their interconnections across various economic and social contexts. The study highlights the significance of RETI in addressing climate change and energy security challenges, focusing on advancements in energy storage and low-carbon technologies, particularly within China. It explores the role of government policies, strategic investments, and public-private partnerships in fostering innovation and facilitating the transition to a low-carbon economy. The analysis extends to the policy contagion effect and green technology diffusion, illustrating mechanisms through which policies spread and technologies are adopted globally. The paper also delves into policy transfer and sustainable energy policy, identifying challenges and opportunities for policy innovation. Case studies exemplify successful policy transfers and regional implementations of RETI, with a focus on China's tailored policy approaches. The conclusion synthesizes key findings and proposes future research directions, including the exploration of integrated lifecycle design, advancements in materials science, and the influence of psychological factors on technology diffusion. This nuanced understanding of the interplay between technology innovation, policy, and sustainability underscores the need for integrated strategies to achieve a sustainable, low-carbon future.

1 Introduction

1.1 Significance of Renewable Energy Technology Innovation

Renewable energy technology innovation (RETI) is pivotal for sustainable development and global energy transitions, addressing greenhouse gas emissions and energy security challenges [1, 2]. Transitioning to renewable energy sources is essential for mitigating climate change while ensuring a reliable energy supply, alongside enhancing natural resource efficiency crucial for sustainability [3]. RETI also contributes to energy independence and supports a low-carbon economy, representing a strategic response to environmental imperatives and economic resilience [4]. The COVID-19 pandemic has further complicated this landscape, necessitating innovations that bolster energy system resilience amid global disruptions.

Moreover, RETI is deeply intertwined with policy dynamics, influencing and being influenced by policy frameworks. Zhang et al. [5] highlight the role of policy transfer and visual dynamics in fostering innovation, essential for the global shift towards sustainable energy practices. Collectively, these factors underscore RETI's indispensable role in driving the transition to a sustainable, low-carbon future.

1.2 Scope of the Paper

This paper examines RETI, policy, and sustainability, emphasizing their complex interplay across various economic and social contexts. A significant focus is on RETI's dynamic landscape in China,

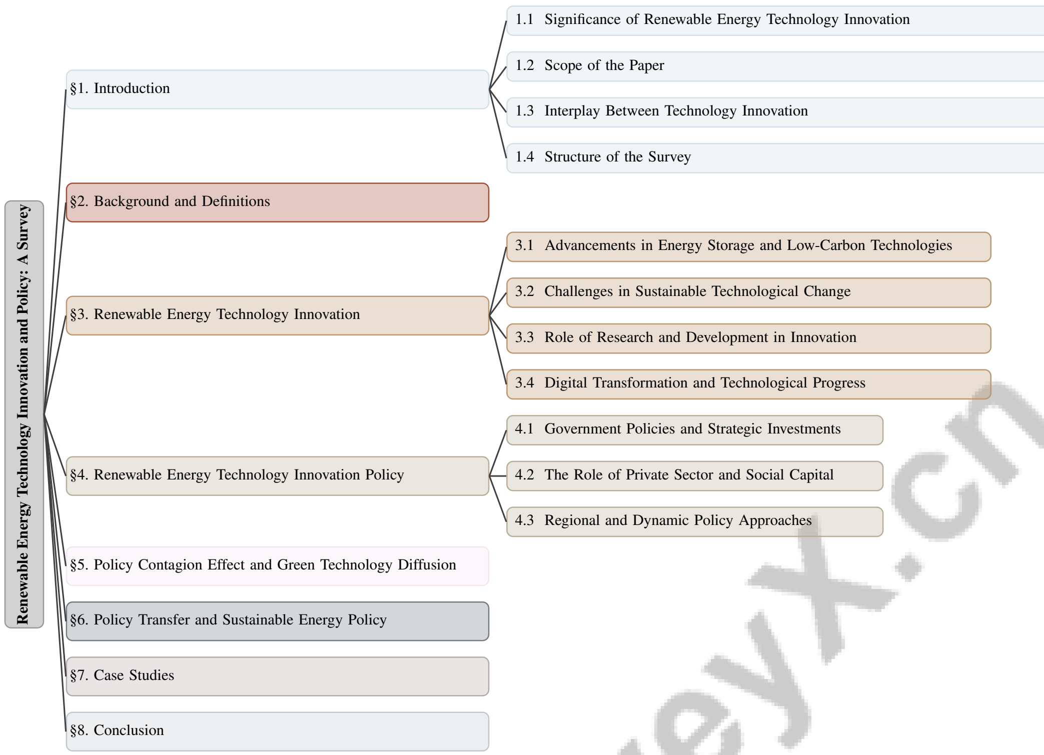

Figure 1: chapter structure

where regional variations critically shape policy outcomes and technological advancements [4]. The study explores the causal relationship between technological innovation and renewable energy development in G10 countries, providing insights into global trends [2]. Additionally, it investigates energy storage technologies, particularly battery storage, in advancing energy system decarbonization [6].

The analysis evaluates 57 indicator sets related to sustainable energy development, establishing a comprehensive framework for understanding sustainability metrics [7]. It also explores low-carbon technology diffusion in Public-Private Partnership (PPP) projects, emphasizing collaborative evolutionary pathways in China [8]. The political dimensions of sustainable energy transitions are scrutinized, particularly the influence of institutional frameworks [9]. The relationship between economic growth and CO2 emissions is examined, focusing on renewable energy consumption's role in emission reduction and sustainable development [10]. The paper surveys materials and technologies relevant to renewable energy and energy efficiency while excluding non-renewable sources [11]. The impacts of the COVID-19 pandemic on renewable energy development and policy implications are also considered, shedding light on market resilience during global disruptions.

Lastly, the significance of dynamic capabilities in the public sector is discussed, advocating a shift from traditional market failure approaches to proactive market-shaping strategies [12]. This comprehensive scope aims to provide nuanced insights into the multifaceted interactions among technology innovation, policy, and sustainability in renewable energy.

1.3 Interplay Between Technology Innovation, Policy, and Sustainability

The dynamic relationship between technology innovation, policy, and sustainability is crucial for advancing renewable energy transitions. Causal interactions between technological innovation and renewable energy development are vital for addressing climate change and promoting sustainable practices [2]. The reliance on fossil fuels for electricity generation significantly contributes to greenhouse gas emissions, necessitating innovative technologies to mitigate these impacts [1]. Policies must support technological advancements while addressing sustainability challenges.

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Historical institutionalism (HI) offers a framework for understanding the political dynamics shaping energy transitions, highlighting how institutional frameworks influence sustainable energy policy development and implementation [9]. The interaction between technology innovation and policy is evident in materials science, which provides pathways for sustainable energy solutions [11]. This advancement necessitates a reassessment of the roles of private industry and the state, emphasizing collaborative efforts in promoting sustainable technological change [13].

Stakeholder interactions under various payment mechanisms exemplify the complex relationship between technology innovation and policy, where financial incentives and regulatory frameworks play crucial roles in facilitating or impeding progress [8]. The COVID-19 pandemic further highlights this interplay, presenting both challenges, such as declines in energy demand, and opportunities for policy innovation aimed at strengthening energy system resilience [14]. Additionally, intensive CO2 emissions can catalyze RETI, indicating that proactive policy measures are essential for driving sustainable energy transitions [4].

These factors underscore the intricate interactions among technology innovation, policy, and sustainability, demonstrating the need for integrated approaches that consider the multifaceted nature of energy transitions. Adopting innovative strategies is essential for achieving a sustainable, low-carbon future, where technological advancements are effectively complemented by comprehensive policies addressing environmental challenges and economic development needs, fostering a green economy that mitigates global environmental risks [11, 13].

1.4 Structure of the Survey

This survey is structured to provide an in-depth analysis of RETI and its related policies, elucidating their complex relationships with sustainability. It integrates findings from various studies that illustrate RETI's significant role in promoting inclusive low-carbon development (ILCD), spatial dynamics, and the necessity of tailored policy frameworks that consider regional differences. By examining the interplay between technological advancements and sustainability objectives, this survey aims to inform decision-making processes that facilitate a successful transition to renewable energy systems [6, 15, 2, 7, 9].

The paper begins with an introduction establishing RETI's significance, outlining the study's scope, and discussing the interplay between technology innovation, policy, and sustainability. The core of the survey is divided into thematic sections. The first major section addresses the current state of RETI, highlighting advancements in energy storage, low-carbon technologies, and challenges of sustainable technological change, along with the pivotal role of research and development and the impact of digital transformation on technological progress.

Subsequently, the survey explores RETI policy, analyzing government policies, strategic investments, and the contributions of the private sector and social capital. This section investigates regional and dynamic policy approaches, providing insights into diverse policy frameworks supporting RETI.

The analysis then shifts to the policy contagion effect and green technology diffusion, examining mechanisms of policy spread and factors influencing green technology adoption, including case studies illustrating real-world examples of policy contagion.

Following this, the survey discusses policy transfer and sustainable energy policy, addressing implementation challenges and identifying opportunities for policy innovation. The presentation of case studies on successful policy transfer aims to illustrate effective strategies for adapting and implementing public policies across varied political and socio-economic contexts, emphasizing critical roles of translation, institutional design, and dynamic capabilities in these processes [16, 17, 9, 12].

The survey concludes with a comprehensive analysis of case studies showcasing effective innovations and policies in renewable energy technology, particularly emphasizing successful regional implementations in China. This focus highlights how digital transformation and green technology innovation positively influence financial performance in renewable energy enterprises, especially in state-owned firms and eastern regions. The findings emphasize technological advancements' critical role in driving China's transition to a low-carbon economy, revealing significant variations in innovation levels across provinces and the importance of tailored regional strategies to enhance renewable energy initiatives' effectiveness [6, 15, 2, 4, 18]. The conclusion synthesizes key findings and discusses implications for future research and policy-making, offering directions for advancing the field of renewable energy technology innovation and policy.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Global Energy Transitions

The global shift to renewable energy is pivotal for developing sustainable energy systems and aligns with the Paris Agreement's objectives [1]. This transition addresses the urgent need to reduce greenhouse gas emissions and dependence on fossil fuels, as highlighted by Chu [11]. It is a strategic imperative for enhancing economic resilience and sustainability. In China, digital transformation significantly boosts the financial performance of renewable energy firms, advancing the digital economy's goals [18]. This trend is part of a broader global initiative leveraging technological advancements to facilitate energy transitions. Jia [8] underscores the global drive towards low-carbon technologies through evolutionary pathways. Historical analyses in the UK, Germany, Denmark, and the US reveal institutional configurations' crucial role in shaping energy policy trajectories [9], which can either support or impede the transition to sustainable energy systems. The COVID-19 pandemic has further influenced global energy transitions, presenting both obstacles and opportunities. Hosseini [19] discusses the pandemic's impact on energy demand and the increased necessity for resilient, adaptable energy systems. This situation highlights the need for robust policies and innovations that can withstand global disruptions while promoting renewable energy. These insights underscore the complex, multifaceted nature of global energy transitions, requiring integrated approaches that address technological, economic, and institutional dimensions.

2.2 Key Concepts

Understanding key concepts in renewable energy technology innovation and policy is crucial for navigating sustainable energy transitions. The *policy contagion effect* describes how successful policies spread across regions and sectors through mechanisms like policy learning and imitation, promoting the global adoption of effective energy policies [16]. *Green technology diffusion* refers to the spread and adoption of low-carbon technologies across various sectors, often facilitated by Public-Private Partnership (PPP) projects that help overcome barriers to technological change and stimulate renewable energy innovation [8]. This diffusion is shaped by market dynamics, regulatory frameworks, and technological advancements, collectively influencing the pace and success of green technology adoption [18]. *Policy transfer* involves adapting successful policies from one context to another, aimed at optimizing outcomes in the target environment. This process underscores the challenges and opportunities in implementing sustainable energy policies globally, requiring careful consideration of socio-political and economic contexts to tailor policies to local needs [16, 1]. Additional concepts include *energy disaggregation* and *non-intrusive load monitoring*, which use adversarial learning and deep neural networks to enhance energy efficiency and innovation [20]. These technological advancements are essential for managing global environmental risks and achieving the radical changes necessary for sustainable energy transitions [13]. The challenges of sustainable energy development are compounded by issues such as lack of transparency, insufficient stakeholder engagement, and the need for comprehensive representation of economic, social, and environmental dimensions [7]. Addressing these challenges requires a holistic approach that integrates technological, policy, and societal factors to facilitate the transition to a sustainable, low-carbon future.

In recent years, the exploration of renewable energy technologies has gained significant momentum, underscoring the necessity for innovative approaches to address global energy challenges. To elucidate the complexities of this field, we can refer to Figure 2, which illustrates the hierarchical structure of key themes in renewable energy technology innovation. This figure not only highlights advancements in energy storage and low-carbon technologies but also delineates the challenges associated with sustainable technological change. Furthermore, it emphasizes the critical role of research and development, as well as the impact of digital transformation on technological progress. Each category presented in the figure is meticulously divided into subcategories, encompassing specific innovations, barriers, and strategies that are pivotal in driving the transition towards a sustainable, low-carbon future. By integrating this visual representation, we can better understand the interconnected nature of these themes and their implications for future research and policy development.

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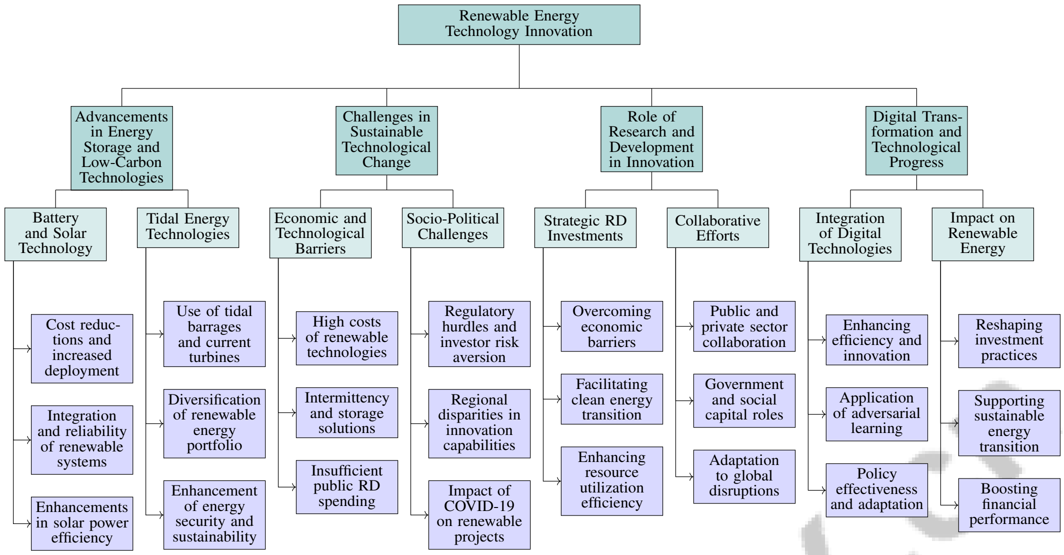

Figure 2: This figure illustrates the hierarchical structure of key themes in renewable energy technology innovation, highlighting advancements in energy storage and low-carbon technologies, challenges in sustainable technological change, the role of research and development, and the impact of digital transformation on technological progress. Each category is further divided into subcategories that encompass specific innovations, barriers, and strategies driving the transition towards a sustainable, low-carbon future.

3 Renewable Energy Technology Innovation

3.1 Advancements in Energy Storage and Low-Carbon Technologies

Recent advancements in energy storage and low-carbon technologies are central to sustainable energy transitions. As illustrated in Figure 3, the figure highlights key advancements in energy technologies, focusing on energy storage, renewable energy, and technological innovation. Notably, it showcases significant developments in battery technology, solar efficiency, and tidal energy, alongside the critical role of innovation in enhancing resource efficiency and informing policy assessments. Battery technology has seen significant cost reductions and increased deployment, enhancing the integration and reliability of renewable energy systems, thus supporting decarbonization efforts [6]. Solar power efficiency improvements further bolster solar energy's global market viability, with advancements in solar and wind technologies playing a crucial role in reducing greenhouse gas emissions compared to fossil fuels [11, 1]. Tidal energy technologies, such as tidal barrages and current turbines, illustrate innovation by harnessing natural resources to diversify the renewable energy portfolio and enhance energy security and sustainability [21]. Evaluations of green technology transformation, particularly in China's high-tech industries, show improved resource utilization efficiency driven by technological innovation [3]. Transparent and methodologically sound indicator selection is essential for accurately assessing technological progress [7]. Understanding the interplay between societal values and political institutions is vital for shaping energy policies that support these innovations [9]. Collectively, advancements in energy storage and low-carbon technologies are pivotal in facilitating global energy transitions towards a sustainable, low-carbon future.

3.2 Challenges in Sustainable Technological Change

Sustainable technological change in the renewable energy sector encounters economic, technological, and socio-political challenges. High costs associated with renewable technologies hinder widespread adoption, while the intermittency of renewable sources necessitates efficient storage solutions [6]. Insufficient public RD spending further limits the development of innovative storage technologies [6]. Regulatory hurdles, including managing diffuse emissions and overcoming path dependencies favoring incumbent technologies, present additional challenges [13]. Investor risk aversion towards radical innovations stifles progress [13], and existing policy frameworks often focus on correcting

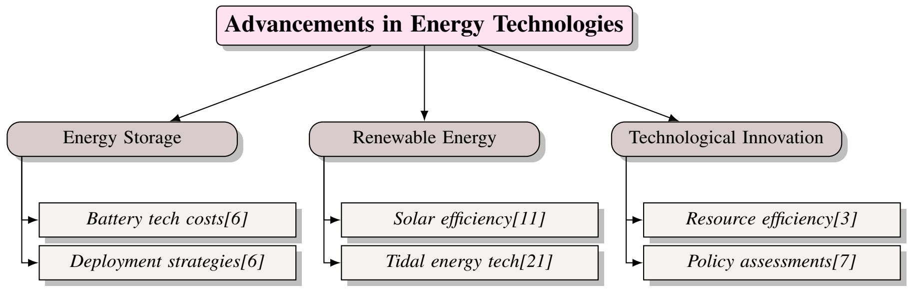

Figure 3: This figure illustrates the key advancements in energy technologies, focusing on energy storage, renewable energy, and technological innovation. It highlights significant developments in battery technology, solar efficiency, and tidal energy, as well as the role of innovation in resource efficiency and policy assessments.

market failures rather than fostering necessary innovation [12]. Socio-political barriers, such as regional disparities in technological innovation capabilities and a shortage of skilled personnel, impede the transition to renewable energy systems [4, 3]. The COVID-19 pandemic has exacerbated these challenges, leading to halted renewable energy projects and a regression towards cheaper fossil fuels, threatening sectoral progress. Effective assessment of sustainable technological change requires indicator sets encompassing economic, social, and environmental dimensions [7]. The risk of reverting to high emissions and urban air pollution post-pandemic underscores the need for robust policies prioritizing sustainability [22]. Addressing these challenges demands integrated strategies that consider economic, technological, and socio-political factors to drive sustainable technological change in the renewable energy sector. In tidal energy, high construction costs for tidal barrages and the nascent stage of tidal current turbine technology, lacking large-scale economic viability, illustrate broader difficulties faced by emerging renewable technologies in achieving commercial scalability and integration into existing energy infrastructures.

3.3 Role of Research and Development in Innovation

Research and Development (RD) is crucial for innovation in renewable energy technologies, enhancing efficiency, reducing costs, and facilitating the transition to sustainable energy systems. Strategic RD investments are essential for overcoming economic barriers and integrating renewable technologies into existing infrastructures, driving down costs, and enabling the clean energy transition [6]. The advancement of renewable energy technologies is closely linked to socio-technical systems, where societal and organizational dynamics influence technological change [13]. Engaging stakeholders in the RD process ensures the relevance and acceptance of new technologies, identifying and addressing potential barriers to innovation [7]. Digital transformation enhances the financial performance of renewable energy enterprises, with green technology innovation serving as a complete mediator [18]. Research methods like Adversarial Energy Disaggregation (AED) illustrate how RD can improve energy efficiency and propel technological progress [20]. Empirical evidence supports the connection between green technological innovation and resource utilization efficiency, underscoring RD's role in optimizing natural resource use [3]. The integration of materials science into renewable energy technologies further demonstrates RD's potential to enhance these technologies' effectiveness [11]. Collaborative efforts between public and private sectors are essential for advancing RD initiatives and facilitating the diffusion of green technologies. Government and social capital are crucial in promoting low-carbon technology innovation [8]. An N-shaped environmental Kuznets curve (EKC) emphasizes the critical role of renewable energy and innovation in emission reductions, reinforcing the need for sustained RD efforts for environmental sustainability [10]. The COVID-19 pandemic introduces complexities impacting renewable energy sectors, affecting project development stages, supply chains, and policy responses [19]. Understanding these interactions is vital for developing resilient RD strategies that can adapt to global disruptions while continuing to drive innovation in renewable energy technologies.

3.4 Digital Transformation and Technological Progress

Digital transformation is integral to advancing technological progress within the renewable energy sector, offering substantial opportunities for sustainable growth, particularly in China [18]. This transformation involves integrating digital technologies into energy systems, enhancing efficiency, performance, and innovation in renewable energy enterprises. A significant aspect of this digital transformation is the application of adversarial learning in energy disaggregation, revolutionizing energy efficiency and management [20]. By utilizing deep neural networks to optimize energy consumption, this approach supports sustainability and resource efficiency goals. The iterative environment grounding method proposed by Zhang et al. illustrates how digital transformation can enhance policy effectiveness and technological adaptation [5]. This method involves minimizing domain gaps and training policies in adjusted environments, facilitating more effective policy transfer and implementation in the renewable energy sector. The COVID-19 pandemic has underscored the need for resilient and adaptable energy systems, with digital transformation providing pathways to address these challenges [22]. The categorization of existing research into themes such as temporalities of energy system change and structures of energy governance highlights the multifaceted impact of digital technologies on the energy sector. These insights reveal digital transformation's potential to reshape investment practices and social behaviors, supporting the transition to sustainable energy systems. Future research in tidal energy should focus on leveraging digital technologies to reduce costs and improve the efficiency of tidal current turbines [21]. Developing supportive policies that encourage investment in digital innovations is crucial for advancing tidal energy capabilities, emphasizing the broader role of digital transformation in fostering technological progress across various renewable energy domains. These developments illustrate how digital transformation enhances technological progress in renewable energy and facilitates the integration of innovative solutions into existing infrastructures. This transformation is essential for achieving a sustainable, low-carbon future, as it improves efficiency and innovation in digital technologies, particularly in the renewable energy sector. Research indicates that digital transformation significantly boosts the financial performance of renewable energy enterprises by fostering green technology innovation, vital for driving sustainable growth and reducing greenhouse gas emissions [2, 18].

4 Renewable Energy Technology Innovation Policy

4.1 Government Policies and Strategic Investments

Government policies and strategic investments are central to advancing renewable energy technology innovation (RETI), serving as key drivers for sustainable energy solutions. Effective policy frameworks, particularly in high CO2 emission regions, are critical for promoting green technological innovation [3, 4]. Policies facilitating digital integration within renewable energy enterprises enhance system efficiency and underscore the importance of strategic investments in digital infrastructure [18]. The 'one province, one policy' strategy exemplifies the need for region-specific policies to maximize innovation [15].

As illustrated in Figure 4, the hierarchical structure of government policies and strategic investments in advancing renewable energy technology innovation highlights key areas such as policy frameworks, public-private partnerships, and strategic investments. Public-Private Partnership (PPP) projects, shaped by governmental policies and financial incentives, foster environments conducive to low-carbon technology innovation [8]. Aligning these incentives with sustainability objectives stimulates investments in renewable energy, advancing decarbonization goals. An interdisciplinary approach, integrating political science and energy studies, elucidates how institutional dynamics influence policy efficacy in energy transitions [9]. Institutional frameworks are crucial in either facilitating or obstructing innovative energy solutions.

Strategic government investments are vital for overcoming economic barriers and deploying innovative technologies, thus promoting decarbonization and sustainability [11]. Collaborative stakeholder efforts are essential for driving technology innovation, emphasizing coordinated actions [1]. The COVID-19 pandemic has introduced complexities requiring policy adjustments to support renewable projects amidst global disruptions [19]. Strategic investments in renewable energy development are urgent to mitigate fossil fuel consumption's adverse effects and enhance energy security [10].

Mission-oriented innovation policies should focus on clear missions and coordinated public investments to achieve societal goals, catalyzing technological innovation [12]. Addressing challenges in policy transfer methods, which often fail to manage domain gaps, requires understanding unique opportunities and barriers in renewable energy technologies for effective policy interventions [5].

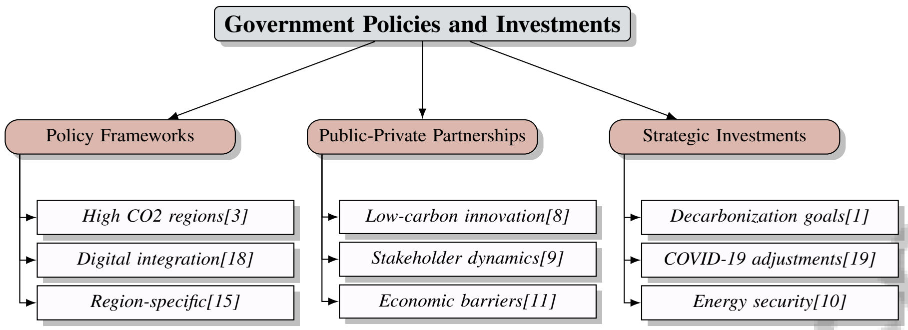

Figure 4: This figure illustrates the hierarchical structure of government policies and strategic investments in advancing renewable energy technology innovation, highlighting key areas such as policy frameworks, public-private partnerships, and strategic investments.

4.2 The Role of Private Sector and Social Capital

The private sector and social capital are pivotal in driving innovation within the renewable energy technology sphere. Motivated by market opportunities, the private sector is crucial for technological advancement and commercialization. Digital transformation in renewable enterprises illustrates the private sector's role in enhancing efficiency and performance, accelerating the transition to sustainable energy systems [18]. This transformation reflects a trend where private enterprises utilize innovations for competitive advantages and contribute to decarbonization.

Private sector investment in RD is essential for reducing renewable technology costs and integrating them into existing infrastructures [6]. Public-Private Partnerships (PPPs) demonstrate collaboration between public and private sectors, aligning financial incentives and regulatory frameworks to support low-carbon innovation [8]. Social capital, comprising networks and norms facilitating collective action, is equally important for innovation. It enhances community engagement and stakeholder participation, crucial for adopting renewable technologies. Institutional frameworks shape social capital's effectiveness in energy transitions, supporting trust and collaboration among stakeholders [9].

The COVID-19 pandemic has underscored the private sector's resilience and social capital's significance in navigating disruptions. The pandemic has accelerated the need for adaptable energy systems, with the private sector maintaining energy supply and stability. Social capital, through resource mobilization and cooperation, has supported communities in responding to pandemic challenges [22].

4.3 Regional and Dynamic Policy Approaches

Regional and dynamic policy approaches to renewable energy necessitate tailoring strategies to local contexts. Such customization addresses unique regional challenges and opportunities. Regional characteristics significantly influence policy outcomes and technological progress, highlighting the need for policies responsive to local factors [4]. Strategies leveraging local resources promote innovation and development, with the 'one province, one policy' approach exemplifying effective regional policy interventions [15].

Dynamic policy-making involves adapting policies to evolving circumstances. Integrating digital technologies into policy frameworks exemplifies how dynamic policies enhance renewable systems' efficiency [18]. This transformation supports decarbonization by enabling responsive policy interventions. Institutional frameworks are crucial for regional and dynamic policy approaches, supporting policy innovation and implementation. Understanding political and institutional dynamics enhances regions' capacity to implement effective policies [9].

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The COVID-19 pandemic has highlighted the need for resilient policy approaches capable of withstanding disruptions. Robust policies prioritizing renewable energy development are imperative to mitigate fossil fuel consumption impacts and support a low-carbon future [22]. Dynamic policies incorporating pandemic lessons can enhance energy systems' resilience and facilitate sustainable transitions.

5 Policy Contagion Effect and Green Technology Diffusion

Understanding policy contagion dynamics is pivotal for advancing sustainable energy systems and facilitating green technology diffusion. This section investigates the mechanisms enabling renewable energy policy transfer across jurisdictions, focusing on strategic interactions among government entities, social capital, and consumers. These interactions elucidate factors driving policy adoption and the diffusion of innovative practices, with the following subsection detailing the specific mechanisms underlying policy contagion.

5.1 Mechanisms of Policy Contagion

Policy contagion mechanisms are crucial for understanding how renewable energy policies spread across regions and sectors, supporting the global shift to sustainable energy systems. Strategic interactions among government entities, social capital, and consumers significantly influence policy adoption [8, 13]. Recognizing these dynamics is essential for effective policymaking and promoting green technology diffusion.

Innovative approaches to policy contagion, such as Federated Learning for ABAC Policy Transfer (FLAP), utilize structured methodologies like similarity analysis, rule adaptation, and policy enrichment to facilitate Attribute-Based Access Control (ABAC) policy transfers [23]. This highlights the role of digital technologies in enhancing policy transfer and adaptation, supporting renewable energy transitions.

Dynamic capabilities within the public sector are vital for implementing mission-oriented policies, enabling governments to adapt to changing circumstances and challenges [12]. These capabilities foster policy contagion by providing flexibility and resilience to navigate complex socio-political landscapes, facilitating successful policy transfers.

A theoretical framework integrating sociological and political science insights emphasizes dynamic interactions among actors involved in policy translation, highlighting socio-political dynamics driving policy contagion [17]. This underscores the need to consider cultural and institutional contexts for appropriate policy adaptation to local conditions.

The Iterative Domain Adaptation Policy Transfer (IDAPT) method exemplifies innovative approaches to policy contagion, offering robust solutions for visual and dynamic domain gaps [5]. By minimizing interactions with target environments, this method enhances policy transfer efficiency, supporting renewable energy policy proliferation across diverse sectors.

As depicted in Figure 5, policy contagion and its effects on green technology diffusion are particularly relevant in public policy and innovation contexts. The first analysis explores low-carbon technology innovation diffusion in Public-Private-Partnership (PPP) projects using evolutionary game theory to assess payment mechanisms, providing insights into how governmental and consumer payment strategies influence environmentally friendly technology adoption. The second analysis compares various reinforcement learning (RL) algorithms' performance in terms of pole length and Power Take-Off (PTO) performance within a Markov Decision Process (MDP) framework. Together, these analyses enhance understanding of how policy contagion can facilitate or impede green technology diffusion, emphasizing strategic policy design and implementation [8, 16].

5.2 Factors Influencing Green Technology Diffusion

Green technology diffusion is shaped by a complex interplay of economic, social, and technological factors that can accelerate or hinder adoption. Economic and social development imbalances create disparities in resource access and capabilities, limiting certain regions' ability to implement innovative technologies effectively [15]. Addressing these disparities is essential for promoting inclusive green technology diffusion.

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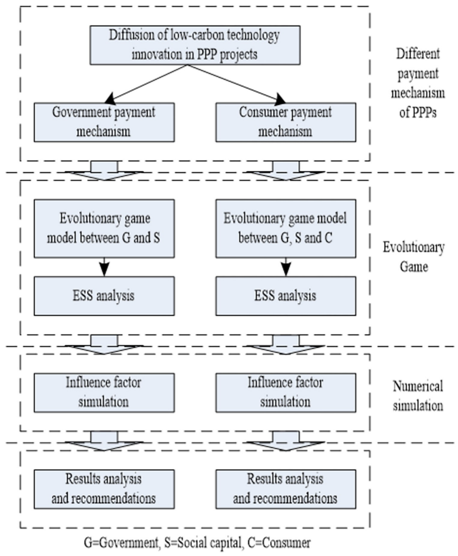
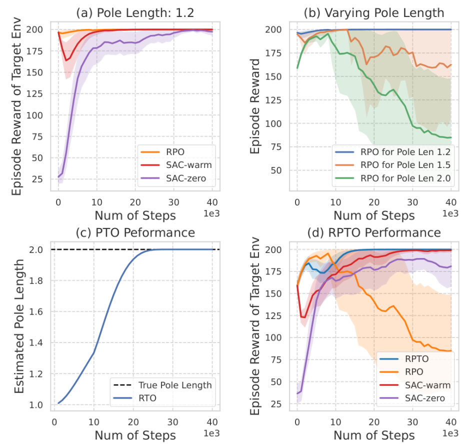


(a) Diffusion of Low-Carbon Technology Innovation in PPP Projects: Evolutionary Game Analysis of Different Payment Mechanisms[8]



(b) Comparison of Pole Length and PTO Performance in RL Environments[16]

Figure 5: Examples of Mechanisms of Policy Contagion

As illustrated in Figure 6, the primary factors influencing the diffusion of green technology can be categorized into three main areas: economic and social factors, technological advancements, and the impacts of policy and the COVID-19 pandemic. Key elements depicted in the figure include resource access disparities, advancements in energy storage solutions, and the effects of the pandemic on policy frameworks, each playing a significant role in shaping the landscape of green technology adoption.

Technological advancements are critical for accelerating green technology diffusion, contributing to sustainable economic growth and enhancing energy system efficiency [10]. Developing efficient energy storage solutions is vital for addressing renewable energy source intermittency and facilitating integration into existing infrastructures [11]. Exploring alternative materials for energy conversion can improve green technologies' performance and viability across sectors.

The COVID-19 pandemic has introduced uncertainties regarding long-term effects on renewable energy adoption rates and government policies' effectiveness in mitigating impacts [19]. This underscores the necessity for resilient and adaptable policy frameworks supporting continuous green technology diffusion amid global disruptions. Understanding the socio-political and economic contexts of technology implementation is crucial for crafting effective policies addressing pandemic-related challenges and other external shocks.

5.3 Policy Contagion in Practice: Case Studies

Policy contagion, defined as policies spreading across jurisdictions, is illustrated through real-world case studies highlighting policy transfer mechanisms and dynamics. Sekharan [24] demonstrates successful policy transfers in partially observable environments, providing a foundational framework for adapting and implementing policies in diverse contexts. This emphasizes developing robust methodologies for policy transfer, especially in complex environments with incomplete information.

Empirical studies by Hassenteufel [17] further illustrate the intricate process of policy translation across levels and contexts. These studies reveal socio-political and cultural factors influencing policy adaptation and implementation, emphasizing the need for nuanced local context understanding to ensure effective policy transplantation.

These case studies offer valuable insights into policy contagion practices, providing practical examples of successful policy transfers across regions and sectors. By analyzing factors contributing to

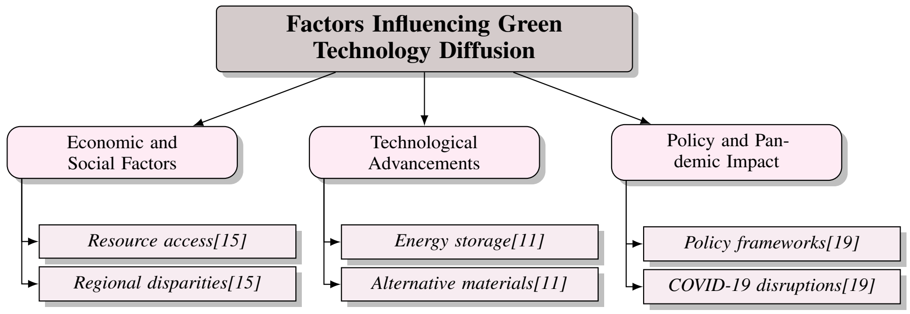


Figure 6: This figure illustrates the primary factors influencing the diffusion of green technology, categorized into economic and social factors, technological advancements, and policy and pandemic impacts. Key elements include resource access disparities, advancements in energy storage, and the effects of COVID-19 on policy frameworks.

effective policy transfer, these studies enhance understanding of strategic frameworks promoting global adoption of innovative and sustainable energy policies. This includes examining translation and translators' roles in policy processes, robust indicators for monitoring sustainable energy development, and driving forces behind renewable energy technological innovation in climate change and CO2 emissions contexts. Such insights are crucial for ensuring energy policies are adopted and contextually relevant and impactful across diverse political systems [7, 17, 4].

6 Policy Transfer and Sustainable Energy Policy

6.1 Challenges and Barriers in Policy Implementation

The implementation of sustainable energy policies encounters numerous economic, institutional, and technological obstacles. A primary challenge is the socio-economic impact of energy transitions, often overlooked, which results in insufficient consideration of behavioral changes necessary for policy success [1]. Additionally, uncertainties in green technological innovation, due to low innovation inputs and weak internal capabilities, complicate the policy landscape and hinder effective implementation [3].

Power dynamics among policy actors further complicate the translation process [17]. Conflicts and misalignments often occur when policies are transferred across diverse institutional and cultural contexts. The reliance on initial datasets in methods such as Iterative Domain Adaptation Policy Transfer (IDAPT) highlights the need for robust data to support effective policy adaptation [5].

Government support is crucial for fostering technological innovation, but its effectiveness is often limited by incoherent policy frameworks that fail to address diverse stakeholder interests and regional variations [4]. Moreover, the high costs associated with human annotation for generating paired datasets necessary for training in policy implementation restrict the scalability of advanced policy transfer methods [25].

The COVID-19 pandemic has added layers of complexity, raising uncertainties about long-term behavioral changes in energy consumption and the effectiveness of proposed policies [22]. These challenges highlight the need for adaptive and resilient policy frameworks capable of responding to global disruptions and evolving energy demands. As illustrated in Figure 7, the primary challenges in policy implementation can be categorized into socio-economic impacts, institutional dynamics, and technological obstacles, emphasizing the key issues and references from the literature. Addressing these multifaceted challenges requires integrated strategies that consider diverse economic, institutional, and technological landscapes. A comprehensive approach should incorporate socio-economic factors, establish robust data infrastructures, and develop dynamic policy frameworks that promote sustainable technological innovations while addressing political dimensions and distributional impacts, ensuring environmental sustainability and social equity [9, 13].

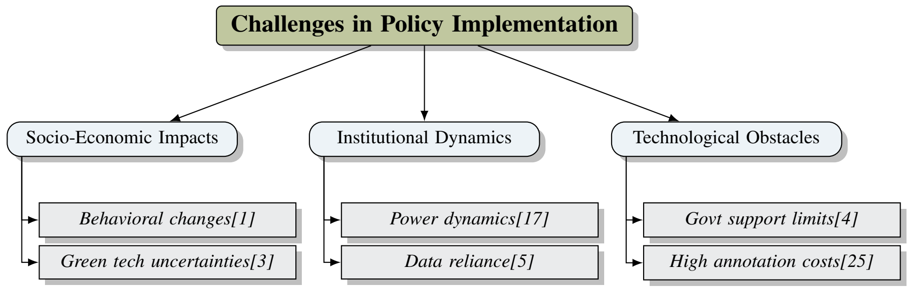


Figure 7: This figure illustrates the primary challenges in policy implementation, categorized into socio-economic impacts, institutional dynamics, and technological obstacles, highlighting the key issues and references from the literature.

6.2 Opportunities for Policy Innovation

Policy innovation presents significant opportunities to enhance sustainable energy transitions. A key area is developing policies that balance innovation and deployment of energy storage technologies, essential for overcoming barriers and ensuring advancements contribute to broader decarbonization goals [6]. The integration of methodologies like Federated Learning for ABAC Policy Transfer (FLAP) offers a promising avenue for policy innovation. This formal methodology utilizes local decision examples and context information, enabling effective policy adaptation across diverse environments and demonstrating the potential of digital technologies to facilitate tailored policy interventions [23].

Continued investment and research are crucial for overcoming barriers to renewable energy technology adoption [11]. Commitment to policy frameworks prioritizing innovation and supporting new technology development is essential for driving sustainable energy transitions. Future research should focus on enhancing algorithms for online learning and extending these methods to more complex environments, improving the adaptability and effectiveness of policy frameworks [24].

The integration of Relative Policy Transition Optimization (RPTO) with domain adaptation techniques offers another innovation opportunity, potentially leading to dynamic curriculum learning strategies that enhance policy interventions' flexibility and impact in the renewable energy sector [16]. Additionally, employing pair augmentation and active learning techniques provides a novel approach to reducing annotation costs and improving policy-making processes' scalability. By leveraging these techniques, policymakers can develop more efficient strategies for implementing sustainable energy policies, facilitating widespread adoption and impact [25].

6.3 Case Studies of Successful Policy Transfer

Successful policy transfer and adaptation in renewable energy are illustrated through case studies showcasing effective mechanisms and strategies. The Federated Learning for Attribute-Based Access Control Policy Transfer (FLAP) framework exemplifies transferring complex policies across organizational contexts by utilizing local access control decision examples and context information [23]. This underscores the importance of leveraging local data and contextual understanding to ensure transferred policies remain relevant and effective in new environments.

FLAP's application in renewable energy policy transfer demonstrates how digital technologies can enhance policy frameworks' adaptability and scalability, enabling efficient and tailored interventions. By employing federated learning, FLAP minimizes the need for extensive data sharing, preserving privacy and reducing data breach risks. This innovation highlights digital tools' significant role in facilitating global renewable energy policy dissemination. By adapting and implementing successful strategies across regions, these tools can enhance digital transformation and green technology innovation, promoting sustainable growth and improving financial performance, especially in state-owned firms and economically advanced regions [15, 7, 2, 18].

FLAP's success in policy transfer reflects a broader trend toward integrating advanced technological solutions into policy-making processes, facilitating dynamic and responsive frameworks capable of adapting to unique regional and sectoral challenges. By investigating key elements that enable effective policy transfer, including federated learning integration and contextual adaptation, these case studies provide critical insights for formulating innovative strategies essential for advancing sustainable energy systems. This exploration highlights translation processes and transfer entrepreneurs' roles in shaping public policy while emphasizing digital transformation and green technology innovation's significance in enhancing renewable energy enterprises' financial performance [18, 6, 17, 1].

7 Case Studies

7.1 Regional Implementation of RETI and Policies in China

China's regional implementation of renewable energy technology innovations (RETI) highlights the intricate interaction between regional dynamics, policy frameworks, and technological advancements. Through strategic investments, China demonstrates its commitment to renewable energy by fostering innovation and enhancing energy efficiency. The 'one province, one policy' strategy allows for tailored interventions that address specific regional needs, facilitating the adoption and diffusion of renewable technologies [15]. This approach leverages regional strengths and addresses local challenges, promoting a more effective deployment of renewable energy solutions.

Digital transformation plays a critical role in supporting RETI by boosting the financial performance of renewable energy enterprises [18]. The integration of digital technologies improves system efficiency and performance, underscoring the necessity of investing in digital infrastructure to facilitate regional energy transitions and align with decarbonization and sustainability objectives.

Public-Private Partnership (PPP) projects are vital in overcoming barriers to low-carbon technology innovation by aligning financial incentives with sustainability goals [8]. These partnerships combine public and private sector expertise and resources, fostering a collaborative environment conducive to developing and deploying innovative energy solutions. The success of PPPs illustrates the potential of cooperative frameworks to enhance regional RETI implementation.

Institutional frameworks also play a significant role in shaping policy effectiveness and technological progress in RETI [9]. These frameworks provide crucial support for policy innovation, ensuring that regional strategies are in harmony with national objectives and contribute to the global transition towards sustainable energy systems.

8 Conclusion

8.1 Future Research Directions

Research in renewable energy technology innovation and policy must advance to address critical areas that enhance sustainability and energy transition effectiveness. A significant research opportunity lies in the granular exploration of Integrated Lifecycle Design (ILCD), which incorporates qualitative factors into evaluation frameworks for a comprehensive understanding of renewable energy systems. This approach can illuminate the lifecycle impacts of renewable technologies, guiding the development of sustainable practices.

Innovations in materials science for batteries and the exploration of novel storage technologies are imperative for enhancing energy storage efficiency and cost-effectiveness. These advancements are crucial for integrating renewable energy systems and achieving broader decarbonization and energy security objectives. Moreover, there is a need for further research into the long-term environmental effects of tidal energy extraction and the economic viability of tidal current turbines.

Understanding the psychological factors and network environments that influence stakeholder behavior in low-carbon technology diffusion is another pivotal research area. Insights into these factors can refine strategies for stakeholder engagement and accelerate the adoption of renewable technologies. Investigating specific factors that hinder causation in certain countries and exploring strategies to bolster technological innovation in these contexts is also essential.

Applying historical institutionalism across diverse political contexts can offer valuable insights into designing institutional arrangements that support sustainable energy transitions. Such research could identify frameworks that foster innovation and facilitate energy transitions across various regions.

Exploring the long-term impact of energy innovation on emissions and examining the Environmental Kuznets Curve (EKC) in different contexts can enhance the understanding of economic development and environmental sustainability relationships. This research can inform policies that balance economic growth with environmental protection.

The impact of varying data sharing percentages and types on the policy transfer process warrants investigation to refine frameworks for effective policy transfer and adaptation. This research aims to enhance the scalability and applicability of policy frameworks across diverse contexts. Future work could also focus on improving the robustness of methods like IDAPT to various domain gaps and applying them to more complex real-world scenarios.

Developing frameworks to assess the effectiveness of dynamic capabilities in public sector contexts is crucial for understanding how these capabilities can drive innovation and support sustainable energy transitions. This research can inform policy design that enhances the resilience and adaptability of public institutions in addressing evolving energy challenges.

Transfer learning to apply pre-trained models across different households presents a promising direction for innovation in energy disaggregation technologies. This research can improve the accuracy and efficiency of energy monitoring systems, contributing to effective energy management and conservation practices.

Integrating social dimensions into energy policies and exploring innovative financing models can enhance public acceptance of renewable technologies, facilitating their widespread adoption and impact. This research supports the development of inclusive and equitable energy policies that address diverse stakeholder needs. Additionally, addressing challenges in robotic implementations and improving the accuracy of image-to-semantics mapping can refine policy transfer processes.

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