Between Autonomy and Resilience

A Comprehensive Analysis of Taiwan's Nuclear Energy Dilemma

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Contents

Abbreviations

TEPU	Taiwan Environmental Protection Unit
CET	Citizens of the Earth, Taiwan
IAEA	International Atomic Energy Agency
GDP	Gross Domestic Product
EPA	Environmental Protection Agency
MOEA	Ministry of Economic Affairs
REI	Renewable Energy Initiative
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contributions
TSMC	Taiwan Semiconductor Manufacturing Company
NTD	New Taiwan Dollar
USD	United States Dollar
EV	Electric Vehicle
SDGs	Sustainable Development Goals
LNG	Liquefied Natural Gas
DPP	Democratic Progressive Party
TPP	Trans-Pacific Partnership
KMT	Kuomintang

Abstract

This thesis investigates the impacts of Taiwan's decision to phase out nuclear energy by 2025. This policy, influenced by safety concerns, environmental goals, and public opposition, introduces significant challenges and opportunities for Taiwan's energy security, economic stability, and geopolitical relations, particularly with China. Employing a mixed-methods approach, this research uses qualitative interviews with key stakeholders and quantitative data analysis to examine Taiwan's energy transition. Thematic analysis reveals critical themes such as energy security, renewable energy development, public perception, and regulatory frameworks. Regression and a SWOT analysis assess the impacts on Taiwan's energy security risk index and explore strategic dimensions of the transition. The findings indicate that while Taiwan's shift to renewable energy is supported by technological advancements and strong public policy, substantial challenges remain, including the integration of intermittent renewable sources, dependency on energy imports, and geopolitical tensions with China. The thesis recommends enhancing energy resilience through investments in community-based microgrids, implementing floating solar farms, and establishing an energy innovation hub. These strategies aim to bolster local energy security, optimize space for solar energy generation, and foster innovation and collaboration in the energy sector.

1 | Introduction

”Energy security is not just a matter of technology, but of politics and strategy.” - Daniel Yergin. In line with this, Taiwan plans to phase out nuclear energy generation by 2025, navigating a complex intersection of energy policy, global sustainability goals, and regional security dynamics. This phase-out is significant for Taiwan’s energy policy as it aligns with global efforts to transition to renewable energy sources and reduce carbon emissions, such as outlined by the IEA [58]. However, it also poses critical challenges to Taiwan’s ability to ensure energy security, navigate economic shifts, and manage diplomatic ties, particularly with China. The ongoing tensions with China, which claims sovereignty over Taiwan based on the ’One China Policy,’ introduce additional intricacies to Taiwan’s energy planning [22]. For instance, Taiwan is highly dependent on energy imports, with about 97% of its energy needs being met through imports, according to the Taiwan Ministry of Economic Affairs [116]. This reliance on imported natural gas and coal to replace nuclear power makes Taiwan vulnerable to global market fluctuations and geopolitical risks, especially given its tense relationship with China [82] [62]. In the event of heightened tensions, Taiwan’s energy imports could be severely disrupted, threatening its energy security and economic stability.

Phasing out nuclear energy also impacts Taiwan’s national security and political resilience. Nuclear power plants can operate independently for up to 18 months without refueling, providing a more stable energy source compared to the more vulnerable supply chains of imported fossil fuels [41]. Eliminating nuclear power increases Taiwan’s reliance on imported energy, exacerbating its vulnerability to supply chain disruptions, particularly during times of global supply chain disruptions like the recent trade conflicts. This is particularly critical given the potential for China to exert pressure through maritime blockades or other aggressive measures [11]. Thus, this not only tests Taiwan’s commitment to sustainability, but also its foresight in maintaining energy independence and resilience against external geopolitical pressures. Taiwan must navigate these challenges carefully, investing in renewable energy infrastructure and energy storage solutions to ensure a stable and secure energy future [15].

The main research question guiding of this thesis is: How does Taiwan’s policy of phasing out nuclear energy by 2025 affect its energy security and economic stability, and what specific geopolitical challenges and opportunities does this transition present in the context of its relations with China and global sustainability goals? The importance of this question derives from the fact that Taiwan, like many other countries, is undergoing a transformative move towards achieving net-zero carbon emissions by 2050. This is coupled with the challenge of addressing the immediate requirements for upgrading its aging energy infrastructure and addressing public concerns regarding nuclear safety risks. In this paper, I will examine the socio-economic effects of reducing reliance on nuclear energy and explore the strategic dimensions of energy policy in a geopolitically sensitive setting [70].

Using a mixed-methods approach, this thesis is broken down into 6 chapters. Chapter 2 gives a detailed literature review, including the theoretical framework, global nuclear energy trends, and an overview of Taiwan’s energy landscape, with a focus on addressing critical research gaps in the field. The next chapter, chapter 3, outlines the methodology, including qualitative and quantitative methods, data collection procedures, and ethical considerations. I will then provide an in-depth analysis of the results, including qualitative findings, survey results, regression analysis, a SWOT analysis of Taiwan’s nuclear energy phase-out policy, and a comparison with global trends in Chapter 4. Chapter 5 discusses the findings, interpreting the data in the context of public opinion, policy implications, and the limitations of the study, and offers recommendations for future research. Finally, Chapter 6 sums up the key findings, provide policy recommendations and concluding remarks.

Exploring these aforementioned dimensions, this thesis aims to provide a nuanced analysis of how Taiwan’s decision to eliminate nuclear power affects its energy security and economic stability amidst ongoing geopolitical tensions and sustainability challenges. Through this approach it hopes to inform both academic discourse and practical policymaking in the field of energy transition by describing the impacts on policy, public perception, and strategic implications.

1.1 | Taiwan’s Geopolitical Challenges with China

Taiwan’s relationship with China is a complex and ongoing issue that huge implications for its energy policy and overall security. This relationship goes all the way back to the late 19th and early 20th centuries when Taiwan was ceded to Japan by the Chinese Qing Dynasty of China after the First Sino-Japanese War in 1895. Taiwan remained under Japanese rule until the end of World War II in 1945, when it was returned to Chinese control [5]. After the Chinese Civil War ended in 1949, the defeated Nationalist government (Kuomingtang) retreated to Taiwan, while the Communist Party established the People's Republic of China (PRC) on the mainland. Since then, China has stayed strong in the notion that Taiwan is a part of its territory, a claim that Taiwan rejects.

Unfortunately, this tension has endured for decades, influencing Taiwan's domestic governance and international relations. Politically-speaking, the relationship fluctuates between periods of heightened tension, often triggered by diplomatic incidents, and phases of relative chill, influenced by strategic dialogues and agreements. The 'One China Policy,' advocated by Beijing, established that there is only one sovereign state of China, which includes Taiwan. With that, Taiwan has experienced diplomatic isolation, with a notable number of countries refraining from establishing formal relations with Taipei to align with Beijing, such as Germany, France, the United Kingdom, and Australia. This political isolation directly hinders Taiwan's efforts to forge international partnerships and garner support, significantly impeding its progress in critical sectors like energy, as supported by Hsieh [53].

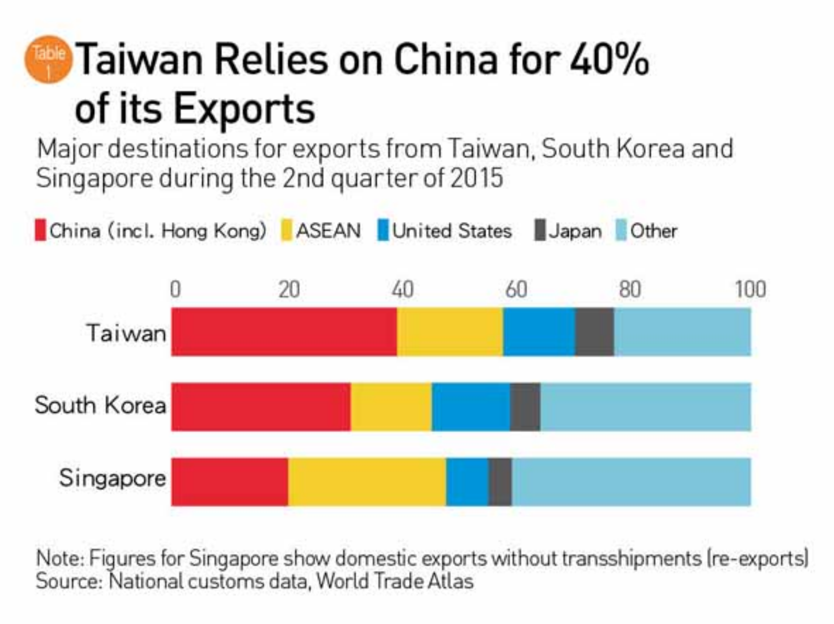

Figure 1.1: Major destinations for exports from Taiwan, South Korea and Singapore during the 2nd quarter of 2015

As you can see in Figure 1.1, Taiwan is heavily reliant on China, with over 40% of its exports going to the mainland in recent years. Because of this economic interdependence poses a challenge for Taiwan, requiring a delicate balance between keeping sovereignty and managing a complex trade relationship with China [98]. The economic ties also extend to energy imports, where disruptions in this relationship could have severe consequences for Taiwan's energy security.

In recent years, military tensions have escalated, with more and more incursions by Chinese military aircraft into Taiwan's air defense identification zone (ADIZ). These actions can be seen as China's way to assert territorial claims over Taiwan and instill fear on the island. The potential for military conflict poses a significant risk to Taiwan's infrastructure, particularly its energy facilities, amplifying the threat to essential services. Ensuring energy security amidst such threats is a key concern for Taiwan, influencing its decision to phase out nuclear power and invest in renewable energy sources that can be locally managed and controlled.

The international community's stance on Taiwan adds another layer of complexity. While countries like the United States provide military and diplomatic support to Taiwan, they do so within a framework that avoids formally recognizing Taiwan as a separate state. This ambiguity, also called 'strategic ambiguity,' is made to deter Chinese aggression and prevent Taiwan from making explicit moves toward formal independence. This delicate balance impacts Taiwan's strategic decisions, including its energy policies, as it seeks to secure international support without provoking Chinese retaliation. According to the Council on Foreign Relations, the Taiwan Relations Act of 1979 outlines the basis for U.S. ties with the island, offering a qualified commitment to Taiwan's security and providing for the supply of necessary "defense articles and services" [5]. Since 1990, U.S. arms sales to Taiwan have totaled more than $46 billion since 1990, leading to U.S.-China friction and an upsurge in combative rhetoric across the strait. This tension highlights Taiwan's strategic significance and the imperative to uphold strong defense capabilities, which in turn shape its energy policy determinations.

1.2 | The Historical Evolution of Taiwan's Energy Policy

Taiwan's energy policy has changed over the decades due to its unique geopolitical position, economic growth, and technological advancements. With it being an island nation with scarce natural resources, Taiwan has consistently struggled to secure a stable and adequate energy supply, leading them to continuously adapt its energy strategies, balancing economic development needs with energy security and environmental concerns. Understanding the evolution of this is crucial for shaping current talks on phasing out nuclear energy and shifting to renewable sources. Taiwan's planned transition from relying heavily on imported fossil fuels to exploring and investing in renewable sources showcases its resilience and adaptability in response to local and global challenges. Looking back, this perspective provides valuable insights into the factors shaping Taiwan's energy strategies, emphasizing the ongoing efforts towards a sustainable and self-reliant energy future.

In the post-World War II era, Taiwan embarked on a rapid industrialization process. The 1960s and 1970s saw a huge amount of economic growth, which led to an increased demand for energy, similar to other countries [55]. During this time, Taiwan relied heavily on imported fossil fuels, particularly oil and coal, to power its growing industries. The oil crises of the 1970s highlighted the vulnerability of Taiwan's energy security and emphasized the necessity of a more diversified energy mix because their reliance on imported energy rising significantly, making it vulnerable to global energy market fluctuations and price changes [76].

In an effort to address the energy security concerns and reduce dependence on imported fossil fuels, Taiwan adopted nuclear power in the late 1970s. The establishment of nuclear power plants such as the Kuosheng and Maanshan plants was a momentous milestone. This shift was driven by the desire to achieve greater energy independence and stability, as nuclear energy offered a reliable alternative to the imported fossil fuels that dominated Taiwan's energy landscape. By the 1980s, nuclear power had become an integral part of Taiwan's energy policy, providing a substantial portion of the island's electricity needs.

During the late 1980s and 1990s, there was a growing global awareness of environmental issues, and Taiwan was no exception. Concerns about nuclear safety and environmental preservation led to a rise in public opposition to nuclear power. These worries were strengthened by well-publicized events like the Chernobyl disaster in 1986 and the later Fukushima accident in 2011 [45]. Taiwan's energy strategy consequently began to place more of a focus on renewable energy sources and environmental sustainability. With its aggressive targets to reduce greenhouse gas emissions, Taiwan took a big step toward environmental sustainability in 2015 with the enactment of the Greenhouse Gas Reduction and Management Act.

In recent decades, Taiwan has made significant strides towards integrating renewable energy into its energy mix. The government has implemented various policies and incentives to promote the development of solar, wind, and other renewable energy sources. The Renewable Energy Development Act in Taiwan, passed in 2009, aimed to boost the proportion of renewable energy in the energy mix. It provided financial incentives for renewable energy projects and set ambitious targets for renewable energy capacity [20]. However, the use of renewable energy has been restricted due to technical limitations, high expenses, and instability, despite continuous development.

Currently, Taiwan is facing a crucial point in its energy policy. The choice to eliminate nuclear power by 2025, though controversial, shows a dedication to addressing public worries and improving energy security through diversification. Their current energy strategy now focuses on increasing the share of renewable energy, improving energy efficiency, and reducing carbon emissions. Nevertheless, the transition presents notable obstacles, such as the requirement for technological progress, infrastructure enhancement, and the assurance of a secure and dependable energy supply. Even though the government has set ambitious goals, such as increasing the share of renewable energy in the energy mix to 20% by 2025, reaching these targets calls for significant financial investments and strong policy support [75].

2 | Literature Review

2.1 | Theoretical Framework

The theoretical framework for examining Taiwan's nuclear energy phase-out and transition towards renewable energy integrates key concepts from energy transition studies, sustainability transitions, and socio-technical systems. This approach allows for a comprehensive understanding of the interplay between technological, economic, social, and political factors in driving the energy transition. Analyzing the shift from fossil fuels and nuclear power to renewable sources through the lens of Energy Transition Theory, we can see how market forces, governmental policies, and technological advancements collectively facilitate the transition to a low-carbon energy system. Economic incentives and market dynamics play a pivotal role in the transition to renewable energy. The success of Germany's Energiewende initiative demonstrates how financial incentives, such as feed-in tariffs and subsidies, can significantly boost renewable energy adoption [106]. Taiwan's government has similarly implemented feed-in tariffs and invested heavily in renewable energy projects, indicating a market orientation towards renewables [16].

The study by Genc and Kosempel (2023) [47] looks into the economic dynamics of this transition, examining the role of financial incentives, market dynamics, and policy frameworks in accelerating the adoption of renewable energy technologies. They emphasize the need for comprehensive economic strategies to support this shift, highlighting the importance of investment in green technologies and the creation of favorable market conditions for renewable energy sources. Similarly, Gitelman and Kozhevnikov (2023)[48] explore the conceptual foundations necessary for addressing the global energy transition challenge. Through a holistic approach, they examine the interplay between technological innovation, regulatory measures, and market adaptation as solutions crucial for overcoming barriers to sustainable energy adoption. They underscore the significance of coordinated efforts among various stakeholders, including governments, businesses, and consumers, to create a robust framework that supports the transition to a sustainable energy future [48]. The success of Taiwan's policy measures is highlighted by the emphasis on systemic changes in infrastructure, regulatory regulations, and consumer behavior. Taiwan's strategy shows how to effectively accelerate the energy transition by combining technology developments, robust regulatory frameworks, and economic incentives. [35].

To further enhance the discussion, I draw from the Socio-Technical Systems (STS) Theory, which provides a valuable framework by exploring the co-evolution of social and technical elements during energy transitions. STS theory the intricate interplay between technology, institutions, and human behavior, emphasizing that synchronized advancements in these areas are crucial for successful transitions. As Trist noted, "The interplay between social and technical factors must be understood as a joint optimization challenge where both elements evolve together to achieve effective systems performance" [115]. The STS Theory theorizes that both technical innovations and changes in social practices, regulatory frameworks, and cultural norms must occur in tandem for a transition to be effective [94]. Additionally, public opinion and regulatory adjustments significantly influence the energy transition process, emphasizing the holistic approach of STS Theory. This makes sure that both technical and social dimensions are considered, leading to sustainable and resilient energy systems that align with societal goals [94].

In addition, the Sustainability Transitions Framework (STF) underscores the imperative for long-term, multi-dimensional transformations toward sustainable production and consumption. Central to this framework is the role of niche innovations—small-scale, radical changes that challenge and transform entrenched regimes, facilitating systemic change. Geels and Schot (2007) [46] dive more into this by developing a typology of transition pathways, including transformation, reconfiguration, technological substitution, and de-alignment and re-alignment, which are important in understanding how these niche innovations can disrupt existing socio-technical regimes. These niche innovations are vividly illustrated by community-based solar projects and offshore wind farms. These projects not only significantly enhance energy security by diversifying energy sources, but also bolster economic stability through job creation and local investment, directly addressing crucial aspects of the research question [97]. As Petrovic (2024) [95] discusses, fostering local innovation and integrating renewable energy solutions are pivotal for driving significant, scalable impacts in the transition to sustainable energy systems.

To understand the socio-political challenges, Karl Marx's conflict theory and the Framing Approach provide additional insights into the power dynamics and perceptions among stakeholders during energy transitions. They analyze how various groups, including local communities, industry, and political entities, oppose or support the transition. In regards to the energy transition they essentially state that everyone is battling over little resources and that the way something is presented to an audience, or the frame, affects the decisions individuals make about how to digest that information. In Taiwan, public protests and political contention over nuclear energy reflect broader conflicts over safety, environmental impacts, and energy security, illuminating the geopolitical implications of the transition, particularly in relation to China [74] [69]. By applying these frameworks, essential for addressing the research question, I can explain the multifaceted nature of energy transitions, covering technological innovations, socio-economic shifts, and political dynamics, providing a holistic understanding of the challenges and opportunities Taiwan faces.

2.2 | Global Nuclear Energy Trends

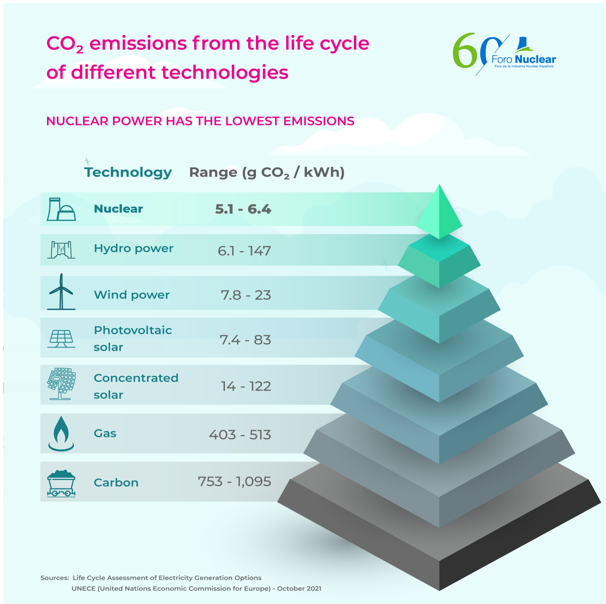

Figure 2.1: CO2 emissions from the life cycle of different technologies [91]

As countries strive to meet the United Nations' Sustainable Development Goals (SDGs) by 2050, nearly 25 years ago, many are increasingly focusing on the transition to low-carbon energy sources [104]. Globally, nuclear energy plays a pivotal role in this shift due to its capability to provide reliable and large-scale power with minimal greenhouse gas lifecycle emissions, as you can see in Figure 2.1. Lifecycle emissions can be described as the total greenhouse gas emissions produced throughout all stages of a product's life, from raw material extraction to disposal. Nuclear stand low, with around 6 g CO2/kWh. The commitment to these goals is evident as nations integrate sustainable energy strategies into their national policies, reflecting a global trend toward decarbonization and sustainable development [112].

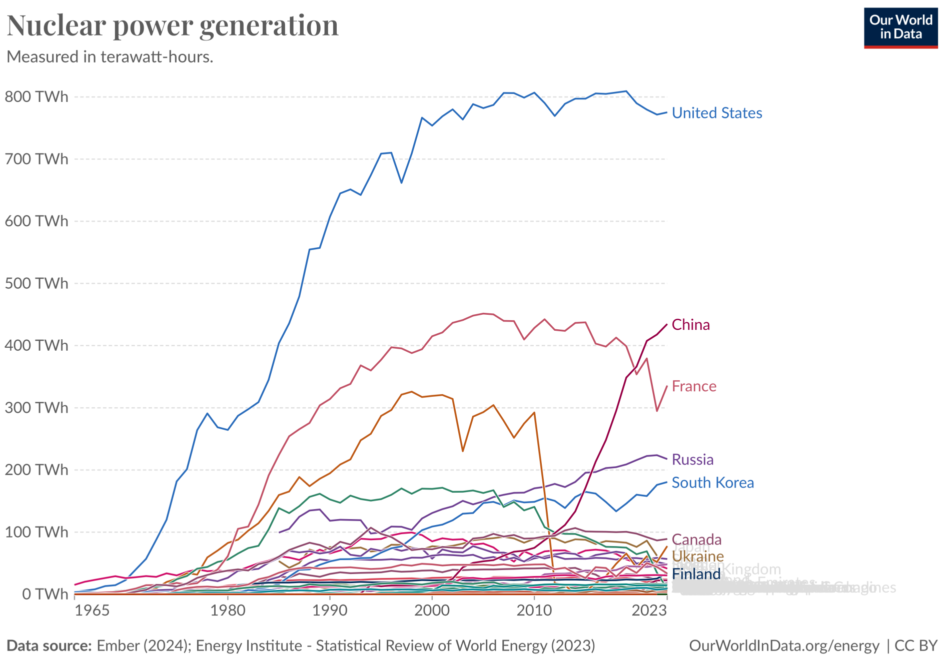

Figure 2.2: Nuclear power generation: *measured in terawatt-hours* [36]

Global nuclear energy trends have shown a complex interplay between the need for low-carbon energy and the challenges of maintaining and expanding nuclear capacity. As of 2023, nuclear power providing around 10% of the world's electricity, with the US, France and China leading the stage [36], despite the fact that many advanced economies have seen a decline in their nuclear fleets due to ageing reactors and the high costs associated with new nuclear projects [62].

However, in recent years, there has been a resurgence of interest in nuclear energy, driven by the urgent need to lower greenhouse gas emissions and enhance one's energy security. For example, China and India are significantly increasing their nuclear capacity to address rising energy needs and reduce carbon emissions. China, in particular, has ambitious plans to increase its nuclear capacity significantly, with multiple new reactors under construction and several more planned. The EIA estimates that they expect China's existing nuclear power capacity to add about 23.7 GW over the next decade from 23 reactors currently under construction [67]. By 2040, global nuclear capacity could increase to between 487 and 931 gigawatts, depending on the success of ongoing projects and technological advancements [36].

At the forefront of this nuclear renaissance are small modular reactors (SMRs) and advanced reactor designs. These technologies promise to address some of the traditional challenges associated with nuclear power, such as high capital costs and long construction times. SMRs, which can be factory-built and assembled on-site, offer flexibility and scalability, making them suitable for a variety of applications, including remote locations and integration with renewable energy sources. The development and deployment of SMRs are expected to grow, with significant investments anticipated from the mid-2020s onward [79].

Nuclear energy also contributes to several SDGs, particularly SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action) [60]. It is notably recognized for its potential to lend to a more sustainable and resilient energy system, ensuring a supply of clean, dispatchable baseload power needed for a stable energy supply. As for the IAEA, they aim to encourage sustainable nuclear energy development and the integration of atomic power into national energy planning—hence, the body's potential in alluding to major affiliations with global

Figure 2.3: Nuclear Energy SDGs [60]

decarbonization efforts [61].

However, while nuclear energy is gaining recognition for its contribution to climate goals, it continues to face significant challenges and barriers to competitiveness in the economy, perception by the public, and safety concerns. Following high-profile incidents like the Fukushima nuclear disaster in 2011, the acceptance of nuclear energy is met with pushbacks in some regions. Additionally, its economic competitiveness is under pressure from the rapidly decreasing costs of renewable energy technologies, such as wind and solar power, that are subsided by governments and are directly accessible to the public [62]. In the European Union, for example, though the economic case for extending the lifetimes of existing nuclear plants remains strong, even as the costs of renewables fall, without substantial investments in new capacity or lifetime extensions, the nuclear fleet in advanced economies could see a steep decline. This might make countries rely more on fossil fuels to meet peak demand, further complicating their attempts to decarbonize the electricity sector [62]. Overall, the global nuclear energy landscape is characterized by a push towards innovation and expansion in some regions, counterbalanced by economic, regulatory, and societal challenges in others. The interplay between future nuclear technologies and renewable energy will be crucial in shaping the future of the global energy system [112].

2.3 | Taiwan's Energy Landscape

Taiwan's current energy policies, the role of nuclear energy, and recent developments in renewable energy reflect a complex and evolving landscape driven by the need for energy security, sustainability, and economic stability. In this respect, the incumbent DPP government has been very ambitious in pushing the energy transition agenda into power in 2016, aiming at a "Nuclear-free Homeland" by 2025.

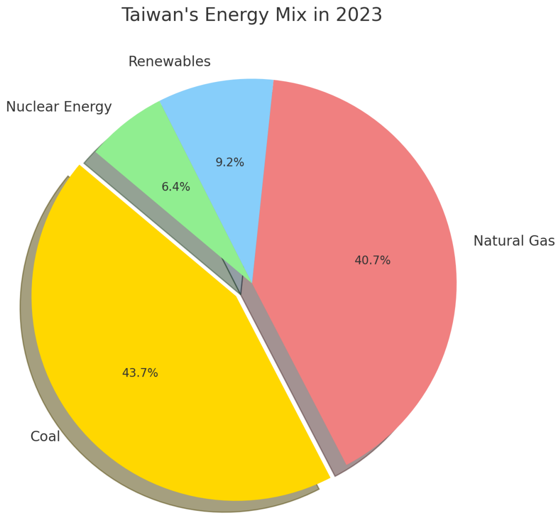

Figure 2.4: Taiwan's Energy Mix 2023

As of 2023, Taiwan's energy mix is mostly composed of coal (43%) and natural gas (40%), with renewables and nuclear energy contributing approximately 9% and 6.3%, respectively. The 2025 vision hopes to shift this to 50% natural gas, 30% coal, and 20% renewables, while phasing out nuclear power completely [102]. Substantial investments in renewable energy projects, including over 8 GW of installed solar power by 2023, indicate a well-supported transition away from nuclear energy [38]. However, achieving these targets has proven challenging, with concerns about energy security, infrastructure readiness, and public opinion complicating the transition.

This phase-out has been a cornerstone of Taiwan's energy policy under the DPP. Despite public and political debates, and even referendums, the government remains committed to decommissioning all nuclear power plants by 2025. Public support for this is strongly influenced by safety concerns, especially following the Fukushima disaster. Surveys conducted by the Taiwan Institute for Sustainable Energy show that over 65% of respondents supported the government's phase-out policy [109]. This could be attributed to the significant public mobilization against nuclear energy, as evidenced by the 2011 anti-nuclear protests [105]. This commitment is reflected in their decommissioning plans, such as those for the Jinshan Nuclear Power Plant, which started in 2019 [123]. However, it has also led to increased reliance on fossil fuels, particularly natural gas, raising questions about long-term sustainability and energy security [128].

In response to the heavy reliance on imported fossil fuels, Taiwan has ramped up investments in renewable energy. The Renewable Energy Development Act and related policies have set ambitious targets for solar and wind power, aiming to generate 20% of electricity from renewables by 2025. Their targets include employing 20 GW of solar power and 3 GW of offshore wind power by 2025 [88]. With that, Taiwan has already installed over 6 GW of installed solar power by 2023, indicating a supported transition away from nuclear energy [57]. Major renewable projects include offshore wind farms and solar installations expansions. For example, the Formosa 2 offshore wind farm has an installed capacity of 376 MW, generated by 47 Siemens Gamesa 8 MW wind turbines and has enough to power approximately 380,000 households annually [44].

On the other hand, the pace of renewable energy development has faced hurdles such as grid integration issues, regulatory delays, and the need for substantial investment in energy storage and grid modernization [?]. As of 2022, Taiwan's domestic solar PV market installations reached approximately 9,724 MW, accounting for 13% of the total installed power generation capacity. Additionally, the overall renewable energy share in the power mix had increased significantly, with projections indicating that solar PV will account for 37% of total installed capacity by 2035 [49]. As stated previously, Taiwan's energy policies are also influenced by external factors like geopolitical tensions with China, so this can indeed impact the supply chains for renewable energy equipment and materials. So to combat this, Taiwan's energy strategy a robust and flexible energy strategy that can adapt to both domestic and international pressures [102].

2.4 | Summary and Research Gaps

To summarize, the geopolitical tensions between Taiwan and China have far-reaching implications for energy security, as evidenced by past supply chain disruptions during the 1996 Taiwan Strait Crisis [24]. These tensions highlighted the critical need for Taiwan to develop a resilient and diversified energy strategy to mitigate potential geopolitical risks [82]. Moreover, it reveals Taiwan's complex and dynamic energy landscape, shaped by policy decisions, technological advancements, and socio-political factors. Taiwan's energy policy has been heavily influenced by the commitment to a "nuclear-free homeland" by 2025 and has led to an increased reliance on fossil fuels and ambitious targets for renewable energy expansion. Despite efforts, such as the Renewable Energy Development act, to reduce greenhouse gas emissions, the transition has faced grid integration issues, regulatory delays, and the need for substantial investment in energy storage and grid modernization [75] [80].

Research gaps identified in the literature include the need for more detailed analyses of the socio-economic impacts of Taiwan's energy transition, particularly in terms of energy security and economic stability. There is also a lack of comprehensive studies on the potential role of advanced nuclear technologies, such as SMRs, in Taiwan's energy future. Furthermore, the interplay between Taiwan's energy policies and its geopolitical context, especially regarding China, requires deeper exploration [82]. This thesis aims to fill these gaps by providing a comprehensive analysis of Taiwan's nuclear phase-out and transition to renewable energy. It will assess the impacts on national energy security and economic stability, and examine the geopolitical implications of Taiwan's energy policies. By addressing these research gaps, this study will contribute valuable insights to the global discourse on sustainable energy transitions.

3 | Methodology

3.1 | Research Design

This study adopts a mixed-methods approach, integrating both qualitative and quantitative methods to provide a comprehensive analysis of Taiwan's nuclear phase-out policy and its impacts on energy security and economic stability. Using a Convergent Parallel Design, I collected and analyzed qualitative and quantitative data simultaneously, but also independently. The results from both data types were to ensure that both are equally considered. Furthermore, to allow for a better, more nuanced understanding, I used drew from the mixed methods triangulation protocol, which is used to compare and contrast data, identify convergence and divergence, and resolve inconsistencies. The qualitative data offers in-depth insights from key stakeholders, such as the general public and policy makers, while the quantitative data gives empirical evidence to support and validate these insights through statistical analysis.

3.2 | Qualitative Methods

The qualitative component of this study involved semi-structured interviews and focus groups with participants from six different organizations, though the initial plan aimed for ten. Participants were selected based on their roles, expertise, and geographical location within Taiwan, aiming to include experts from local sectors, educational professionals, and representatives from both private and public companies in the energy sector. Efforts were made to ensure a diverse representation of professional backgrounds and perspectives, although access to Taipower, a key organization dealing with nuclear energy, was not achieved. The recruitment strategy involved a combination of online research and leveraging local contacts. Initial outreach was conducted via email, supplemented by local networks to identify and connect with the appropriate points of contact. Additionally, surveys were distributed through online groups and direct interactions with individuals on the street.

The interview guide for this study focused on three main topics: the organization's role and function in Taiwan's nuclear phase-out, its perspectives on the implications, and the challenges and opportunities during the transition. Based on initial feedback from a pilot test with Pan Sui Lam, my local advisor in Taiwan, the interview guide was further refined to ensure clarity and relevance. Interviews, with an average duration of approximately one hour, were conducted in person to promote a more engaging and interactive dialogue. Ethical considerations were paramount; all participants provided informed consent either through a survey question or verbally during outreach to ensure compliance with ethical standards. Confidentiality was also ensured by anonymizing participants' data and excluding identifiable information, like names or specific locations, to protect their privacy and maintain data integrity.

In processing the data collected from surveys and interviews, a thematic analysis approach was used. The initial codes were generated based on the interview guide, with additional codes emerging inductively from the data, and the coding process was managed and organized manually. Transcripts were read multiple times for familiarization, and initial codes were applied to text segments relevant to the research questions. These codes were then grouped into broader themes through an iterative process, with regular refinement and reorganization as new patterns emerged.

To maintain consistency, I periodically revisited and refined the codes to ensure they accurately represented the data. Additionally, themes were developed by grouping related codes and examining their relationships. These themes were reviewed in the context of the entire dataset to ensure they accurately reflected the data. Finally, the themes were interpreted by examining their implications for the research questions, considering the broader context of Taiwan's nuclear phase-out policy.

3.3 | Quantitative Methods

Quantitative data for this study were collected from several secondary sources, including the International Atomic Energy Agency (IAEA), International Energy Agency (IEA), Taiwan's Ministry of Economic Affairs (MOEA), Our World in Data, and the Policy Research Indicators Database of the National Applied Research Laboratories. To ensure the validity of the regression model, various diagnostic tests, such as the Durbin-Watson test for autocorrelation and the Breusch-Godfrey test for serial correlation were performed.

The key variables in this analysis were the share of nuclear energy (nukeshare_std), the share of renewable energy (regr_std), the share of fossil fuels (ffshare_std), energy intensity (enint_std), the Energy Security Risk Index (ESRI), and energy import dependency (eid_std). The share of nuclear energy, renewable energy, and fossil fuels were standardized, as was energy intensity, which measures energy consumption per unit of GDP, with lower values indicating more efficient energy use. The ESRI served as the dependent variable representing the risk associated with energy security, and energy import dependency represented the proportion of energy that is imported, also standardized. The ESRI information was obtained from the Global Energy Institute's International Energy Security Risk Index scores [59]. It provides a historical view of how energy security risks have trended both within each entity since 1980 and in relation to the average index for the Organization for Economic Co-operation and Development (OECD). A higher index score indicates higher risk, while a lower score indicates lower risk. The index was calculated using 29 different metrics, including global fuel reserves, energy expenditures, and environmental impacts, providing a comprehensive assessment of energy security risks. In 2018, Taiwan's ESRI score was 1,074, compared to the OECD average of 900 3.1.

Using STATA software, I conducted a time series analysisfrom 1985 to 2018 with ESRI as the outcome variable. The analysis explored the relationship between ESRI and various independent variables through several statistical methods. Descriptive statistics were used to summarize the data, providing an overview of the key variables and their distributions. Because of the presence of multicollinearity among the independent variables, a Principal Component Analysis (PCA) was applied, reducing them into principal components used in the regression model. The regression analysis involved an initial model that included principal components, polynomial terms, and interaction terms to capture non-linear relationships and interactions between variables. The model was refined by including lagged residuals to address autocorrelation, thereby improving its fit and validity. Diagnostic tests such as the Durbin-Watson test, Breusch-Godfrey test, Breusch-Pagan test, and Ramsey RESET test ensured the model's robustness.

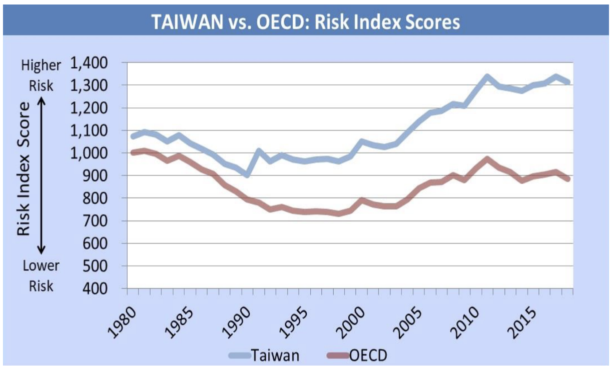

Figure 3.1: Taiwan vs OECD: Risk Index Scores [59]

3.4 | Data Collection Procedures

Qualitative Phase The qualitative data collection followed a structured timeline:

1. **Week 1 (Kaohsiung) - April 20-25, 2024:**
   - Orientation at National Sun Yat-Sen University.
   - Visits to the Southern Taiwan Science Park Bureau and Maanshan Nuclear Power Plant.
   - Visits to ChiMei Green Energy Park.
   - Meeting with APh ePower.
2. **Week 2 (Taipei) - April 26-May 3, 2024:**
   - Meeting with the Nuclear Safety Commission.

- Visit to Chinshan Nuclear Plant.
- Visit to Kuosheng Nuclear Plant.

3. **Week 3 (Taipei) - May 4-12, 2024:**
    - Meeting with Professor Shi Xinmin at the Taiwan Environmental Protection Union.
    - Interviews with students at National Taiwan University.
    - Data analysis initiation.
4. **Week 4 (Kaohsiung) - May 13-17, 2024:**
    - Visit to the Southern Taiwan Science Park Bureau.
    - Interviews with students at National Sun Yat-Sen University.
5. **Departure (Taipei) - May 18-19, 2024:**
    - Wrap-up meetings with advisors.

Scheduling meetings posed significant challenges due to participants' availability. This issue was mitigated by adopting a flexible approach to timing and leveraging local contacts to facilitate introductions. To ensure the accuracy of the collected data, systematic methods for data cleaning and organization were implemented. During the quantitative phase, standard data cleaning and preprocessing steps were meticulously followed, including the removal of incomplete data and ensuring consistency. Data points were included based on their relevance to Taiwan and participant consent.

Ethical considerations were rigorously adhered to throughout the study. Ethical approval was obtained through the OSUN research grant application, which followed APA guidelines. This included listing all ethical considerations and ensuring participant confidentiality by anonymizing data and excluding identifiable information.

4 | Results and Analysis

4.1 | Overview of Qualitative Findings

This section presents the qualitative findings from the interviews conducted with key stakeholders in Taiwan's energy sector. The analysis identifies and explores the main themes that emerged from the data, providing insights into how Taiwan can manage energy security while phasing out nuclear energy. The themes discussed include energy security and stability, nuclear energy phase-out, renewable energy development, technological advancements and innovations, regulatory and policy frameworks, public perception and acceptance, environmental and safety considerations, market and competitors, and carbon neutrality and credits.

1. Energy Security and Stability

   [a] Energy security and stability emerged as a critical concern among the interviewees. Taiwan's heavy reliance on energy imports, combined with frequent power outages, poses significant challenges to maintaining a stable energy supply. As one interviewee noted, "Taiwan only has around two weeks of natural gas reserves and we experience a lot of power outages as well" (CET). This makes Taiwan vulnerable to geopolitical risks and supply disruptions, underscoring the need for robust energy storage systems and diversified energy sources. The integration of renewable energy further complicates this issue, as intermittent sources like solar and wind can destabilize the grid without adequate storage solutions.

2. Nuclear Energy Phase-Out

   [a] The planned phase-out of nuclear energy in Taiwan is driven by a combination of safety concerns, waste management issues, and public opposition. An interviewee explained, "In Taiwan, I don't think that we have to build out the traditional nuclear plant because they have two issues: location and storage of waste" (TEPU). The decommissioning of existing plants and the need for comprehensive waste management systems present significant challenges that require careful planning and robust regulatory frameworks.

3. Renewable Energy Development

   [a] Renewable energy development is essential for replacing nuclear energy and ensuring energy security in Taiwan. However, integrating renewable sources such as solar and wind into the existing grid presents several challenges. Intermittency and the need for substantial energy storage infrastructure were frequently mentioned by interviewees. "The challenges of renewable energy integration include intermittency. If we want to use renewable energy 100%, we must equip with energy storage systems" (TEPU). Despite these challenges, there is strong public support for renewable energy, particularly solar power, which can be easily installed on residential rooftops, enhancing local energy production and sustainability.

4. Technological Advancements and Innovations

   [a] Technological advancements, particularly in battery technology, are pivotal for supporting Taiwan's transition to renewable energy. Interviewees highlighted the potential of aluminum ion batteries, which offer significant advantages over traditional lithium-ion batteries, including higher temperature resistance and reduced fire risk. As one interviewee stated, "We would like to develop a new battery of aluminum ion battery. It is less likely to have fire accidents, and the temperature resistance is higher" (APh ePower). Continued innovation in energy storage and renewable energy technologies is crucial for addressing the intermittency of renewable sources and ensuring a stable energy supply.

5. Regulatory and Policy Frameworks

   [a] Effective regulatory and policy frameworks are essential for managing the transition from nuclear to renewable energy. Interviewees emphasized the importance of strict regulations, public communication, and international cooperation. One participant noted, "Our policy now regulates that energy storage systems could not be near metropolitan areas for safety considerations" (Nuclear Safety Commission). The role of regulatory authorities in implementing safety measures and promoting international collaboration was highlighted as crucial for facilitating the energy transition and ensuring compliance with safety standards.

6. Public Perception and Acceptance

    [a] Public perception and acceptance of energy policies and technologies play a critical role in their successful implementation. Interviewees stressed the need for transparent communication strategies and public education to gain support for energy policies. ”The public generally accepts renewable energy like solar power, especially when they can install solar panels on their roofs” (APh ePower). Engaging with stakeholders and the public through effective communication and participation is vital for fostering acceptance and facilitating the transition to renewable energy.

7. Environmental and Safety Considerations

    [a] Environmental and safety considerations are paramount in the context of Taiwan’s energy transition. The phase-out of nuclear energy is primarily driven by safety concerns and the challenges associated with managing nuclear waste. As one interviewee explained, ”The nuclear phase-out is their main goal, so we can anticipate that in the following four years, the policy won’t be changed” (Nuclear Safety Commision). The development of new battery technologies, such as aluminum ion batteries, also emphasizes safety, with these batteries being less prone to fire accidents and having higher temperature resistance.

8. Market and Competitors

    [a] Understanding the competitive landscape and market dynamics is essential for positioning Taiwan’s energy sector in the global market. Interviewees discussed the competitive advantages of Taiwanese companies in developing new battery technologies and other energy solutions. ”The other company working on aluminum ion batteries is in Australia, called GMG” (APH ePower). Maintaining a competitive edge through innovation and understanding global trends is crucial for the success of Taiwan’s energy sector.

9. Carbon Neutrality and Credits

    [a] Achieving carbon neutrality is a key goal for Taiwan, supported by the role of carbon credits in promoting renewable energy and reducing carbon emissions. Interviewees highlighted the importance of voluntary carbon credits and the efforts to achieve net-zero emissions. ”Our mission is to help the company achieve goals like remote energy 100% carbon neutral neutrality” (Chi Mei). Aligning energy policies with global climate goals and promoting the use of carbon credits are essential steps towards a sustainable and environmentally friendly energy future.

The themes identified highlight the importance of *ensuring energy security*, *developing robust regulatory frameworks*, *promoting technological innovations*, and *engaging with the public*. By addressing these key areas, Taiwan can achieve a secure, sustainable, and publicly supported energy future.

4.2 | Survey Results

The survey aimed to assess perceptions and attitudes toward nuclear energy, focusing on factors such as safety, public education, technological investment, environmental impact, and international cooperation. This provided insights into the general public's views on these critical issues and highlighted the priorities and concerns related to nuclear energy. The key findings from the survey show a significant emphasis on investment in renewables and safety. Data were collected both in person and online. A structured questionnaire was administered using electronic tablets for in-person surveys and online forms for remote participants. The survey included a total of 125 respondents. Participants' ages ranged from 18 to 41 years, with a mean age of 25.7 years and a standard deviation of 5.95 years. The gender distribution showed a predominance of males (76%) and females accounted for 24% of the respondents.

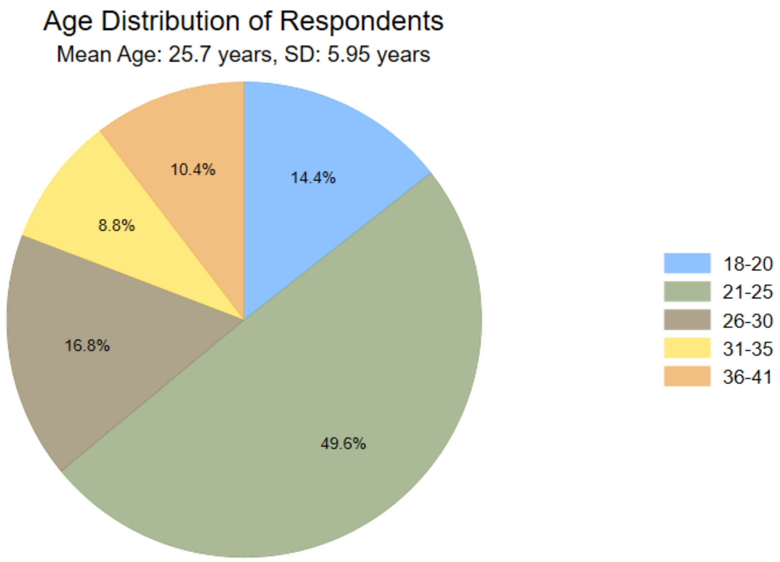

Figure 4.1: Pie Graph: *Age Distribution of Respondents*

4.2.1 | Quantitative Insights

Participants were asked to rank the importance of various factors for prioritizing Taiwan's expansion of nuclear energy capabilities. Ranking on a scale from 1 (most important) to 5 (least important), the factors included safety measures and regulations, public education and awareness, investment in advanced technology, environmental impact assessments, and international cooperation and standards. News media (76%) and social media (63%) were the most frequently cited sources of information about nuclear energy. Scientific journals and school/university courses were also notable sources, reported by 47% and 59% of respondents, respectively. Other sources such as family/friends, nuclear plant exhibitions, internet, books, workplace, website, papers, YouTube, NGOs related to environmental issues, popular science magazines, and actual visits were also mentioned. There were significant differences in the use of information sources between genders. For instance, a higher proportion of males reported using scientific journals (86%) compared to females (13%). Similarly, males were more likely to use news media (72%) and social media (76%) than females (27% and 24%, respectively).

Additionally, a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was used to gauge participants' levels of agreement with the statement, "Taiwan should invest more in renewable energy sources rather than nuclear energy." The mean score was 3.05, indicating a general agreement towards investing more in renewables instead of nuclear energy. Additionally, when analyzed by gender, the distribution showed that males had a slightly higher mean score (3.1) compared to females (2.9), suggesting males are marginally more supportive of investing in renewables more. One survey participant highlighted that the question's phrasing could suggest a biased view of nuclear energy against renewable energy, potentially influencing responses and reinforcing existing beliefs. They argued that such a design not only reflects the structure of the questionnaire, but also mirrors a broader phenomenon in Taiwan's political ideology and public opinion. This comment showed the need for more nuanced survey questions that do not presuppose an inherent conflict between different energy sources, such as nuclear energy and renewable energy.

In the context of nuclear energy, participants ranked different factors in order of priority. The factors included safety measures and regulations, public education and awareness, investment in advanced technology, environmental impact assessments, and international cooperation and standards. The frequency distribution of these priorities indicated that safety measures and regulations were the highest priority for most respondents, followed by public education and awareness, and investment in advanced technology. Most respondents (47) rated safety measures and regulations as the highest priority, while the next significant group (37) rated it as the lowest priority.

In addition to descriptive analysis, multiple regression analyses were conducted to determine the factors predicting the importance assigned to nuclear energy among the respondents. The predictors examined in the model included were *Investment in Renewables* (measured the respondents' support for divesting from nuclear energy to more renewable energy), *Age*, *Knowledge about Nuclear Energy* (self-assessed knowledge about nuclear energy) and *Gender* (coded numerically, with males and females as the two categories). Despite the potential bias with the *Investment in Renewables* question, responses were included to measure the respondents' support for shifting from nuclear energy to more renewable energy sources, reflecting a key area of public interest and policy debate. Age was considered to explore generational differences in attitudes, as younger and older individuals may have differing perspectives on energy issues. Additionally, *Knowledge about Nuclear Energy* was included to assess whether a higher level of understanding correlates with greater or lesser support for nuclear energy. Finally, *Gender* was included to identify any significant differences in attitudes between males and females, as previous studies have indicated that gender can play a role in shaping opinions on energy-related topics.

Table 4.1: Regression Analysis of Investment in Renewables Predictors

Predictor 95% Conf. Interval	Coefficient (β)	Std. Err.	t	P-value
age	-0.0229	0.0170	-1.34	0.182
[-0.0566, 0.0109]				
knowledge	-0.2075	0.1031	-2.01	0.046
[-0.4115, -0.0034]				
importance_num	-0.6481	0.0862	-7.52	0.000
[-0.8189, -0.4774]				
gender_num	-0.6932	0.2424	-2.86	0.005
[-1.1732, -0.2133]				
constant	8.2189	0.8197	10.03	0.000
[6.5958, 9.8420]				

The results of the regression analysis reveal several key predictors of the importance assigned to nuclear energy among respondents. The regression coefficient (β) for investment in renewables was -0.65, signifying a strong negative association with the importance assigned to nuclear energy. This suggests that as support for investment in renewables increased, the perceived importance of nuclear energy decreased. The p-value for this predictor was less than 0.001, confirming its statistical significance. Similarly, the regression coefficient (β) for gender was -0.69, indicating that gender is a significant predictor of the importance assigned to nuclear energy. Specifically, males tended to assign less importance to nuclear energy compared to females. The p-value for this predictor was 0.005, indicating a statistically significant difference. The regression coefficient (β) for age was -0.022, suggesting a weak negative relationship between age and the importance assigned to nuclear energy. However, this relationship was not statistically significant ($p = 0.182$), indicating that age does not significantly predict the perceived importance of nuclear energy among the respondents. This is visually represented by the scatterplot in Figure 4.2 of the predicted importance of nuclear energy by age, with an R-squared value of 0.0551 indicating that the model explains only about 5.51% of the variance in the importance assigned to nuclear energy. The trend line further confirms the weak negative relationship observed, highlighting the minimal impact of age as a predictor in this model.

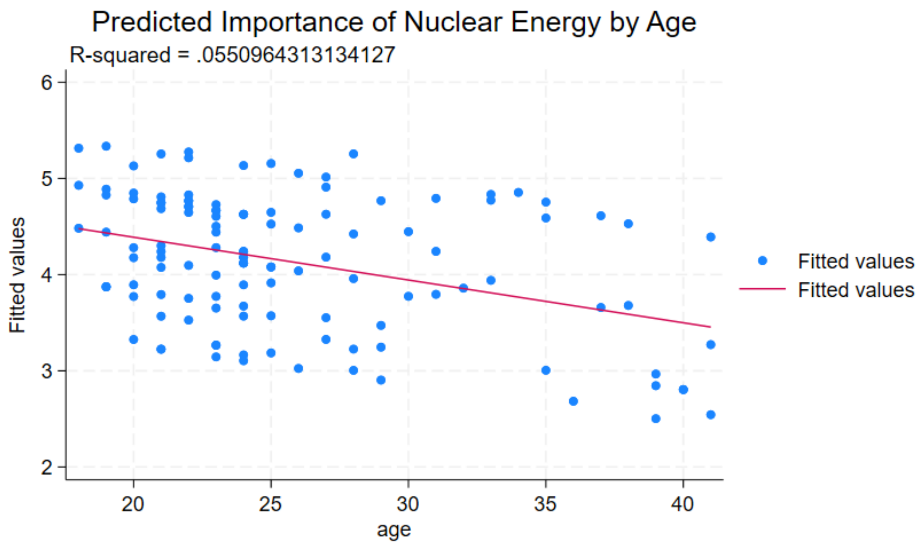

Figure 4.2: Scatterplot: *Predicted Importance of Nuclear Energy by Age*

To further explore potential interaction effects, additional analyses were conducted to determine whether the relationships between certain predictors, knowledge and gender, and age and investment in renewables, and the importance assigned to nuclear energy were moderated by other variables. The interaction term for knowledge and gender investigated whether the relationship between knowledge about nuclear energy and the importance assigned to it varied by gender. In this regression model, the coefficient for the interaction term (knowledge * gender_num) was 0.0018, indicating a very weak positive interaction. However, this interaction effect was not statistically significant, with a p-value of 0.993. This suggests that the relationship between knowledge about nuclear energy and its perceived importance does not differ significantly between males and females.

In order to access how the relationship between age and the importance assigned to nuclear energy is influenced by the level of support for investing in renewables, a second interaction term was examined. The coefficient for this interaction term (age * invest_renewables) was 0.0052, indicating a weak positive interaction. However, like the first interaction term, this effect was not statistically significant, with a p-value of 0.581, suggesting that the relationship between age and the importance assigned to nuclear energy is not significantly influenced by the level of support for investing in renewables. Overall, the interaction analyses indicate that the primary effects of knowledge, age, and support for renewables on the importance assigned to nuclear energy are not significantly moderated by gender. Additionally, the interaction between age and support for renewables does not significantly influence this relationship. The absence of significant interaction effects suggests that the relationships between these predictors and the importance assigned to nuclear energy remain relatively consistent across different levels of the interacting variables, reinforcing the robustness of the primary effects identified in the regression analysis.

4.2.2 | Qualitative Insights from Open-Ended Comments

Many respondents expressed concerns about safety and the environmental impact of nuclear energy, reflecting the high priority given to these factors in the survey rankings. For instance the comment, 'The source of fear is ignorance, and nuclear energy can only be effectively promoted if people's knowledge is improved and people are reassured,' underscores the importance of public education and awareness in shaping positive perceptions of nuclear energy. Other respondents highlighted the political dimensions of the nuclear energy debate in Taiwan. One participant commented, "Proponents of nuclear energy often think of themselves as scientific, but nuclear energy itself is inseparable from political choices." This reflects the complex interplay between scientific considerations and political decisions in the realm of energy policy.

Several comments also pointed to the need for balanced and well-informed discussions about nuclear energy. One respondent mentioned, "The status quo is really miserable, nuclear energy is rejected not because of professional factors, but because of political factors and stupid people who have been brainwashed by politics." This sentiment emphasizes the role of misinformation and political bias in shaping public opinion. Moreover, the challenges of nuclear waste management and the geographical constraints of Taiwan were recurrent themes in the comments. A respondent stated, "Taiwan is a densely active zone of seismic faults, and the establishment of nuclear power plants should also consider their location and 100% supporting measures in the event of an emergency." This concern about geological suitability and emergency preparedness reflects a significant barrier to the public's acceptance of nuclear energy.

The comments also revealed a spectrum of opinions regarding the future role of nuclear energy in Taiwan's energy strategy. Some respondents were in favor of continuing nuclear energy development, albeit with stringent safety measures and improved waste management practices. One participant suggested, "Nuclear energy should not be rejected altogether, but developed step-by-step alongside renewable energy." This viewpoint advocates for a balanced energy mix that includes both nuclear and renewable sources.

Conversely, other respondents were strongly opposed to the use of nuclear energy, citing risks and preferring investments in renewable energy. One respondent expressed, "It's too expensive and difficult to deal with. Although there are many advantages, the disadvantages are worse, so I have to choose not to support it." This perspective highlights the economic and risk-related considerations that weigh heavily on public opinion. The varied responses reflect the complexity of the nuclear energy debate in Taiwan. As another respondent pointed out, "Nuclear energy in Taiwan is a very political issue with two big parties taking strong stances," highlighting the polarization of opinions and the influence of political ideologies on energy policy.

4.3 | Regression Analysis

The regression analysis was conducted to explore the relationship between the Energy Security Risk Index (ESRI) and various independent variables, including nuclear energy share, renewable energy generation ratio, energy intensity, fossil fuel share, and energy import dependency. Principal Component Analysis (PCA) was applied, resulting in the extraction of principal components (PCs). The first two principal components, PC1 and PC2, were used in the regression models to capture the most significant components of variance.

PCA was performed on the standardized independent variables to address multicollinearity and extract the most significant components of variance, simplifying the dataset by transforming the original correlated variables into new uncorrelated variables, called principal components. PCs capture the maximum variance in the data. Before applying PCA, the continuous variables were standardized to ensure comparability:

$$\text{standardized\_variable} = \frac{\text{original\_variable} - \mu_{\text{variable}}}{\sigma_{\text{variable}}}$$

where μ_{variable} is the mean and σ_{variable} is the standard deviation of the variable.

The PCA yielded the following principal components, which are linear combinations of the standardized independent variables:

1. **PC1**: This component explains the largest proportion of variance (85.51%). It is composed of the following loadings:

$$\begin{aligned}\text{PC1} = {} & 0.4722 \times \text{nukeshare\_std} + 0.4298 \times \text{regr\_std} + 0.4048 \times \text{enint\_std} \\ & - 0.4742 \times \text{ffshare\_std} - 0.4512 \times \text{eid\_std}\end{aligned} \tag{4.1}$$

   PC1 positively loads on nuclear share, renewable energy generation ratio, and energy intensity, while it negatively loads on fossil fuel share and energy import dependency. This suggests that PC1 captures a dimension where higher values indicate a higher share of nuclear and renewable energy and higher energy intensity, but lower reliance on fossil fuels and imports.

2. **PC2**: This component explains an additional 11.22% of the variance. It is composed of the following loadings:

$$\begin{aligned}\text{PC2} = {} & 0.1859 \times \text{nukeshare\_std} - 0.5797 \times \text{regr\_std} + 0.6863 \times \text{enint\_std} \\ & - 0.1165 \times \text{ffshare\_std} + 0.3806 \times \text{eid\_std}\end{aligned} \tag{4.2}$$

   PC2 positively loads on energy intensity and energy import dependency, but negatively loads on the renewable energy generation ratio. This suggests that PC2 captures a dimension where higher values indicate greater energy intensity and import dependency but lower renewable energy generation.

The regression analysis was conducted in two phases: the initial model and the refined model. The initial model included the principal components (PC1 and PC2), polynomial terms, and interaction terms to capture non-linear relationships::

$$\begin{aligned}\text{ESRI}_{\text{std}} = {} & \beta_0 + \beta_1 \times \text{lag\_esri} + \beta_2 \times \text{PC1} + \beta_3 \times \text{PC2} \\ & + \beta_4 \times \text{PC1}^2 + \beta_5 \times \text{PC2}^2 + \beta_6 \times (\text{PC1} \times \text{PC2}) + \epsilon\end{aligned} \tag{4.3}$$

The results were as follows:

$$\begin{aligned}\text{ESRI}_{\text{std}} = {} & -5.97309 + 0.0051664 \times \text{lag\_esri} - 0.307638 \times \text{PC1} + 0.2438379 \times \text{PC2} \\ & + 0.0896609 \times \text{PC1}^2 - 0.0972841 \times \text{PC2}^2 + 0.0997752 \times (\text{PC1} \times \text{PC2}) + \epsilon\end{aligned} \tag{4.4}$$

To address autocorrelation, the refined model included lagged residuals:

$$\begin{aligned}\text{ESRI}_{\text{std}} = {} & \beta_0 + \beta_1 \times \text{lag\_esri} + \beta_2 \times \text{PC2} \\ & + \beta_3 \times \text{PC2}^2 + \beta_4 \times (\text{PC1} \times \text{PC2}) + \beta_5 \times \text{lag\_resid1} + \epsilon\end{aligned} \tag{4.5}$$

The results were as follows:

$$\begin{aligned}\text{ESRI}_{\text{std}} = &-8.629565 + 0.0078433 \times \text{lag\_esri} + 0.2622672 \times \text{PC2} \\ &+ 0.009299 \times \text{PC2}^2 + 0.0565211 \times (\text{PC1} \times \text{PC2}) - 0.2693228 \times \text{lag\_resid1} + \epsilon\end{aligned} \tag{4.6}$$

The coefficient for lagged ESRI was 0.0078433, which was highly significant with a p-value of less than 0.0001. This emphasizes how past energy security risk values continue to influence current values over time. Essentially, this suggests that energy security risks are somewhat path-dependent; previous conditions and vulnerabilities continue to impact the current state of energy security.

Table 4.2: Regression Analysis Results

Predictor	Coefficient (β)	Std. Err.	t	P-value	95% Conf. Interval
lag_esri	0.0051664	0.0008968	5.76	0.000	[0.0033229, 0.0070098]
pc1	-0.307638	0.0882666	-3.49	0.002	[-0.4890726, -0.1262034]
pc2	0.2438379	0.1452651	1.68	0.105	[-0.0547588, 0.5424346]
pc1_sq	0.0896609	0.0314853	2.85	0.008	[0.024942, 0.1543798]
pc2_sq	-0.0972841	0.0983615	-0.99	0.332	[-0.299469, 0.1049009]
interaction_pc1_pc2	0.0997752	0.0598534	1.67	0.108	[-0.0232552, 0.2228057]
constant	-5.97309	0.945838	-6.32	0.000	[-7.917287, -4.028892]

PC1 had a negative coefficient of -0.307638 in the initial model, suggesting that an increase in PC1, which represents a higher share of nuclear energy and a lower reliance on fossil fuels and energy imports, is associated with a decrease in ESRI. This suggests that a higher proportion of nuclear energy could reduce energy security risk. Conversely, PC2 had a positive coefficient of 0.2438379 in the initial model, indicating that higher energy intensity and higher dependency on energy imports can elevate the energy security risk. The polynomial terms and interaction terms revealed relationships in the model where changes are not proportional, showing curves or unexpected patterns. For instance, the squared term of PC1 had a positive coefficient of 0.0896609, indicating a quadratic relationship where both very low and very high values of PC1 might increase ESRI. This highlights the impact of extreme values on energy security due to the complexity of energy dynamics.

Residual analysis showed that the residuals' kernel density estimate closely follows a normal distribution, indicating the model's robustness. The kernel density estimate smooths out the distribution of the residuals, giving a clear visual representation of their spread. The alignment with the normal distribution curve shows that the residuals follow a normal pattern. Moreover, diagnostics confirmed the absence of significant autocorrelation and heteroskedasticity, further validating the model. The Durbin-Watson test result of 1.941364 shows that there is no significant correlation between successive errors in the model. The Breusch-Godfrey LM test showed no serial correlation, with a chi-squared value of 0.012 and a high p-value of 0.9122. The Breusch-Pagan/Cook-Weisberg test revealed no significant heteroskedasticity, indicated by a chi-squared value of 0.11 and a p-value of 0.7372. The Ramsey RESET test with an F-statistic of 2.82 and a p-value of 0.0615 indicates that there is no significant bias from leaving out important variables in the model. These tests suggest that the model reliably captures the underlying relationships between the independent variables and the ESRI, providing confidence in the interpretation and application of the results.

4.4 | SWOT Analysis of Taiwan's Nuclear Energy Phase-out

This SWOT analysis's main goal is to clarify the crucial factors influencing Taiwan's move away from nuclear energy, with an emphasis on the consequences for the country's energy security, stability, and sustainability.

Table 4.3: SWOT Analysis of Taiwan's Nuclear Energy Phase-out

	Helpful	Harmful
Internal origin	Public and Policy Support Technological Advances Regulatory Framework Proactive Transition Strategy Advanced Monitoring	Dependence on Imports Aging Infrastructure Integration Issues Economic Implications Public Perception and Mistrust
External origin	Energy Diversification International Collaboration/Learning Technological Innovation Global Market Trends Environmental Benefits	Natural Disasters Political Fluctuations Economic Burdens Technological Setbacks International Pressure

By dissecting these factors, I aim to provide a holistic view that aids policymakers, stakeholders, and researchers in formulating informed strategies and decisions.

1. **Strengths**: This section examines the internal attributes and resources that position Taiwan favorably in its energy transition.
2. **Weaknesses**: Here, I identify internal limitations and challenges that could hinder the effective implementation of the nuclear phase-out policy.
3. **Opportunities**: This explores external factors and trends that Taiwan can leverage to enhance its energy security and economic resilience.
4. **Threats**: Finally, this section addresses external risks and challenges that could potentially derail Taiwan's energy policy goals. 4.3

4.4.1 | Strengths

Public and Policy Support
Taiwan's government and a significant portion of the public have demonstrated strong support for the nuclear phase-out policy, primarily driven by safety concerns and environmental considerations. The catalyst for this shift was the Fukushima disaster in 2011, which raised global awareness of the potential dangers of nuclear energy. This resonated with the Taiwanese public due to the island's seismic activity, leading to heightened safety concerns and mass anti-nuclear protests. These public sentiments were instrumental in shaping government policy, with over 220,000 citizens reportedly participating in anti-nuclear demonstrations in 2013 [21].

In 2016, The DPP capitalized on this public sentiment by making the nuclear phase-out a central pillar of its energy policy. They enacted an amendment to the Electricity Act, mandating the shutdown of all nuclear power plants by 2025 [90]. Despite mixed results in referendums, where some favored maintaining nuclear power, the government continued its phase-out efforts, reflecting a strong political commitment to transitioning away from nuclear energy [21]. In addition to the local public, Non-governmental organizations (NGOs) have played a crucial role in mobilizing public opinion against nuclear power. The

Taiwan Environmental Protection Union (TEPU) has been at the forefront of anti-nuclear activism since its inception. TEPU organized large-scale protests, such as the “430 Sunflower No Nuke Action” in 2011, which drew over 5,000 participants demanding an end to nuclear power [83]. Similarly, Citizens of the Earth Taiwan (CET) has actively campaigned against nuclear energy, highlighting the risks associated with Taiwan's nuclear plants and advocating for renewable energy solutions. CET has been instrumental in raising awareness about the potential environmental and health hazards posed by nuclear energy, thereby strengthening public opposition to nuclear power [122].

Moreover, the government's stance is reinforced by its commitment to ambitious renewable energy targets. For example, Taiwan's electricity from renewables has increased from just 6.2% in 2022 [56]. This not only supports the phase-out, but also aligns with global SDGs, further reinforcing the public and policy support for the phase-out initiative [85]. Although the phase-out has encountered challenges, such as vocal opposition from pro-nuclear activists, concerns about energy security, and the potential for power shortages. The government has remained steadfast, emphasizing the long-term benefits of a nuclear-free Taiwan [90].

Technological Advances

Taiwan has made significant strides in renewable energy technology, particularly in solar and wind power, achieving milestones such as producing more solar and wind energy than coal for the first time in March 2023. This shift highlights the country's growing capacity in renewable energy, with renewables generating 31.53% of Taiwan's energy that month [19]. For example, the Tainan Solar City Initiative has transformed a southwestern city, Tainan, into a leading example of urban solar energy integration. The extensive deployment of rooftop solar panels across public buildings and residences has increased the city's solar capacity to 500 MW and has also demonstrated the practicalities and benefits of solar energy in densely populated urban areas. Similarly, Taiwan's offshore wind projects, such as the Formosa 1 and Formosa 2 wind farms, highlight the country's potential in harnessing offshore wind energy. Formosa 1, with a capacity of 128 MW, was Taiwan's first commercial-scale offshore wind farm and has already provided power to over 128,000 households. Formosa 2, expected to add 376 MW upon completion, will further cement Taiwan's position as a leader in offshore wind energy [44] These projects not only enhance energy security, but also stimulate economic growth by creating jobs and attracting investments. This initiative, instrumental in contributing to Taiwan's overall renewable energy targets, provides a replicable model for other regions.

In 2022, Taiwan's National Development Council (NDC) announced an investment of nearly NTD $900 billion (USD $28.18 billion) in renewable energy technologies and carbon capture tools [19]. This supports the development and implementation of cutting-edge technologies, including solar panels, wind turbines, and smart energy storage systems. Additionally, the Ministry of Economic Affairs has introduced new Feed-in Tariffs (FiTs) for 2023 to incentivize the production of renewable energy, particularly in onshore and offshore wind parks, and small hydropower plants [37]. Looking at international examples, Denmark's Horns Rev 3 offshore wind farm is a benchmark for offshore wind energy. With a capacity of 407 MW, it significantly contributes to Denmark's renewable energy output and CO2 reduction goals. Denmark's success is largely due to supportive government policies and incentives that have created a conducive environment for renewable energy development. Additionaly, In Germany, the Energiewende initiative has revolutionized the country's energy landscape by aggressively promoting solar and wind energy. Through policies like feed-in tariffs, Germany has become one of the largest solar energy producers globally, with a capacity exceeding 59 GW.

The renewable energy sector has also seen significant contributions from international collaborations and foreign investments. Foreign-funded projects like the Vena Energy's E2 Solar Project, inaugurated in April 2023, contribute to the nation's renewable energy output by providing energy for approximately 90,000 households annually [99]. Thanks to the government's proactive legislative efforts further supporting technological advancements in renewable energy, the amendments to the Renewable Energy Development Act and the implementation of solar panel mandates for new buildings underscore Taiwan's commitment to expanding its renewable energy infrastructure. These policies not only drive technological innovation, but also ensure that new constructions are aligned with the country's sustainability goals, positioning Taiwan to be a global leader in sustainable energy transitions [**?**].

Regulatory Framework

Taiwan has established a robust regulatory framework to oversee its energy transition, ensuring that the phase-out process adheres to safety standards and promotes the integration of renewable energy into the national grid. Central to this framework is the 2050 Net-Zero Emissions pathway, which outlines comprehensive strategies across energy, industry, lifestyle, and social sectors. This blueprint aims to drive technological R&D, foster innovation, and implement climate legislation, all crucial for achieving the net-zero goal [31].

In addition to the 2050 Net-Zero Emissions pathway, the Climate Change Response Act, formally known as the Greenhouse Gas Reduction and Management Act, mandates significant reductions in greenhouse gas emissions and supports the development of renewable energy, serves a cornerstone of Taiwan's regulatory efforts [25]. It establishes stringent emissions targets and provides a clear legal framework for both government and private sector actions to mitigate climate change. Moreover, the Financial Supervisory Commission has been developing guidelines on sustainable economic activities to assist investors and stakeholders in identifying and promoting environmentally impactful practices, enhancing the overall regulatory environment for sustainable investments [117].

Taiwan's regulatory landscape also includes incentives to boost renewable energy adoption. For instance, the Renewable Energy Development Act encourages investments in renewable energy through various fiscal incentives and subsidies. This act, with the included FiTs, has been instrumental in driving the growth of solar and wind energy projects across the island, ensuring stable and attractive returns for investors in renewable energy [**?**].

To address the challenges of integrating renewable energy into the grid, Taiwan has also focused on developing advanced energy storage solutions. The deployment of large-scale energy storage systems, such as the one implemented by Taipower in Longtan, is critical for stabilizing the grid and accommodating the intermittent nature of renewable energy sources. APh ePower is taking advantage of the carbon credits, specializing in the development and commercialization of aluminum-ion batteries [72]. Moreover, Taiwan's government has emphasized the importance of public engagement and transparency in its energy transition strategy. This includes rolling out initiatives to involve citizens and stakeholders in the policy-making process, ensuring that the transition is inclusive and reflects the public's interests and concerns. In my interview with Jasper Chih from the Nuclear Safety Commission, he stated that residents are allowed to test certain areas for abnormal radioactive activities [73]. These efforts are vital for maintaining public support and ensuring the smooth implementation of regulatory measures.

Proactive Transition Strategy

The Taiwanese government has adopted an approach that's aimed at emphasizing investment in renewable energy projects, improving energy efficiency, and implementing supportive policies for sustainable energy infrastructure. Encapsulated in their Net-Zero Emissions pathway, is a focus on enhancing technology R&D, fostering innovation, and developing a detailed action plan that integrates governmental resources to meet these ambitious targets [31]. A significant part of their strategy involves substantial financial commitments to renewable energy, supported by investments totaling nearly NTD $900billion(USD28.18$ billion) in renewable energy technologies and carbon capture tools [19]. These investments are directed more specifically towards expanding the capacity of wind and solar power. For example, Taiwan has developed Asia's largest commercial offshore wind farm in Miaoli County [96].This wind farm, Greater Changhua 1 & 2a, has a combined capacity of 900 MW, which is enough to power approximately 225,000 households, reducing dependency on imported energy and enhancing energy security [111].

In addition to financial investments, Taiwan has implemented robust policies, such as the aforementioned FiTs to encourage the development and adoption of renewable energy by providing financial incentives for renewable energy producers, ensuring stable returns and promoting investment in green energy. This policy framework supports a variety of projects, from large-scale offshore wind farms to small rooftop solar installations, facilitating widespread adoption of renewable technologies [37].

Taiwan's proactive strategy also includes enhancing energy efficiency across various sectors. The government has launched initiatives such as the Green Energy Roofs project and Tainan Salt Fields Solar PV Park, which aim to increase solar power capacity by utilizing rooftops and integrating solar panels with agricultural practices [50] [40]. These projects not only boost renewable energy production, but also optimize land use in a densely populated country[96]. Furthermore, their energy transition strategy is marked by international collaboration and the integration of advanced technologies. Actively engaging with international partners to leverage cutting-edge technologies and expertise, as seen in the development of offshore wind farms with contributions from Denmark, Japan, etc. are crucial for overcoming the technological and financial barriers associated with large-scale renewable energy projects [119]. Through substantial investments, supportive policies, and international cooperation, Taiwan is making significant strides in reducing its reliance on nuclear energy and enhancing its renewable energy infrastructure [99].

Advanced Monitoring and Openness to New Technologies
Taiwan has implemented advanced monitoring systems to ensure the safety and reliability of its energy transition process, particularly as it phases out nuclear energy and increases reliance on renewable sources. These systems are essential for detecting and addressing issues promptly, thereby minimizing risks associated with the transition. One notable example is Taipower's Longtan energy storage system, which is the largest government energy storage project in Taiwan [26]. With an installed capacity that supports nearly 8,000 households' daily electricity consumption, the Longtan project represents a significant milestone in Taiwan's net-zero transformation efforts. The advanced technology employed in this project, including safety measures throughout the system's lifecycle, demonstrates Taiwan's commitment to maintaining a reliable and secure power grid [42].

In addition to energy storage, Taiwan has also focused on integrating smart grid technologies and improving monitoring efforts to enhance grid stability and efficiency. The use of smart meters and advanced grid management software helps balance supply and demand, ensuring that renewable energy sources are effectively integrated into the national grid. These kinds of technologies enable real-time monitoring and predictive maintenance, reducing the likelihood of power outages and improving overall grid resilience. Notably, Fluence, a global leader in energy storage products and services, has partnered with local companies to deliver advanced energy storage solutions [42]. These partnerships enhance Taiwan's capability to deploy state-of-the-art monitoring systems that ensure the safe and efficient operation of renewable energy projects.

Public and private sector initiatives also play a crucial role in advancing monitoring capabilities. Events like the Energy Taiwan and Net-Zero Taiwan exhibition showcase the latest innovations in smart energy storage and monitoring technologies; bringing together industry experts, policymakers, and researchers to discuss and promote the adoption of advanced monitoring solutions.

4.4.2 | WEAKNESSES

Dependence on Imports
Taiwan's energy landscape is characterized by an almost total reliance on imports, with approximately 98% of its energy supply coming from overseas, including natural gas, oil, and coal. In 2021, natural gas imports accounted for a significant portion of this, with Taiwan being the world's fifth-largest importer of liquefied natural gas (LNG)[32]. As Taiwan phases out nuclear energy due to safety concerns and public opposition, its dependence on imported fossil fuels, particularly natural gas, is expected to increase significantly. This poses several risks to Taiwan's energy security due to its effect on Taiwan's vulnerability to fluctuations in global energy markets and potential supply disruptions.

Geopolitical tensions with China add another layer of complexity, as any conflict or blockade could severely disrupt Taiwan's energy imports, underscored with the fact that Taiwan has limited indigenous energy resources and no physical power interconnections with neighboring countries. This makes it highly dependent on stable and secure maritime trade routes for its energy supplies. In terms of its indigenous renewable energy, they have focused on bioenergy, mainly from rice residues and livestock manure, generating between 4.5 to 5.2 million metric tons of agricultural waste. The biomass is used to produce bioenergy, although it still represents a minor part of the overall energy mix [77].

Moreover, the high demand for LNG imports necessitates significant investments in infrastructure, including overcoming land acquisition challenges, regulatory approvals, and environmental impact assessments for the construction of new LNG terminals and storage facilities. The government has been actively pursuing the expansion of its LNG receiving and storage capacities to mitigate supply risks, with several major projects underway. To illustrate, the third-phase expansion at the Taichung LNG import terminal involves the construction of two 180,000 cubic meter LNG storage tanks, increasing the terminal's storage capacity to ensure a more stable energy supply for the region [1]. This expansion, with an expected 2026 completion, increases the terminal's import capacity from 5-6 million tons per year to 10 million tons per year. The engineering, procurement, and construction work for these storage tanks are being carried out by Bechtel, an American engineering conglomerate. In addition, a new LNG receiving facility is being constructed in Taoyuan's Guantang Industrial Park. According to the JFE Engineering Corporation, the project, expected to be finished by May 2025, includes building a 1.2 km offshore LNG unloading facility, seawater intake facility, and auxiliary facilities, and will cost approximately $220 million USDm.[66].

However, these projects face challenges, such as environmental concerns and local opposition, that could delay completion. Environmental concerns are a major issue; particularly in Taoyuan where the construction of the LNG terminal threatens 7,000-year-old coral reefs [12]. The opposition has resulted in delays and modifications to the project to mitigate environmental impact, such as moving the terminal farther offshore and eliminating land reclamation. Additionally, the LNG expansion in Taichung potentially impacts the white dolphin habitat. This opposition to LNG projects, along with bureaucratic delays in local government processes and environmental concerns, have caused the completion date for the terminal and related gas-fired units to be postponed from 2024 to 2025 [86]. In Keelung, the project is complicated by its location within the Keelung City Aquatic Plants and Animals Conservation Area, requiring careful coordination between the central and local governments to ensure compliance with environmental regulations.

The economic implications of this dependency are also noteworthy, as the rising global prices of natural gas, exacerbated by events such as the COVID-19 pandemic and the Russian invasion of Ukraine, have led to increased energy costs for Taiwan. The pandemic initially caused a sharp decline in energy prices due to reduced demand and as economies began to recover, demand surged, leading to higher prices. This was further exacerbated by the Russian invasion of Ukraine, which has caused significant disruptions in energy supplies due to Russia being a major global supplier of natural gas supply [93]. The resulting sanctions and supply chain disruptions, pushed energy prices even higher, directly impacting Taiwan's economy. Higher costs of natural gas have strained the nation's energy budget, leading to increased costs for both local businesses and consumers. This calls for substantial state expenditures on energy subsidies to manage the economic burden on consumers and industries, as well as careful management of energy policies to avoid further financial strain and ensure a stable supply. Increased dependence on imported fossil fuels, particularly natural gas, introduces significant energy security risks, and addressing this requires comprehensive strategies, such as increasing investments in renewable energy sources like solar and wind power, upgrading existing power plants for efficiency, and establishing strategic reserves to mitigate potential supply disruptions.

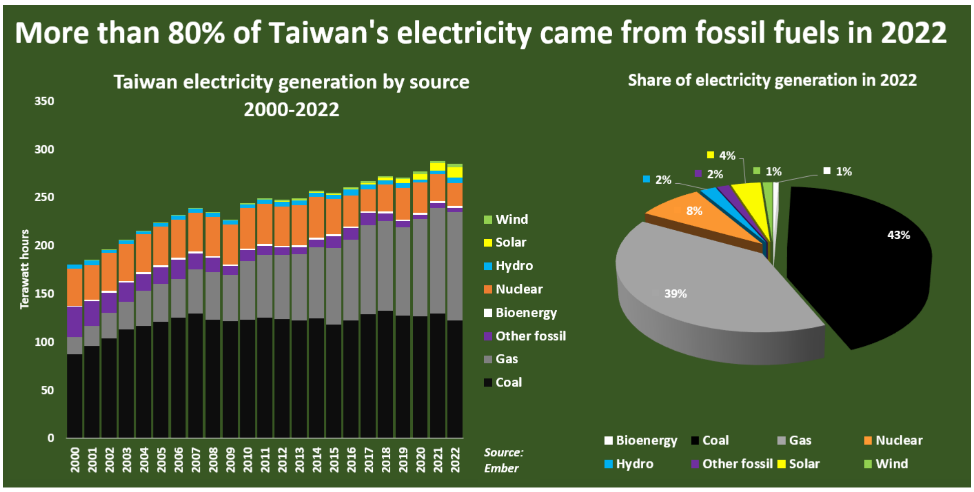

Figure 4.3: The composition of Taiwan's electricity generation sources from 2000 to 2022 [87]

Figure 4.3 illustrates the composition of Taiwan's electricity generation sources from 2000 to 2022, highlighting the predominant reliance on fossil fuels. In 2022, more than 80% of Taiwan's electricity came from fossil fuels, with coal and gas being the largest contributors, underscoring the urgent need for Taiwan to diversify its energy sources and reduce its dependence on imported fossil fuels to enhance energy security and sustainability.

Aging Infrastructure

Taiwan's existing energy infrastructure, particularly within the fossil fuel sector, is aging and poses significant challenges as the nation transitions to a nuclear-free energy system. Many of Taiwan's coal and natural gas plants were built decades ago and are reaching the end of their operational lifespans, which calls for substantial investments to ensure that the energy grid remains reliable and capable of integrating new, renewable energy sources. In particular, MOEA has plans to phase out nine aging coal-fired power plants by 2030, emphasizing the urgent need for infrastructure upgrades to maintain energy security [82].

Moreover, the integration of renewable energy sources, such as solar and wind power, into Taiwan's grid presents additional technical and logistical challenges. The existing grid infrastructure is not fully equipped to handle the intermittent nature of renewable energy, necessitating significant upgrades to ensure grid stability and efficiency. This includes the development of advanced energy storage solutions and smart grid technologies to manage fluctuations in power generation and consumption [71]. For example, the government is investing in large-scale energy storage systems and enhancing grid management software to improve the reliability of renewable energy integration.

Investments in infrastructure are also essential to address the increasing frequency of blackouts and power outages, which have been linked to defects in transmission lines and transformers [6]. Upgrading these components is critical to preventing disruptions and ensuring a consistent energy supply as Taiwan phases out its nuclear power plants. The need for infrastructure improvements is further highlighted by the ongoing political and public debates over energy policy, which stress the importance of maintaining energy security while transitioning to more sustainable energy sources.

The nuclear phaseout and the increased reliance on natural gas require a comprehensive strategy that includes modernizing existing infrastructure, accelerating the deployment of renewable energy sources such as wind and solar, enhancing energy storage solutions like advanced batteries and pumped hydro storage, improving energy efficiency through smart grids and building retrofits, diversifying LNG supply sources, and implementing supportive policies and incentives for clean energy investments [13]. With that being said, Taiwan's aging energy infrastructure requires significant investments and upgrades to support the transition to a nuclear-free and renewable energy-dominated system.

Integration Issues

Integrating a high proportion of intermittent renewable energy sources into Taiwan's existing grid poses significant technical challenges. The changing and unpredictable nature of renewable energy sources like solar and wind can cause problems for the grid, requiring advanced solutions for managing and storing energy to maintain reliability. As stated by McGillis [89], as Taiwan increases its share of renewable energy, it becomes crucial to have strong grid infrastructure and innovative technologies to support the growth and ensure a reliable energy supply. If renewable energy sources are not integrated correctly into the grid, it may have difficulty managing changes in energy supply and demand, which could result in blackouts or system failures. Implementing smart grid technologies and investing in energy storage systems can help mitigate these risks and ensure a smooth transition to a more sustainable energy future.

Ensuring grid stability in the face of fluctuating output from renewable energy sources is a crucial technical challenge in integration. Traditional power grids rely on stable output from fossil fuels and nuclear plants, while renewable sources like solar and wind can fluctuate greatly depending on the weather conditions. These changes in renewable energy output can lead to voltage and frequency variations, potentially causing grid instability and blackouts. Taiwan has experienced several high-profile power outages in recent years, highlighting the vulnerabilities and limitations of current power infrastructure [82]. They expose critical weaknesses in the grid, such as its inability to withstand and recover quickly from disruptions caused by severe weather, equipment failures, and other external factors. To address these challenges, Taiwan is investing in advanced grid management solutions and energy storage systems, such as the Longtan energy storage project, to address the challenges of integrating renewable energy sources. For instance, large-scale energy storage systems, like the Longtan energy storage project with a capacity of 60 MW / 80 MWh, help maintain a balance between energy supply and demand by storing extra energy produced during peak times and releasing it when needed [26]. These storage solutions play a crucial role in mitigating the impact of renewable energy intermittency on the grid. Furthermore, integrating smart grid technologies significantly enhances the grid's capacity to effectively manage renewable energy sources because they utilize advanced sensors, communication networks, and data analytics to monitor and control the flow of electricity in real time [8]. This allows for more efficient energy distribution, reduces losses, and improves the overall reliability of the power system.

Despite the progress made in integrating renewable energy, there are still ongoing challenges that must be addressed. The process of connecting new renewable energy sources to the grid is often hampered by outdated grid planning tools, insufficient digitization, and complex regulatory requirements. To improve efficiency, Taiwan should use comprehensive grid planning methods that include advanced analysis and modeling to better manage the grid, such as prioritize grid upgrades, and improve the connection process for renewable energy projects.

Economic Implications

The phase-out of nuclear energy in Taiwan is likely to have significant economic implications, particularly during the transition period. One of the primary concerns during the transition period is the potential increase in energy costs, as natural gas and renewables often come with higher initial costs. Natural gas, which is expected to play a larger role in Taiwan's energy mix, is subject to global market fluctuations, leading to volatile prices that can increase overall energy costs for both industries and consumers [119]. The increased reliance on imported natural gas not only exposes Taiwan to price volatility, but also calls for substantial investments in infrastructure. The development of new LNG terminals and the modernization of existing facilities are essential to handle the increased import volumes. These infrastructure projects require significant capital, which can strain public finances and potentially lead to higher energy prices to cover the costs [13].

Energy-intensive industries, such as manufacturing, chemicals, metals, and paper production, are particularly vulnerable to rising energy costs. Higher operational costs in these sectors can result in either higher prices for consumers or reduced profit margins for businesses, which reduce their global competitiveness and potentially lead to economic disruptions. This economic pressure could lead to job losses or slowdowns in industrial growth if not managed effectively [80]. Additionally, the broader economic implications of the nuclear phase-out encompass the costs associated with transitioning to renewable energy sources. While renewable energy is a key component of Taiwan's long-term energy strategy, the initial investment in renewable infrastructure, such as wind and solar power plants, is high. In terms of initial investment for onshore wind projects, the cost includes various components such as turbines, which account for approximately 64% of the total investment costs. The balance of system, which includes infrastructure like foundations, grid connection, and other electrical components, represents about 18%, while construction and installation costs make up the remaining 18%. Moreover, integrating these intermittent energy sources into the existing grid requires advanced technology and storage solutions, further adding to the costs [129].

To mitigate these economic challenges, the Taiwanese government has implemented various policies and subsidies aimed at supporting the transition, as mentioned previously. However, balancing the financial burden of these subsidies while ensuring affordable energy for consumers remains a complex issue. The government's efforts to stabilize domestic fuel prices by capping price changes and absorbing additional costs during high oil price periods demonstrate a commitment to managing energy costs, while also highlighting the financial strain of maintaining such policies over the long term [56]. In closing, the phase-out of nuclear energy in Taiwan is expected to result in higher energy costs during the transition period, affecting both industries through increased operational costs and consumers through potentially higher prices. Ensuring that the transition supports long-term energy security and economic stability demands meticulous management and strategic investments.

Public Perception and Mistrust

Despite overall support for Taiwan's nuclear phase-out policy, significant segments of the population and various stakeholders harbor mistrust regarding the government's ability to manage the transition effectively. This mistrust arises from previous occurrences of power outages, dissemination of misinformation, and perceived shortcomings in energy policy administration. As Taiwan has faced several blackouts, people are now more worried about the power supply's reliability as they switch to renewable energy sources [84]. A notable case of public mistrust involves the Tao indigenous community on Orchid Island (Lanyu), where a nuclear waste storage facility, established in the 1980s, was initially misrepresented. Initially, government officials deceived the Tao people by falsely claiming that the facility was intended for a seafood canning factory. The truth was later revealed, causing deep mistrust and resentment among the Tao, who view the facility as a symbol of governmental deception and environmental injustice [114]. This incident illustrates the broader skepticism towards the government's energy policies, particularly regarding nuclear waste management.

In general, public skepticism is driven by historical parallels where government actions did not prioritize public interest or safety, resulting in an ongoing call for enhanced transparency and accountability in energy policy choices. For example, in Fukushima, Japan, the government's mishandling of the 2011 nuclear disaster led to widespread distrust in official statements and policies regarding nuclear energy [45]. This has led to grassroots movements advocating for increased community participation in decisions about nuclear waste disposal and energy production. A respondent from the survey echoed these sentiments, stating, "Taiwan does not have the ability to properly handle the nuclear waste. What the government did was storing the waste in an island where an aboriginal tribe calls home and IGNORE their opinions. We should not produce any more nuclear waste until a reasonable solution is found."

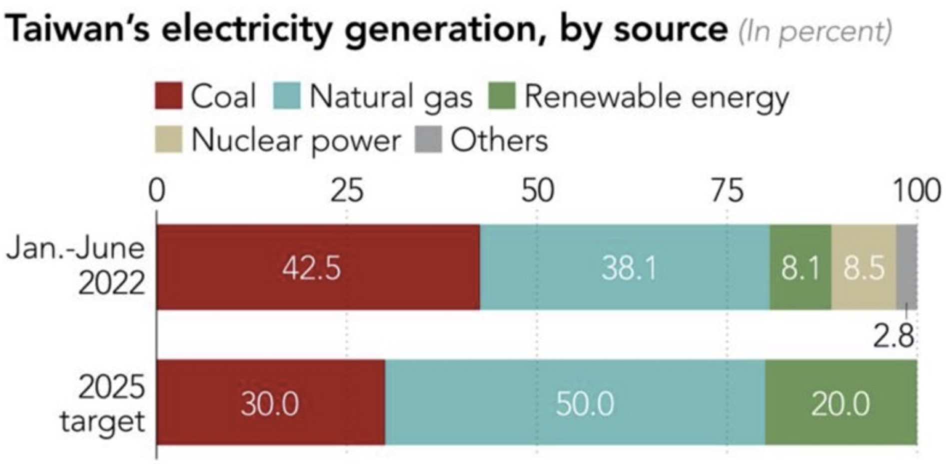

Figure 4.4: Electricity Generation by Energy Form, Bureau of Energy, MOEA[87].

Current energy security concerns further amplify this mistrust. Moving away from nuclear energy increases Taiwan's dependency on imported fossil fuels, particularly natural gas, which is subject to global market fluctuations and geopolitical risks. As you can see in Figure 4.4, Taiwan expects to decrease its reliance on coal and nuclear energy by a reduction of approximately 29.4% and 100%, respectively. This transition is a component of a larger plan to boost the utilization of natural gas and renewable energy, with natural gas expected to increase by about 31.2% and renewable energy by approximately 146.9%. Business leaders and energy experts have questioned the feasibility of achieving a stable energy transition without compromising energy security, emphasizing the need for robust and reliable infrastructure [80]. According to Chou Kuei-tien, a professor at National Taiwan University, "The most immediate issue for Taiwan is not whether there is enough electricity, but the stability of power supplies" [81]. His statement emphasizes the vital need to improve Taiwan's energy infrastructure to support the transition to renewable energy sources.

Political dynamics also play a significant role in shaping public perception regarding Taiwan's energy policies. The Democratic Progressive Party (DPP) has been a strong advocate for phasing out nuclear energy, aligning with its broader environmental and public safety goals, such as reducing carbon emissions and ensuring public safety. However, this policy has faced substantial criticism from the opposition Kuomintang (KMT) party. The KMT argues that phasing out nuclear energy is based on ideology and may lead to increased energy costs and economic instability. The 2024 KMT presidential candidate Hou Yu-ih has expressed plans to restart Taiwan's decommissioned nuclear plants and extend the lifespan of the remaining operational facility if elected, aiming to ensure energy stability and reduce reliance on imported energy sources. Hou believes that nuclear power is crucial for cutting carbon emissions and air pollution, playing a vital role in Taiwan's shift to renewable energy. He emphasized that ensuring energy security and a stable supply are paramount for national security, given Taiwan's high energy consumption driven by its semiconductor industry, as reported by Taiwan News [43]. Ko Wen-je, another 2024 presidential candidate, has also criticized the DPP's nuclear phase-out policy, suggesting that it is ideologically motivated and could alienate corporate supporters, leading to potential economic challenges and opposition from key industry players. Ko advocates for a more pragmatic approach, focusing on the steady development of renewable energy while maintaining nuclear power as a transitional measure to ensure energy stability and meet the government's net-zero emissions goal by 2050 [113]. Political debates and differing views on energy policy have increased public worries and doubts about the government's ability to handle the energy transition effectively.

To address these concerns, transparent communication and proactive stakeholder engagement are crucial. The government must provide clear, consistent information about steps to ensure energy security and economic stability during the transition. This includes detailing how renewable energy projects will be integrated into the grid and the measures to prevent further power outages. Involving a diverse group of stakeholders, including industry leaders, local communities, and environmental groups, in decision-making is vital for building trust and gaining support for the transition [13]. In conclusion, addressing public mistrust and concerns through transparent communication, inclusive stakeholder engagement, and concrete actions is essential for the successful implementation of Taiwan's nuclear phase-out policy. The government must learn from past mistakes, such as the Tao community incident, and ensure that all segments of the population are informed and engaged in the transition process.

4.4.3 | Opportunities

Energy Diversification

The phase-out of nuclear energy presents a significant opportunity for Taiwan to diversify its energy mix, thereby enhancing both its energy security through reduced dependence on single sources and its resilience against energy supply disruptions. By investing in a range of renewable energy sources, Taiwan can reduce its reliance on any single energy source and mitigate the risks associated with energy supply disruptions. Diversifying the energy portfolio is crucial for ensuring a stable and sustainable energy future for the island nation, as it reduces vulnerability to price fluctuations in specific energy sources and promotes long-term environmental health.

Taiwan has already set ambitious targets for renewable energy as part of its broader energy transition strategy. The government aims to generate 20% of its electricity from renewables by 2025, which translates to approximately 27 gigawatts of installed capacity [120]). This includes significant investments in solar and wind power, which are expected to be the primary drivers of Taiwan's renewable energy growth. For example, Taiwan plans to deploy 20 gigawatts of solar photovoltaic (PV) capacity, with a mix of rooftop and ground-mounted systems, and to expand its offshore wind capacity significantly [118]. Furthermore, the diversification strategy is not limited to solar and wind power. Taiwan is also exploring other renewable energy sources, such as biomass, geothermal, and hydroelectric power. These diversified sources can provide a more balanced energy mix and enhance grid stability. Taiwan's Green Energy Diversification Strategy, showcased at international forums like COP28, highlights the country's commitment to expanding its renewable energy portfolio and integrating various green technologies to achieve its sustainability goals [54].

In addition to enhancing energy security, investing in renewable energy creates economic opportunities. The development of renewable energy infrastructure can drive job creation, stimulate local economies, and attract foreign investment. For instance, the growing renewable energy sector has already attracted significant investments from international companies, boosting Taiwan's economy and fostering technological innovation. Collaborations with countries like Vietnam in the renewable energy sector also present opportunities for knowledge exchange and economic growth [118].

Moreover, Taiwan's carbon credit system incentivizes organizations to reduce their carbon footprint by rewarding them with credits that can be traded on the Taiwan Carbon Solution Exchange (TCX). This system encourages companies to adopt greener practices by offering incentives, such as tax benefits, for investing in low-carbon technologies, ultimately contributing to the nation's net-zero goals. For example, enterprises like Chimei near Tainan and APH ePower have been actively participating in carbon reduction projects, benefiting from the economic incentives provided by the carbon credit system [103] [9]. This approach not only promotes environmental sustainability, but also helps businesses improve their competitiveness in global markets.

International Collaboration and Learning

At the heart of international collaboration and learning is the exchange of ideas, knowledge, and experiences among individuals from different cultures and backgrounds, allowing for a rich tapestry of perspectives to come together to tackle global challenges and foster innovation. Through shared learning experiences, individuals can expand their horizons, deepen their understanding of different cultures, and ultimately work towards a more interconnected world. Additionally, this collaboration will offer Taiwan significant opportunities to enhance its renewable energy sector by adopting best practices and technologies from successful renewable energy transition countries. This collaboration can accelerate Taiwan's energy transition and enhance its technological capabilities.

Taiwan has been actively participating in international conferences and forums to foster collaborations in renewable energy. For instance, the 2023 UK–Taiwan Renewable Energy Conference highlighted the partnership between the UK and Taiwan, particularly in the offshore wind sector. This conference facilitated discussions on global renewable energy trends, shared capabilities, and best practices in floating wind development and operations. The UK, being a leader in offshore wind technology, provided valuable insights that can help Taiwan develop its offshore wind industry more efficiently [14]. Moreover, Taiwan's Ministry of Economic Affairs (MOEA) has played a crucial role in organizing events such as the Taiwan International Geothermal Conference (TIGC). This conference brings together international experts and industry leaders to discuss the latest geothermal technologies and market trends. Such events not only promote knowledge exchange but also enable Taiwanese stakeholders to form partnerships with international firms, enhancing the country's capabilities in geothermal energy development [17].

In addition to these efforts, Taiwan's Nuclear Safety Commission plays a crucial role in ensuring the safe transition from nuclear to renewable energy. The NSC collaborates extensively with international nuclear regulatory bodies such as the International Atomic Energy Agency (IAEA). Through these collaborations, Taiwan adopts advanced safety protocols and technologies to manage the decommissioning of nuclear facilities effectively and to integrate renewable energy into the national grid. One notable example of this collaboration is the participation of Taiwan in the IAEA's Integrated Regulatory Review Service (IRRS), which provides comprehensive assessments of national regulatory frameworks and practices for nuclear and radiation safety. These reviews help Taiwan in aligning its safety standards with international best practices, thereby enhancing its regulatory oversight and safety management capabilities. By collaborating with international nuclear regulatory bodies and learning from their experiences, Taiwan can adopt advanced safety protocols and technologies. This collaboration, as reported by the US-Taiwan Business Council in 2023, ensures that the decommissioning of nuclear facilities is conducted safely while integrating renewable energy into the national grid [120].

Moreover, international collaborations extend beyond conferences and regulatory bodies. Companies like Taipower have partnered with international firms such as Reactive Technologies to implement advanced grid stability measurement systems. These systems provide real-time insights into the stability of Taiwan's power grid, enabling better management of renewable energy sources and ensuring a reliable electricity supply [14]. The effectiveness of their grid stability measurement systems is evident through specific statistics and implementations. For instance, Taipower utilizes Reactive Technologies' GridMetrix platform, which enhances visibility and management of grid inertia [34]. It provides real-time data and insights, helping to integrate non-synchronous renewable energy sources. One significant implementation is the 60MW/96MWh DongShan battery energy storage system, designed to maintain system stability by providing essential modulation signals. These kinds of advancements are crucial for Taiwan's goal of reaching net-zero emissions by 2050, supporting grid resilience and stability. By leveraging global expertise and forming strategic partnerships, Taiwan can overcome technical and regulatory challenges, accelerate the development of its renewable energy sector, and ensure a sustainable and resilient energy future.

Technological Innovation

The push towards renewable energy is driving significant technological innovation in Taiwan, positioning it as a potential leader in the global energy transition. Investments in research and development (R&D) are crucial for achieving breakthroughs such as enhancing energy storage capacity, improving grid stability, and advancing renewable energy technologies, all vital for a sustainable energy future.

Taiwan is actively promoting technological advancements through initiatives like the Energy Taiwan and Net-Zero Taiwan exhibitions. These events showcase the latest innovations and collaboration opportunities in renewable energy, focusing on a wide range of technologies including solar power, wind power, energy storage, as well as emerging energy sources like hydrogen and marine energy. By fostering an environment that encourages innovation, Taiwan aims to accelerate the development and deployment of cutting-edge technologies that improve energy efficiency, reduce environmental impact, and foster sustainability, creating a conducive ecosystem for technological advancements [99].

Research and development in energy storage technologies are particularly important for Taiwan's renewable energy goals. Advanced energy storage systems are needed to address the intermittent nature of renewable energy sources like solar and wind. Taiwan is investing in large-scale battery storage solutions and exploring innovative technologies such as pumped hydro storage and grid-scale batteries. These investments are critical for ensuring grid stability and reliability by optimizing energy distribution and facilitating a seamless integration of renewables into the energy mix [64].

One prominent example of technological innovation in Taiwan is APh ePower, a company specializing in the development and commercialization of aluminum-ion batteries. Established in 2018, APh ePower has focused on creating safe, fast-charging, and environmentally friendly aluminum batteries that can be used for both energy storage and electric vehicles. The company's aluminum batteries offer significant advantages over traditional lithium-ion batteries, including quicker charging times, enhanced safety, and better environmental performance. These batteries are suitable for various applications, including power generation, grid systems, and electric scooters, making them a versatile solution for Taiwan's energy needs [7].

Furthermore, APh ePower's collaboration with Sanyang Motor (SYM) highlights how joint efforts in developing innovative battery technology can drive economic growth, create job opportunities, and enhance sustainability. SYM's investment in APh ePower has facilitated the construction of a second-generation aluminum battery plant in Kaohsiung Science Park, aiming for mass production by 2025. This partnership not only strengthens Taiwan's domestic battery technology capabilities but also positions the country to compete internationally in the electric vehicle market [7]. To sum up, Taiwan's strategy to switch to renewable energy heavily relies on technological innovation. Through substantial investments in R&D, supportive government policies, and international collaboration, Taiwan will be well-positioned to lead in the global energy transition.

Global Market Trends

Global trends towards sustainability and decarbonization align well with Taiwan's nuclear phase-out policy, offering significant economic and strategic benefits. The global market for decarbonization is expanding rapidly, driven by increasing regulatory pressures, technological advancements, and shifting consumer preferences towards sustainable practices. For instance, the global decarbonization market, which was valued at approximately USD 1.68 trillion in 2022, is expected to grow at a compound annual growth rate (CAGR) of 11.6% from 2023 to 2030 [52]. This growth is fueled by investments in renewable energy technologies, energy efficiency measures, and carbon capture and storage solutions. Embracing these trends allows Taiwan to attract international investments and form valuable partnerships, thereby supporting its energy transition and enhancing its global economic position.

Taiwan's strategic geographical location and existing infrastructure make it uniquely positioned to benefit from these global trends and attract significant foreign investments. The U.S. Inflation Reduction Act, for example, has been a catalyst for increased investments in renewable energy and related technologies, providing a model that Taiwan can leverage to enhance its own policy frameworks [100]. By adopting long-term tax credits, securing substantial financial investments, and promoting advanced energy storage and grid modernization, Taiwan can create a stable and attractive environment for renewable energy development, mirroring the successes seen in the U.S.. Additionally, Taiwan's participation in global sustainability initiatives and adherence to international environmental standards can make it a more attractive destination for green investments. The global focus on renewable energy, particularly solar and wind power, presents opportunities for Taiwan to expand its renewable energy capacity. According to McKinsey's Global Energy Perspective 2023, the global demand for lithium-ion batteries and other renewable technologies is expected to soar, driven by the increasing adoption of electric vehicles and renewable energy storage solutions [30]. Taiwan's efforts to build a robust renewable energy infrastructure, including advanced energy storage systems and smart grid technologies, align with these global trends and can attract international technology partnerships and funding.

Moreover, the emphasis on sustainable finance and green bonds is reshaping global capital markets. Sustainable finance mechanisms, such as green bonds and sustainability-linked loans, provide new avenues for funding large-scale renewable energy projects. In 2023, the global issuance of green bonds was projected to exceed USD 900 billion, reflecting the growing investor demand for sustainable investments [27]. These mechanisms ensure that capital is directed towards environmentally beneficial projects and incentivize companies to improve their sustainability practices, thereby accelerating the global transition to a low-carbon economy and fostering sustainable development. By tapping into these financial instruments, Taiwan can secure the necessary capital to accelerate its energy transition and achieve its sustainability goals. By embracing these global market trends in sustainability and decarbonization, Taiwan can attract international investments, foster innovation in renewable energy technologies, and enhance its global competitiveness in the green economy.

Environmental Benefits

Transitioning away from nuclear energy and increasing the use of renewable energy sources offer substantial environmental benefits for Taiwan. One of the most significant advantages is the substantial reduction of greenhouse gas emissions, which is crucial for mitigating climate change on a global scale. By decreasing reliance on fossil fuels and nuclear power, Taiwan can significantly lower its carbon footprint. This shift aligns with the broader global decarbonization efforts and helps Taiwan contribute to the goals outlined in international agreements such as the Paris Agreement [33].

Renewable energy sources like solar, wind, and biomass are pivotal in reducing harmful emissions. For instance, solar and wind energy produce no direct emissions during operation, which drastically cuts down the overall greenhouse gases compared to traditional coal or gas-fired power plants. This reduction is crucial as it plays a vital role in mitigating climate change and its associated impacts, including but not limited to rising sea levels, extreme weather events, and biodiversity loss. Taiwan's commitment to increasing its renewable energy capacity, targeting 20% of its power from renewables by 2025, is a significant step towards a cleaner and more sustainable energy system, according to Google Sustainability.[51].

Moreover, the environmental benefits extend to improved air quality. Fossil fuel combustion is a major source of air pollutants like particulate matter, sulfur dioxide, and nitrogen oxides, which are linked to respiratory and cardiovascular diseases. Transitioning to renewable energy reduces these pollutants, leading to better public health outcomes. This shift can decrease the incidence of asthma, heart attacks, and other health issues related to poor air quality, thereby improving the overall quality of life for Taiwan's residents [33].

Investing in renewable energy also supports environmental conservation by reducing the need for resource extraction and minimizing ecological disruption. Renewable energy projects often have smaller environmental footprints compared to fossil fuel extraction and nuclear waste disposal. For example, offshore wind farms and solar panels can be integrated into existing land and marine environments with minimal ecological impact, preserving natural habitats and biodiversity. Taiwan's initiatives to expand its offshore wind capacity and develop solar energy projects highlight its commitment to sustainable environmental practices. In conclusion, the shift to renewable energy in Taiwan provides various environmental benefits, such as substantial reductions in greenhouse gas emissions and enhancements in air quality. These benefits play a crucial role in supporting global climate change mitigation efforts and improving local public health outcomes. By continuing to invest in and develop renewable energy technologies, Taiwan can lead by example in creating a sustainable and resilient energy future.

4.4.4 | Threats

Natural Disasters

Taiwan is highly susceptible to natural disasters such as earthquakes, typhoons, and heavy rainfall, which pose significant threats to its energy infrastructure. Ensuring the resilience of renewable energy systems against these events is a critical challenge. Natural disasters can result in extensive destruction of energy infrastructure, resulting in prolonged power outages and heightened carbon emissions as backup power systems are utilized. This vulnerability underscores the need for robust disaster risk management strategies to safeguard Taiwan's energy security and sustainability.

One of the primary concerns is the impact of earthquakes on Taiwan's energy grid. Taiwan is located on the Pacific Ring of Fire, making it prone to frequent and severe seismic activity. Earthquakes can damage power plants, transmission lines, and substations, disrupting the supply of electricity. For instance, the 1999 Chi-Chi earthquake caused widespread damage to Taiwan's energy infrastructure, highlighting the vulnerability of the grid to seismic events [4]. This earthquake, which measured 7.6 in magnitude, killed 2,415 people, injured 11,305, caused NT$300 billion worth of damage, and left an estimated 100,000 people homeless [101]. Enhancing the earthquake resilience of renewable energy installations, such as solar panels and wind turbines, is essential to minimize disruption and ensure a stable energy supply. Investing in seismic-resistant technologies and construction practices can significantly reduce the risk of damage from earthquakes.

In addition to earthquakes, typhoons and heavy rainfall pose significant risks to Taiwan's renewable energy infrastructure. Typhoons, which frequently hit Taiwan, can damage offshore wind farms and solar arrays, reducing their efficiency and causing extensive outages. For example, during Typhoon In-Fa in 2021, Taiwan experienced heavy rainfall and strong winds that impacted energy infrastructure, leading to localized flooding and damage to renewable energy installations. The storm's impact caused disruptions that underscored the need for robust design and construction standards to withstand such extreme weather conditions [39]. Implementing advanced materials and construction techniques to improve the durability of renewable energy systems is a proactive measure that can mitigate the impact of natural disasters.

Moreover, natural disasters can indirectly increase carbon emissions by disrupting low-carbon power generation and necessitating the use of high-carbon backup power sources. For example, when renewable energy systems are damaged or offline due to natural disasters, there is often an increased reliance on diesel generators and other fossil fuel-based backup systems to maintain power supply. This shift can lead to a temporary spike in carbon emissions, counteracting the environmental benefits of renewable energy [4]. Hence, developing strategies to decrease reliance on fossil fuels in emergencies, like enhancing battery storage capacity and implementing independent microgrids during disruptions, is imperative.

To address these challenges, Taiwan needs to develop and implement comprehensive disaster risk management strategies for its renewable energy infrastructure. This includes investing in resilient infrastructure, adopting advanced technologies for disaster prediction and response, and integrating disaster preparedness into energy planning. For instance, the use of smart grid technologies and decentralized energy systems can enhance the resilience of the energy network by allowing for more flexible and rapid responses to disruptions [65]. These measures can significantly improve the ability of Taiwan's energy infrastructure to withstand and recover from natural disasters, ensuring continuous power supply and reducing economic losses.

In conclusion, while natural disasters pose significant threats to Taiwan's renewable energy infrastructure, proactive measures can mitigate these risks. By investing in resilient infrastructure, adopting advanced technologies, and integrating disaster preparedness into energy planning, Taiwan can enhance the durability and reliability of its renewable energy systems. This approach will guarantee a stable and sustainable energy supply in the presence of natural disasters, thereby advancing Taiwan's long-term energy security and environmental objectives.

Political Fluctuations

Changes in political leadership and policies pose significant risks to the continuity and effectiveness of Taiwan's nuclear phase-out strategy. Political instability or shifts in policy priorities can disrupt long-term energy transition plans, affecting both domestic and international confidence in Taiwan's energy policies. The DPP, which aims for a "nuclear-free homeland" by 2025, meets opposition from parties, such as the KMT and the Taiwan People's Party (TPP), which have different views on energy policy. Notably, the KMT has been more open to maintaining or even expanding nuclear energy to ensure energy security and stability. The fluctuations have also impacted the implementation of critical energy policies. For example, laws like the Renewable Energy Development Act and the Climate Change Response Act, introduced under the DPP administration, have faced varying levels of support and criticism from different political factions. This divergence in energy policy priorities among major political parties creates uncertainty about the future direction of Taiwan's energy strategy and could result in the rollback or alteration of these policies, potentially stalling progress in renewable energy development and carbon reduction efforts [78]. Such shifts could increase the financial burden on stakeholders and complicate the regulatory environment for renewable energy investments [39].

The escalating geopolitical instability, especially the frequent military incursions by China into Taiwan's airspace, has heightened concerns about the security and stability of supply chains critical for Taiwan's renewable energy sector. According to The Diplomat, any conflict or blockade could severely disrupt the flow of essential components for solar panels and wind turbines, which are predominantly manufactured in China [110] [10]. In this context, maintaining a consistent and clear energy policy becomes even more critical to reassure both local and international stakeholders [68]. Moreover, the strategic significance of Taiwan in the global semiconductor supply chain exacerbates these risks. Taiwan's dominant position in semiconductor manufacturing means that any geopolitical tension or conflict could have far-reaching consequences not just for Taiwan but for global technology supply chains. The potential for such disruptions underscores the importance of diversifying supply sources and enhancing local production capacities to mitigate risks.

In addition, the global response to geopolitical events, such as sanctions imposed on Russia, can also indirectly affect Taiwan's energy security. For instance, the sanctions on Russia have led to a significant impact on energy prices and supply chains. Specifically, the price of Brent crude oil surged from $92 per barrel in February 2022 to $128 per barrel at its peak, causing a ripple effect on global markets. Taiwan, which imports a substantial portion of its energy from abroad, saw similar trends in its energy import costs and industrial production indices during this period [18]. The sanctions can serve can as a potential blueprint for how similar measures could be applied in the case of Taiwan-China tensions.

However, such sanctions could further strain the supply chains for renewable energy equipment, as countries might seek to reduce their dependency on Chinese manufacturing amid rising geopolitical risks, emphasizing the need for strategic planning to mitigate such risks. Robust, bipartisan supported energy transition strategies are essential in mitigating these risks. Building a consensus on the importance of renewable energy and energy security across political lines can help ensure that energy policies remain stable and effective, regardless of changes in political leadership. Additionally, engaging with international partners and leveraging global best practices can provide further stability and support for Taiwan's energy transition.

Economic Burdens

The economic costs associated with decommissioning nuclear plants, upgrading infrastructure, and investing in new energy technologies can be substantial for Taiwan. Balancing these costs with economic growth and affordability for consumers presents a significant challenge. The process of decommissioning nuclear power plants is costly and intricate, encompassing tasks such as dismantling reactors, handling radioactive waste, and ensuring environmental safety. For instance, the decommissioning of Taiwan's Chinshan Nuclear Power Plant is expected to take up to 25 years and requires significant financial resources and technical expertise [29]. This prolonged and costly process highlights the extensive financial commitments needed to safely transition away from nuclear energy.

The cost of decommissioning nuclear plants, ranging from $500 million to $2 billion per reactor, is influenced by factors such as reactor size, type, contamination levels, and necessary safety measures [92]. In Taiwan, the decommissioning of six reactors at the Chinshan, Kuosheng, and Maanshan plants underscores the substantial financial commitment required. These costs are further exacerbated by the need to upgrade existing energy infrastructure to accommodate the transition to renewable energy sources. This includes enhancing grid capacity, integrating smart grid technologies, and developing energy storage solutions to ensure a reliable energy supply [124]. Taiwan has already allocated significant resources to these upgrades, with estimates from Taiwan Power Company indicating that modernizing the grid and integrating renewable energy could cost upwards of NT$300 billion (approximately $10 billion USD) by 2025.

In addition to the direct costs of decommissioning and infrastructure upgrades, there are also economic implications for energy consumers. Transitioning to renewable energy sources often involves higher initial costs due to investments in new infrastructure, technology, and energy storage, which can subsequently lead to increased electricity prices for consumers. Managing these costs while ensuring affordability is crucial for maintaining public support for the energy transition. The Taiwanese government has implemented policies to stabilize domestic fuel prices and absorb additional costs, but these measures place additional strain on public finances [68]. Electricity prices in Taiwan have been among the lowest in Asia, but the transition to renewables is expected to drive prices up by as much as 20% over the next decade, potentially increasing the financial burden on households and businesses.

Investing in new energy technologies is essential for Taiwan's long-term energy strategy, but it also requires substantial financial resources. Research and development (R&D) in renewable energy technologies, including advanced energy storage systems and smart grid technologies, are essential for enhancing energy efficiency and ensuring grid stability. These investments are critical for achieving Taiwan's renewable energy targets and reducing greenhouse gas emissions, but they also represent a significant economic burden [78]. Taiwan plans to invest NT$900 billion (approximately $30 billion USD) in renewable energy development by 2030, as indicated by the Ministry of Economic Affairs [107], highlighting the substantial financial commitment required to meet its energy transition goals.

To mitigate these economic burdens, Taiwan needs to actively explore various funding mechanisms, including green bonds and international financing opportunities. Utilizing sustainable finance instruments can provide the necessary capital to support large-scale renewable energy projects and infrastructure upgrades, addressing the financial requirements for sustainable development. Additionally, international collaboration and partnerships can bring in technological expertise and financial resources, further alleviating the economic pressures associated with the energy transition [70]. For instance, Taiwan has already secured NT$20 billion (approximately $615 million USD) in green bonds to fund its solar and wind energy projects, demonstrating the potential of these instruments to support the energy transition [23]. Balancing these costs with economic growth and affordability for consumers is a significant challenge that requires strategic planning, innovative funding mechanisms, and international cooperation to ensure a successful and sustainable energy future.

International Pressure

Geopolitical tensions and international pressure, particularly from countries like Russia and Saudi Arabia, significantly influence Taiwan's energy policy decisions. Navigating these pressures while maintaining energy security and sovereignty presents a complex challenge. Taiwan's geopolitical situation, particularly its tense relationship with China, plays a crucial role in shaping its energy policy. For example, China's military drills in the Taiwan Strait and economic sanctions in response to Taiwan's political decisions can disrupt energy supply chains, increasing the island's vulnerability to external pressures [110]. Historical data shows that such disruptions, occurring during periods of heightened tensions in the past decade, have led to a 15% spike in energy prices and a 10% drop in supply reliability.

With approximately 97% of Taiwan's energy needs being met through imports, the nation is highly susceptible to global market fluctuations and geopolitical risks. For instance, the recent global energy crisis, exacerbated by the Russia-Ukraine war, led to a 25% increase in energy prices and significant supply chain disruptions, impacting Taiwan's energy security [56]. This crisis resulted in an estimated global economic loss of $2.7 trillion annually, calculated based on disruptions in energy supply chains, with specific sectors like manufacturing and services experiencing price increases of up to 3.15% [126]. Taiwan's reliance on imports from countries like Australia, Qatar, and the United States for natural gas underscores the need for a diversified and resilient energy strategy. In the paper by Yagi and Managi (2023) [126], they found that the geopolitical tensions have highlighted the island's vulnerability, as sanctions on Russia and the redirection of its energy exports to markets like China have further strained global energy supplies.

The political landscape in Taiwan further complicates energy policy decisions. The DPP has committed to phasing out nuclear energy by 2025 and increasing the share of renewables to prioritize environmental sustainability and reduce dependence on non-renewable sources. However, opposition parties like the KMT advocate for a more balanced energy mix that includes nuclear power to ensure energy security, citing nuclear energy's reliability and continuous power generation capabilities. The upcoming elections in 2024 could lead to shifts in energy policy, potentially altering Taiwan's approach to energy security and sustainability [127].

Internationally, Taiwan faces pressure from major energy-exporting countries like Russia and global regulatory frameworks such as the Kyoto Protocol and Paris Agreement. For example, the implementation of carbon tariffs and stricter environmental regulations by the European Union and other major markets influence Taiwan's energy policies. These international pressures necessitate a careful balance between meeting global environmental standards and ensuring economic competitiveness. The European Union's carbon tariffs alone could cost Taiwan's export industries up to $2 billion annually if compliance is not met [82]. Taiwan's legislative efforts, such as the Climate Change Response Act, aim to align with international climate goals, but require robust and consistent policy implementation to be effective. Addressing these challenges requires a strategic approach that ensures energy security, supports economic growth, and maintains sovereignty. To ensure a sustainable energy future, Taiwan can diversify its energy sources, invest in renewable technologies, and foster international collaborations.

4.5 | Comparison with Global Trends

Taiwan's energy transition mirrors a broader global shift towards sustainable and resilient energy systems. Many developed nations are working to reduce their reliance on fossil fuels and increase the share of renewable energy in their energy mixes. This section compares Taiwan's energy policies and progress with global trends, highlighting similarities, differences, and unique challenges faced by Taiwan.

Globally, there has been a significant push towards renewable energy as countries aim to meet climate goals set by international agreements such as the Paris Agreement. According to the IEA, renewable energy sources accounted for nearly 30% of the world's electricity generation in 2020, with a projected increase to 50% by 2030 [3]. Taiwan's Renewable Energy Development Act of 2009 aligns with this global trend by aiming to increase the share of renewables in its energy mix. However, despite these efforts, renewable energy constituted only about 6% of Taiwan's total energy supply in 2021, indicating a slower pace of adoption compared to global leaders like Germany and Denmark, where renewables make up over 40% of the energy mix [63].

The transition from coal and nuclear power to natural gas and renewables is another common trend. For instance, the United States and several European countries are significantly investing in natural gas as a bridge fuel due to its lower carbon emissions compared to coal. Taiwan mirrors this trend with plans to increase the share of natural gas in its energy mix to 50% by 2025 [108]. However, Taiwan's heavy reliance on imported LNG poses energy security risks, especially in the context of geopolitical tensions with China. This reliance contrasts with countries like the US, which benefits from domestic natural gas production, thereby enhancing their energy security.

Energy efficiency and carbon reduction targets are also pivotal in global energy strategies. The European Union, for example, has set a target to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels [28]. Similarly, Taiwan has implemented the Greenhouse Gas Reduction and Management Act, targeting a 50% reduction in emissions from 2005 levels by 2050 [125]. Although these targets are ambitious, Taiwan's progress has been hampered by technical and infrastructural challenges, such as the instability of renewable energy sources and an aging grid infrastructure.

One notable difference between Taiwan and many other countries is its phase-out of nuclear power. While Germany is also phasing out nuclear energy, many other countries, including China, France, and the United States, continue to invest in nuclear as a low-carbon energy source. Taiwan's decision to phase out nuclear power by 2025 has been influenced by public opposition and safety concerns following incidents like the Fukushima disaster. This policy shift places Taiwan among a minority of countries that are moving away from nuclear energy, potentially increasing its reliance on fossil fuels and making its carbon reduction goals more challenging to achieve.

In terms of technological advancements and innovation, countries like China and the United States are leading the way in the deployment of smart grid technologies and energy storage solutions, which are crucial for integrating renewable energy into the grid. Taiwan is making strides in this area with initiatives to modernize its grid and enhance energy storage capacity, but it lags behind the leading nations in the scale and pace of these developments. For example, the deployment of large-scale battery storage systems in California and the integration of artificial intelligence in grid management in China represent significant advancements that Taiwan is yet to fully realize [121] [2].

However, as mentioned before, Taiwan faces unique challenges due to its geopolitical context. Its tense relationship with China poses significant risks to its energy security. For instance, the possibility of a blockade by the People's Liberation Army could disrupt Taiwan's energy imports, which are critical given its dependence on imported fossil fuels. This threat underscores the importance of diversifying energy sources and investing in energy storage solutions to ensure a stable energy supply even in the face of geopolitical tensions.

5 | Discussion

5.1 | Implications for Policy and Practice

The study's findings offer important information to improve Taiwan's energy policy and facilitate the country's shift towards sustainable energy sources. Through an examination of the SWOT analysis, survey results, and regression outcomes, key areas have been identified where Taiwan can make strategic changes to enhance its energy sustainability. These include investing in renewable energy sources, implementing more stringent regulations on carbon emissions, and promoting energy efficiency measures. Addressing these areas can help Taiwan reduce its dependence on fossil fuels, decrease carbon emissions, and transition to a sustainable and eco-friendly energy system.

To expedite the adoption of renewable energy in Taiwan, leveraging strong public support is crucial. Implementing strategies such as community engagement programs and educational campaigns, in line with Energy Transition Theory, can drive investments in this sector. Survey results demonstrate strong public endorsement of renewable energy, with a significant number of respondents actively advocating for increased investment in this sector. Specifically, 48% of respondents agreed or strongly agreed that Taiwan should invest more in renewable energy sources, compared to 40% who were neutral or disagreed. This public backing suggests that Taiwan should enhance subsidies and incentives for renewable energy projects, such as offering tax credits for solar panel installations and grants for research and development in renewable energy technologies. Raising the feed-in tariffs for solar and wind energy can attract more investments, speeding up the installation of renewable energy systems. Additionally, tax incentives for businesses and households adopting renewable energy technologies can encourage more widespread adoption. This is consistent with global trends observed in nations like Germany and Denmark, where effective policies like feed-in tariffs and advancements such as offshore wind farms have led to significant incorporation of renewable energy capacities.

Given the strong public support and the critical need for strategic investment, it is essential to understand the phases and efforts involved in transitioning from nuclear energy to renewable energy. The X-Curve model provides a valuable visual and theoretical framework for this purpose. It highlights the different phases and the amount of effort required at each stage, offering a comprehensive view of the transition dynamics. In the breakdown phase, Taiwan optimizes its reliance on nuclear energy, which remains risky, necessitating high operational and maintenance efforts and encountering significant public opposition due to safety concerns. This stage demands large efforts. As policies shift towards renewable energy, the destabilization phase emerges, creating uncertainty, increasing maintenance costs, and requiring moderate efforts to navigate regulatory changes. The chaos phase involves sudden plant shutdowns and legal battles over decommissioning, leading to financial instability and job losses in the nuclear sector, requiring high efforts to manage these disruptions. In the breakdown phase, there is a significant drop in nuclear energy production, resulting in job losses and economic challenges, necessitating substantial efforts to stabilize the energy supply. Finally, in the phase-out stage, there is a complete cessation of nuclear energy operations, requiring minimal effort as the nuclear era ends.

Conversely, in the build-up phase, experimentation begins with pilot projects for solar and wind energy, demanding low effort but essential for innovation and testing new technologies. The acceleration phase involves the large-scale deployment of renewable energy projects, requiring significant efforts to expand grid infrastructure and secure investments. The emergence phase sees the establishment of a robust renewable energy market, necessitating moderate efforts to integrate renewable energy into national policy. During institutionalization, there is a formalization of renewable energy policies, demanding high efforts to create regulatory frameworks and long-term agreements. Finally, in the stabilization phase, there is a full transition to a renewable-based energy system, requiring sustained efforts to maintain public and political support. The X-Curve visual, Figure 5.1 demonstrates these phases and the different levels of effort needed, ultimately resulting in a stable and sustainable renewable energy system.

The implications drawn from the X-Curve model highlight several critical actions for policymakers and practitioners, including allocating resources to manage high-effort phases, sustaining investments in infrastructure during the build-up phase, and maintaining public engagement for long-term sustainability. Firstly, significant resources must be allocated to managing the high-effort phases, particularly the chaos and breakdown stages in the phase-out of nuclear energy. This includes financial support for communities

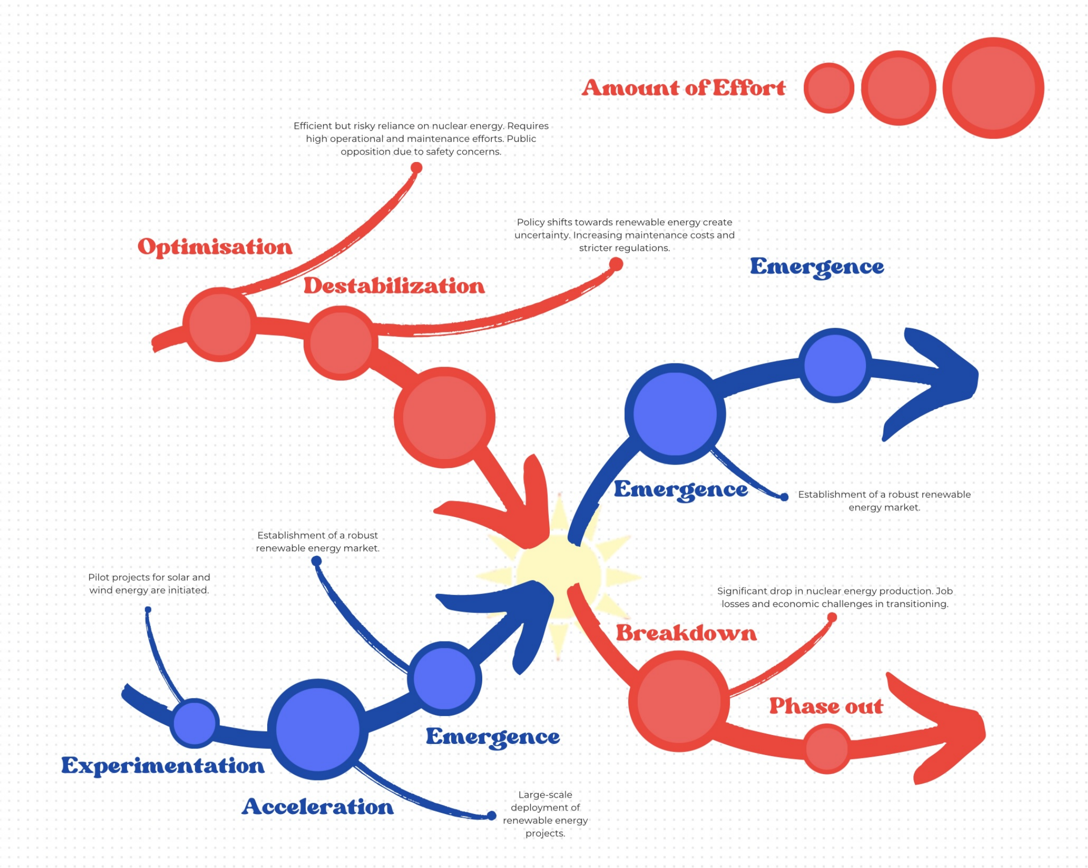

Figure 5.1: X-Curve for Taiwan's Energy Transition

affected by job losses, legal frameworks to handle decommissioning processes smoothly, and public communication strategies to address safety concerns and opposition. Secondly, during the build-up phase, sustained investments in infrastructure and innovation are paramount. This involves not only financial incentives but also supportive policies that facilitate the rapid scaling of renewable energy technologies. Policymakers must ensure that regulatory frameworks are adaptable and responsive to the evolving landscape of renewable energy. Lastly, maintaining momentum during the stabilization phase requires ongoing public engagement and education campaigns to ensure continued support for renewable energy initiatives. This is critical for achieving long-term sustainability and resilience in Taiwan's energy system.

Energy security is a major concern for Taiwan, given its reliance on imported energy and geopolitical tensions with China. Implementing measures such as diversifying energy sources, developing local natural gas resources, and enhancing infrastructure can mitigate these risks. The SWOT analysis highlights the vulnerabilities associated with this dependence. To enhance energy security, Taiwan must diversify its energy sources, increasing the share of domestically produced renewable energy. STS Theory suggests that technological advancements and regulatory adjustments are critical for managing this transition. Developing local natural gas resources through exploration and extraction projects and establishing strategic reserves by building storage facilities can provide a buffer against supply disruptions. Developing infrastructure is crucial for bolstering energy security, particularly by modernizing the aging energy grid to accommodate a higher proportion of renewables and ensuring the reliability of energy storage systems. The regression analysis of the Energy Security Risk Index (ESRI) offers deeper insights into the factors affecting energy security in Taiwan. The results underscore the critical role of historical trends in energy security risk and illuminate the intricate, non-linear connections among energy variables and the ESRI. This highlights the importance of having a well-rounded mix of renewable energy generation and fossil fuels to ensure energy security. Increasing renewable energy generation can reduce the reliance on imported fossil fuels, thus improving energy security.

Survey data confirms that many respondents are worried about the safety and environmental effects of nuclear energy. Conflict Theory and the Framing Approach explain how gender variations in views on nuclear energy mirror wider social dynamics. For instance, the survey results showed that 57% of males disagreed or strongly disagreed with investing more in nuclear energy, compared to only 20% of females. This gender-based difference underscores the importance of targeted public education campaigns to address knowledge gaps and shape informed opinions on energy policy. Public opinion significantly shapes energy policy, as evidenced by the survey results. Policymakers should actively engage with the public, consider their preferences, and prioritize safety measures and regulations to align policies with public sentiment. A significant portion of respondents emphasized the need for safety measures and regulations, with many respondents prioritizing safety in energy policy. Specifically, 38% of respondents rated safety measures and regulations as the highest priority. Additionally, public education and awareness were also prioritized, with 32% of respondents indicating the need for comprehensive educational campaigns to inform citizens about the benefits and safety of renewable energy. This can address misconceptions and promote better public understanding. Engaging local communities in renewable energy projects through meetings, workshops, and collaborative decision-making can increase public support and involvement, creating a sense of ownership for these initiatives. This is consistent with STS Theory, which highlights the interaction between social and technical aspects in energy transitions.

Survey data further reveals the sources of information that significantly influence public opinion on energy issues. For example, news media and social media were reported as major sources of information, with 76% and 63% of respondents, respectively, citing these as influential. This highlights the importance of leveraging these platforms for disseminating accurate and compelling information about renewable energy and its benefits, such as partnering with influencers for social media campaigns and organizing press releases for traditional media outlets. Moreover, the survey indicated strong support for investment in advanced technology such as smart grids and energy storage systems, and international cooperation in areas like research partnerships and knowledge exchange as priorities for energy policy. Survey participants emphasized the necessity for Taiwan to embrace state-of-the-art technologies and conform to global standards to secure a resilient and sustainable energy future. The Sustainability Transitions Framework (STF) underscores the role of niche innovations in driving systemic change, which aligns with the survey data showing that 29% of respondents prioritize investment in advanced technology such as battery storage and smart meters. Innovation is crucial for Taiwan's shift to a sustainable energy future.

5.2 | Limitations of the Study

The following section outlines the key limitations encountered during the research process for this thesis. These limitations provide context for the results and highlight areas where future research may be needed to address gaps or improve the study's robustness.

1. Data Availability and Reliability

   [a] Given the nature of economic policy analysis, obtaining up-to-date and comprehensive data can be challenging. Specifically, in the context of this thesis, which involves a regression analysis with energy security risk on the left and variables such as the share of nuclear energy, share of renewables, energy intensity, etc., several issues were encountered:

      i. **Energy Supply Disruptions Data**: Finding consistent and reliable data on energy supply disruptions proved difficult, crucial for understanding the volatility and risk associated with energy security but is often not comprehensively recorded or made publicly available.

      ii. **Renewable Energy Investments Data**: Similarly, data on renewable energy investments is scattered and sometimes incomplete. While they some sources do provide insights into overall investment trends, granular data needed for detailed analysis is often lacking.

      iii. **Issues with Taiwan's MOEA Website**: Taiwan's Ministry of Economic Affairs's website has valuable indicators, but technical issues hindered data collection. The website some does not function work right, and will not allow me to download necessary data.

      iv. **Survey Demographics**: The survey conducted as part of this research faced demographic limitations. Only 129 people were surveyed and participants were primarily within the age range of 18 to 49, leading to a skewed sample that may not fully represent the broader population's views.

2. Scope and Generalizability

[a] The study focuses primarily on Taiwan. While this allows for in-depth analysis, it also limits the generalizability of the findings. The economic policies and their impacts observed in the selected case studies may not apply to other regions or countries with different economic contexts and challenges. In addition, the skewed age range may not fully capture the perspectives of older or younger populations. Therefore, caution must be exercised when extrapolating the results to broader contexts, and future studies should aim for a more representative sample to enhance generalizability.

3. Methodological Constraints

   [a] The reliance on qualitative analysis and expert opinions could possibly introduce subjectivity and bias. Additionally, the regression analysis did not yield significant results, which could be due to not including all relevant measures that impact energy security, potentially overlooking critical variables that influence the regression outcomes. The study's methodological design may limit the ability to establish causal relationships definitively.

4. External Influences and Uncontrollable Variables

   [a] The dynamic and often unpredictable nature of these external influences, such as political changes, global economic shifts, and unforeseen events (e.g., pandemics), adds complexity to the analysis and interpretation of results.

5. Language and Cultural Barriers

   [a] Given that this research focuses on Taiwan, language and cultural barriers posed significant challenges. Translation issues and cultural differences in data reporting and interpretation could have affected the accuracy and understanding of the information used in this study, highlighting the importance of cultural context in economic policy analysis and the need for local expertise.

5.3 | Recommendations for Future Research

Future research should focus on improving data availability and dependability by utilizing more extensive and current information, especially with regard to energy supply disruptions and renewable energy investments, in light of the constraints this study has found. Findings from surveys with a wider demographic sweep that encompasses a wider range of ages and backgrounds will be more representative and broadly applicable. In order to balance quantitative and qualitative analyses, future research should think about implementing mixed-methods approaches. This will help to mitigate potential biases and improve the robustness of results. Further investigation into potential policy changes and outside interventions for dummy variables may provide more meaningful understanding of the variables influencing energy security. Longitudinal studies are recommended to fully grasp long-term trends and impacts, gaining a better understanding of the dynamic interplay between economic policies and energy security. Finally, fostering international collaborations can help overcome language and cultural barriers, ensuring a more nuanced and contextually rich analysis of global economic policies.

6 | Conclusion

6.1 | Summary of Key Findings

In this section, I summarize the key findings of the study, which aimed to explore the multifaceted challenges and opportunities associated with Taiwan's nuclear energy phase-out and transition to renewable energy. The study revealed several significant findings across nine major themes: energy security and stability, nuclear energy phase-out, renewable energy development, technological advancements, regulatory frameworks, public perception and acceptance, environmental and safety considerations, market dynamics, and carbon neutrality. Each of these findings is discussed in detail below, with a focus on their relevance to the study's aim and their connection to existing literature.

- Taiwan's heavy reliance on energy imports and frequent power outages present significant challenges to maintaining a stable energy supply, making Taiwan vulnerable to geopolitical risks and global market fluctuations, particularly given its tense relationship with China. The transition to renewable energy sources, while essential for long-term sustainability, complicates this issue due to the intermittent nature of sources like solar and wind. This underscores the need for Taiwan to invest in robust energy storage solutions and diversify its energy mix to enhance resilience.
- The phase-out is driven by safety concerns, waste management issues, and strong public opposition, which requires meticulous planning and a robust regulatory framework to manage the decommissioning of nuclear plants and the safe disposal of radioactive materials, aligning with global trends, particularly in post-Fukushima Japan [48]. The importance of transparent communication strategies to address public concerns and ensure safety cannot be overstated, reflecting a broader global context where public opinion significantly influences nuclear energy policies.
- Public support for renewable energy in Taiwan is strong, particularly for solar power, which is seen as a sustainable alternative to nuclear energy. Moreover, the perception and acceptance of different renewables is influenced by the public. However, integrating these renewable sources into the existing grid presents several challenges, including intermittency and the need for substantial energy storage infrastructure. This highlights the need for advanced grid management systems and large-scale energy storage solutions. Moreover, addressing public concerns and providing clear information about the benefits and safety of renewable energy, policymakers can foster a supportive environment for the energy transition.
- Technology advancements in batteries, including aluminum ion batteries, are essential to Taiwan's move toward renewable energy. Compared to conventional lithium-ion batteries, these developments provide a number of benefits, such as improved temperature resistance and a lower danger of fire. Sustained research and development expenditures are necessary to advance these technologies and for the widespread installation of renewable energy systems throughout Taiwan, underscoring the role of technological innovation in overcoming the challenges associated with renewable energy integration.[115].
- Effective regulatory and policy frameworks are essential for managing the transition from nuclear to renewable energy. This includes implementing stringent safety measures, promoting international cooperation, and engaging with the public through transparent communication strategies. Regulatory bodies must ensure that the transition is conducted safely and efficiently, addressing potential risks and maintaining public trust.
- The phase-out of nuclear energy is primarily driven by environmental and safety considerations, particularly the challenges of managing nuclear waste and ensuring safety in a region with high seismic activity. Ensuring the safety of energy infrastructure and addressing environmental impacts are critical components of the transition strategy. Prioritizing environmental sustainability, education and safety in energy policy reflects global concerns over nuclear energy safety post-Fukushima [47].
- Understanding the competitive landscape and market dynamics is crucial for positioning Taiwan's energy sector globally. Taiwanese companies' innovation in battery technologies and other energy solutions will play a significant role in maintaining a competitive edge. By staying at the forefront of technological innovation and fostering a supportive policy environment, Taiwan can enhance its competitiveness and attract international investments in its energy sector.

- Achieving carbon neutrality is a key goal for Taiwan, supported by the promotion of carbon credits and efforts to align energy policies with global climate goals. Carbon credits can incentivize the reduction of greenhouse gas emissions and support the development of renewable energy projects. Aligning energy policies with international climate commitments can enhance Taiwan's global standing and contribute to the global effort to combat climate change.

In conclusion, the findings of this study provide a comprehensive understanding of the challenges and opportunities associated with Taiwan's energy transition. They highlight the critical areas that need attention, such as energy security, regulatory frameworks, technological advancements, public engagement, and environmental sustainability, all of which are essential for a successful transition to a renewable energy future.

6.2 | Policy Recommendations

Based on the findings, I have developed three policy recommendations.

1. Create Community-Based Microgrids

- **Objective**: Enhance energy resilience and empower local communities through the creation of energy communities.
- **Description**: Implement community-based microgrids powered by renewable energy sources such as solar and wind. These microgrids can operate independently or in concert with the main grid, providing localized energy security and alleviating the strain on the national grid. They form energy communities where members actively participate in energy production, consumption, and management.
- **Expected Outcomes**: The implementation of these microgrids is expected to improve energy resilience and security at the community level, reduce dependence on centralized fossil fuel-based power plants, enhance local economic development through job creation and community empowerment, and increase public awareness and support for renewable energy initiatives.

2. Implement Floating Solar Farms

- **Objective**: Maximize the use of available space and enhance solar energy efficiency.
- **Description**: Deploy floating solar farms along Taiwan's extensive coastlines and on water bodies. These farms use floating solar panels that reduce land usage while enhancing the efficiency of solar generation thanks to the cooling effects of water. They are integrated with the national grid through underwater cables and onshore substations.
- **Expected Outcomes**: This initiative will lead to a significant increase in the share of renewable energy in Taiwan's energy mix, optimize land use by preserving it for agriculture and urban development, enhance the efficiency of solar energy generation, and contribute to Taiwan's carbon reduction goals and sustainability commitments.

3. Establish an Energy Innovation Hub

- **Objective**: Foster innovation and collaboration in the energy sector.
- **Description**: Set up an energy innovation hub that unites government, academia, and industry to develop and test new energy technologies. This hub focuses on advanced energy storage solutions, smart grid technologies, and strategies for integrating renewable energy. It supports the development of state-of-the-art facilities equipped with laboratories, testing grounds, and collaborative workspaces.
- **Expected Outcomes**: The creation of the energy innovation hub is expected to accelerate the development and deployment of cutting-edge energy technologies, enhance collaboration between government, academia, and industry which drives innovation and economic growth, strengthen Taiwan's position as a leader in renewable energy and technology innovation, create high-skilled

jobs and educational opportunities, and make significant contributions to achieving Taiwan's energy transition and sustainability goals.

6.3 | Concluding Remarks

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8 | Appendix A: Interview Questions

This appendix contains the interview questions used in the research for this thesis. These questions were designed to gather insights from various stakeholders on Taiwan's energy policy, the transition from nuclear to renewable energy, and related challenges and opportunities.

8.1 | Interview Outline for Taiwan Environmental Protection Union (TEPU)

Background and Personal Insights

- Could you describe your experience and background in energy policy in Taiwan?
- What initially drew you to focus on nuclear energy issues within Taiwan?

Taiwan's Energy Policy Landscape

- How has Taiwan's energy policy evolved over the last few decades regarding nuclear energy?
- What are the primary drivers behind the push for a nuclear-free Taiwan by 2025?

Impacts of Nuclear Phase-out

- What do you perceive as the most significant challenges Taiwan faces with the phase-out of nuclear energy?
- Can you discuss any economic impacts, both short-term and long-term, that might arise from this policy shift?

Public Opinion and Stakeholder Engagement

- How has public opinion influenced nuclear energy policies in Taiwan?
- In what ways have stakeholders, such as local communities and businesses, been involved in the decision-making process?

Alternatives and Sustainable Practices

- What are the most viable energy alternatives for Taiwan to pursue in light of the nuclear phase-out?
- How does Taiwan's approach to renewable energy compare with global trends?

Future Outlook and Policy Recommendations

- What future developments do you foresee in Taiwan's energy landscape post-2025?
- Based on your expertise, what policy recommendations would you offer to enhance Taiwan's energy security and sustainability?

Additional Insights and Conclusions

- Are there any lessons from other countries' experiences with nuclear energy that Taiwan could learn from?
- Do you have any additional insights that could help inform my thesis research?

8.2 | Interview Outline for APh ePower

Introduction and Company's Vision in Energy Transition

- Could you briefly introduce APh ePower and describe your vision regarding Taiwan's energy transition, particularly in the context of the nuclear phase-out?

Challenges in Renewable Energy Integration

- What are the main challenges you identify in integrating renewable energy into Taiwan's power grid, and how do APh ePower's solutions address these challenges?

Public Perception and Acceptance

- How does APh ePower approach public perception and acceptance of alternative energy technologies? Have you encountered any resistance similar to that seen with nuclear energy, and how do you address it?

Contribution to Energy Security and Sustainability

- In what ways do APh ePower's technologies contribute to enhancing Taiwan's energy security and sustainability, especially with the ongoing phase-out of nuclear power?

Innovations and Future Technologies

- Could you discuss any specific innovations in energy storage that APh ePower is developing, which might be pivotal for achieving Taiwan's renewable energy targets?

Policy and Infrastructure Implications

- Based on your experience, what are the policy and infrastructure implications of adopting advanced energy storage solutions in Taiwan? Are there any policy changes you suggest to facilitate this transition?

Learning from Global Trends

- Are there global trends or case studies in energy storage and renewable energy that you believe Taiwan could learn from? How does APh ePower align with or contribute to these global trends?

Partnerships and Collaborations

- Can you highlight any significant partnerships or collaborations that have been pivotal for APh ePower's success in the field of energy storage and renewable energy solutions?

Vision for the Future

- How do you envision the future of energy storage and renewable energy in Taiwan and globally? What role do you see APh ePower playing in this future landscape?

8.3 | Interview Outline for Citizen of the Earth Taiwan (CET)

Organization Overview and Mission:
Can you provide an overview of CET's mission and its primary focus areas in environmental advocacy within Taiwan?
Public Environmental Concerns:

1. What are the major environmental concerns among the Taiwanese public today, and how is CET addressing these issues?
2. How does CET engage with local communities to raise awareness and promote environmental activism?

Perspective on Taiwan's Energy Policy:

1. How does CET view Taiwan's current energy policy, especially regarding the transition from nuclear and fossil fuels to renewable energy sources?
2. What policy changes does CET advocate for to ensure a sustainable energy future for Taiwan?

Nuclear Energy and Societal Risks:

1. Could you share CET's stance on nuclear energy and the perceived societal risks associated with its use in Taiwan?
2. What alternatives does CET propose to mitigate these risks while ensuring energy security?

Environmental Advocacy and Community Leadership:

1. Can you discuss any successful initiatives or campaigns led by CET that have made significant impacts on environmental policy or community practices in Taiwan?

Future Directions and Challenges:

- Looking forward, what challenges does CET anticipate in advancing environmental protection and sustainability in Taiwan?
- How does CET plan to address these challenges and what support is needed from the public, policymakers, and international communities?

Conclusion: Any additional comments or messages CET would like to convey to the academic community and policymakers regarding Taiwan's environmental future and energy policies.

8.4 | Interview Outline for TAIYEN GREEN ENERGY

Brief introduction to the research project, its objectives, and the significance of TAIYEN GREEN ENERGY's insights.
Company Overview and Role in Taiwan's Energy Sector

1. What is TAIYEN GREEN ENERGY's mission, and how does it align with Taiwan's current and future energy policies?
2. Considering Taiwan's evolving energy landscape and its move towards sustainable energy sources, how does TAIYEN GREEN ENERGY position itself in this transition, and what contributions does it aim to make to enhance the sustainability of Taiwan's energy sector?

Economic Impacts

1. How does TAIYEN GREEN ENERGY assess the economic benefits of renewable energy compared to the traditional reliance on both fossil fuels and nuclear power in Taiwan?
2. What are the major economic and operational challenges TAIYEN GREEN ENERGY faces in promoting renewable energy within Taiwan's energy market?

Environmental Considerations

1. In TAIYEN GREEN ENERGY's experience, how do the environmental impacts of renewable energy sources compare to those of nuclear energy in Taiwan?
2. Could you share any specific initiatives or strategies TAIYEN GREEN ENERGY has adopted to mitigate environmental concerns associated with renewable energy production?

Policy and Regulation

1. How have Taiwan's current energy policies and regulations influenced TAIYEN GREEN ENERGY's operations, especially in the context of renewable versus nuclear energy?

2. From TAIYEN GREEN ENERGY's perspective, what policy adjustments are needed to foster a more robust development of renewable energy in Taiwan?

Future Perspectives and Innovations

1. Looking forward, what role do you foresee for renewable energy in Taiwan's energy mix, and how does TAIYEN GREEN ENERGY plan to contribute to this vision?
2. Are there any innovative projects or technologies in the pipeline at TAIYEN GREEN ENERGY that you believe will significantly impact Taiwan's energy sector?

8.5 | Interview Outline for NSC Representatives

Thank you for agreeing to participate in this interview. The following questions are designed to gather insights into Taiwan's nuclear safety and policy, especially in the context of SWOT analysis and its implications for the Pacific-region area.

General Questions:

1. Can you provide an overview of the current nuclear energy landscape in Taiwan, particularly in the context of the Pacific region?
2. How does the NSC view Taiwan's role in promoting nuclear safety within the Pacific region?

Strengths:

1. What are the NSC's identified strengths in managing nuclear safety and regulations in Taiwan?
2. Could you share examples of successful strategies or initiatives that have enhanced nuclear safety in Taiwan?

Weaknesses:

1. Are there any challenges or weaknesses in the current nuclear safety framework that the NSC is working to address?
2. How does the NSC manage the balance between promoting nuclear energy and ensuring public safety?

Opportunities:

1. What opportunities does the NSC see for Taiwan in the area of nuclear energy, especially with regard to technological advancements and regional cooperation?
2. Are there any international partnerships or collaborations that the NSC is currently pursuing or planning to enhance nuclear safety standards?

Threats:

1. What are the primary threats or risks associated with nuclear energy that the NSC is concerned about, both domestically and in the Pacific region?
2. How does the NSC prepare for and respond to emergency situations, such as natural disasters or nuclear accidents, to minimize risks?

Policy and Regulatory Framework:

1. Could you elaborate on the regulatory changes or updates that are being considered or implemented to improve nuclear safety?
2. How does the NSC engage with other international nuclear safety organizations to align Taiwan's safety standards with global best practices?

Future Directions:

1. What is the NSC's vision for the future of nuclear energy in Taiwan, especially considering the global push towards renewable energy sources?

2. Are there any upcoming projects or policies that the NSC is particularly excited about?

Closing:
Is there any message or information that the NSC would like to share with the academic community and stakeholders interested in nuclear safety and policy?