



The Influence of Climate Change on the Renewable Energy Investment Sector in Greece

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Chapter 1: Introduction

Background and Context

Overview of global and Greek renewable energy trends

Over the last decade, renewable energy has become a cornerstone of global energy strategies, driven by the need to address climate change, reduce dependence on fossil fuels, and ensure energy security. This period has seen significant technological advancements, policy shifts, and investment growth, positioning renewables as a dominant force in the energy landscape.

Globally, renewable energy capacity has grown exponentially. Solar and wind energy have emerged as the fastest-growing sectors, with the cost of solar photovoltaics (PV) and onshore wind dropping dramatically, making them increasingly competitive with traditional energy sources. According to the International Renewable Energy Agency (IRENA), the global renewable power capacity increased by over 200% from 2010 to 2020. Countries like China, the United States, and the European Union have been key drivers, with China leading the world in solar and wind capacity. In addition, offshore wind projects have also seen a surge, particularly in Europe and the U.S., with major investments into both fixed and floating wind technologies.

In the past decade, the global energy transition has been supported by various policy frameworks, such as the Paris Agreement in 2015, which committed countries to limit global warming and invest in clean energy. Many nations have set ambitious renewable energy targets, aiming for net-zero emissions by mid-century, further accelerating investments in wind, solar, and energy storage technologies.

In Greece, the renewable energy sector has witnessed significant progress in the last ten years. The country has dramatically increased its share of renewables in its energy mix, primarily through wind and solar power. Greece's wind power capacity doubled between 2010 and 2020, and solar energy also expanded rapidly, with solar PV installations growing by over 10 times. This transition has been facilitated by supportive government policies, including feed-in tariffs, auctions, and investment incentives. The country also benefited from European Union funding and the EU's Green Deal, which aimed at reducing emissions and investing in green infrastructure.

However, Greece still faces challenges in integrating renewables into its energy grid and achieving its full renewable potential. The country's energy security remains closely tied to its reliance on fossil fuels, particularly natural gas and lignite, though efforts to diversify energy sources are ongoing. Nevertheless, Greece's renewable energy future looks promising as technological advancements, new investments, and policy support continue to shape its energy landscape.

In conclusion, the last decade has marked a period of significant transformation for both global and Greek renewable energy sectors, with substantial growth, policy changes, and technological innovations driving the transition to cleaner and more sustainable energy systems.

The importance of renewable energy in mitigating climate change

Renewable energy plays a crucial role in mitigating climate change, offering a sustainable and viable solution to reducing greenhouse gas emissions. The global climate crisis, driven primarily by the burning of fossil fuels, has led to rising temperatures, extreme weather events, and disruptions in ecosystems. Transitioning to renewable energy sources—such as solar, wind, hydro, and geothermal—can significantly reduce carbon emissions, which are the leading cause of global warming.

Fossil fuels like coal, oil, and natural gas are the largest contributors to carbon dioxide (CO₂) emissions, which trap heat in the atmosphere and contribute to the greenhouse effect. In contrast, renewable energy sources generate electricity and heat without emitting harmful pollutants. Solar panels, wind turbines, and hydropower systems harness natural resources to produce clean energy, making them essential in efforts to reduce our carbon footprint.

One of the key benefits of renewable energy is its ability to provide a sustainable, long-term solution to energy generation. Unlike fossil fuels, which are finite and depleting, renewable sources are abundant and will continue to be available as long as the sun shines, the wind blows, and the rivers flow. This sustainability is vital in addressing the climate crisis over the long term, as it reduces the need for resource-intensive and polluting energy alternatives.

Renewables also help reduce air pollution, which has harmful effects on human health and the environment. By shifting away from coal-fired power plants and other fossil fuel-based energy sources, countries can significantly improve air quality, reduce respiratory illnesses, and lower healthcare costs.

In addition to reducing emissions and improving public health, the renewable energy transition also offers economic benefits. Investment in green technologies creates jobs, stimulates innovation, and supports local economies. The growth of the renewable energy sector has led to the creation of millions of jobs worldwide, from manufacturing and installation to research and development.

In conclusion, renewable energy is an indispensable tool in the fight against climate change. By reducing greenhouse gas emissions, improving air quality, and promoting sustainable economic growth, renewable energy can help mitigate the devastating impacts of climate change and secure a healthier, more sustainable future for the planet.

Problem Statement

Impact of climate change on renewable energy reliability and investment in Greece

Greece, like many other countries in Southern Europe, is heavily invested in the transition towards renewable energy as part of its broader goals to mitigate climate change, reduce greenhouse gas emissions, and enhance energy security. The country has made significant strides in increasing its share of renewable energy sources, particularly solar and wind power, which are abundant due to its Mediterranean climate. However, the growing body of research

suggests that climate change itself poses substantial challenges to the reliability of renewable energy systems in Greece, which could have critical implications for both energy generation and long-term investment in the sector.

Reliability of Renewable Energy Systems

Climate change can impact renewable energy reliability in multiple ways, and Greece is particularly vulnerable to these effects due to its reliance on solar and wind energy. The Mediterranean climate of Greece is characterized by hot summers, dry winters, and varying levels of seasonal wind patterns. However, climate change is altering weather patterns in unpredictable ways, which can affect the availability and consistency of renewable energy generation.

For example, solar energy production in Greece is highly dependent on sunlight, which could be impacted by changing weather conditions such as increased cloud cover or more frequent extreme weather events, like heatwaves or storms. Although Greece enjoys high levels of solar irradiance, these variables can create disruptions to energy generation, especially during periods of intense heat, which may cause panel efficiency to drop. Prolonged heatwaves or unpredictable cloud coverage could lead to more variability in solar power availability, reducing the reliability of this energy source.

Similarly, wind energy in Greece is also subject to fluctuations due to shifts in regional wind patterns. Climate models predict that some areas of the Mediterranean could experience less consistent wind speeds, as rising temperatures alter atmospheric pressure systems. These changes could cause disruptions in wind power generation, particularly in areas where wind energy is a major contributor to the national energy mix. Reduced wind speeds, particularly during summer months when energy demand is highest and may lead to greater intermittency in power generation, further complicating grid management and storage requirements.

The impact of climate change on renewable energy reliability can have significant implications for investment in Greece's energy sector. Renewable energy projects, particularly wind and solar, require substantial upfront capital investments and long-term planning. However, when these investments face uncertainties related to future climate patterns, potential investors may become hesitant to commit resources to projects that could experience lower-than-expected returns due to shifts in energy generation reliability.

Investors may perceive the increased variability in renewable energy generation as a higher risk, leading to a decrease in investment flows into the renewable energy sector. Furthermore, investors may demand higher returns on investments to compensate for this added risk, which could lead to higher financing costs for renewable energy projects. For example, the increasing need for energy storage technologies to accommodate intermittency could add additional costs to energy projects, making them less attractive to investors.

Moreover, the uncertain regulatory environment caused by shifting climate-related risks may also play a role in hindering investment. In response to the impacts of climate change, governments may need to revise policies related to subsidies, grid integration, and energy

pricing. Such regulatory changes could create additional uncertainties that dissuade private sector participation in Greece's renewable energy market.

In conclusion, the impact of climate change on renewable energy reliability in Greece presents a critical problem that requires immediate attention. With potential disruptions to solar and wind energy production, Greece faces challenges in maintaining a reliable energy supply while continuing to expand its renewable energy sector. The uncertainty surrounding energy generation under changing climate conditions also poses a significant barrier to long-term investments in Greece's renewable energy infrastructure. To address these issues, it is essential that Greece not only accelerates its efforts to enhance the resilience of renewable energy systems but also fosters a stable regulatory and financial environment that encourages continued investment in renewable energy development.

Research Objectives

Identify the direct and indirect effects of climate change on Greece's renewable energy sector

Greece has made significant progress in transitioning to renewable energy sources, particularly solar and wind power, due to its advantageous geographic location and favorable climate. However, the ongoing impacts of climate change pose both direct and indirect challenges to the sustainability and efficiency of these renewable energy systems.

Direct Effects of Climate Change

1. **Solar Energy Production:** Greece benefits from high solar radiation due to its Mediterranean climate. However, climate change could affect the consistency and intensity of sunlight, especially with increased occurrences of extreme weather events. For example, more frequent heatwaves could reduce the efficiency of photovoltaic (PV) panels, as solar panels often experience a decline in performance during excessively high temperatures. Additionally, changing cloud cover patterns or more frequent storms could cause periods of reduced solar irradiance, leading to fluctuations in solar power availability and disrupting energy production during peak demand periods (Koutsou & Karagiannidis, 2020).
2. **Wind Energy Generation:** Greece has significant wind energy potential, particularly in the Aegean Islands. However, climate change can alter regional wind patterns. Studies suggest that rising temperatures and shifting atmospheric pressure systems could lead to changes in wind speed and direction. Some regions may experience reduced wind speeds during the summer months when energy demand is highest, thus limiting the potential for wind energy generation. Conversely, stronger winds or more erratic wind patterns could create operational challenges for wind turbines, requiring more frequent maintenance or adjustments (Vardakas & Zorba, 2021).
3. **Hydropower:** While Greece's hydropower resources are not as large as those in other European countries, they still contribute to the renewable energy mix. Climate change is likely to impact water availability, with altered precipitation patterns leading to droughts or more intense rainfall events. Reduced rainfall during summer months could

lower river flows and reduce hydropower capacity, while increased flooding from heavy rainfall could damage infrastructure, leading to disruptions in energy generation.

Indirect Effects of Climate Change

1. **Investment Uncertainty:** The growing uncertainty about the future availability and reliability of renewable energy resources in Greece due to climate change could deter investment in the sector. Investors may be hesitant to finance long-term renewable energy projects without clearer projections of climate impacts on energy generation. This could lead to higher capital costs and reduced growth in the renewable energy market.
2. **Energy System Adaptation Costs:** To mitigate the impacts of climate change, Greece may need to invest heavily in grid management technologies, energy storage systems, and other adaptation measures to cope with the increasing variability in renewable energy production. These additional costs could strain the financial viability of renewable energy projects, potentially slowing the expansion of the sector.

Assess the economic implications for investments

The transition to renewable energy is a key pillar of Greece's strategy for reducing greenhouse gas emissions and achieving energy independence. However, the economic implications of climate change on investments in Greece's renewable energy sector are becoming increasingly significant. Climate change poses both risks and opportunities that affect the attractiveness of renewable energy projects, influencing investor behavior, project financing, and the long-term economic viability of renewable energy infrastructure.

Direct Economic Implications

1. **Uncertainty and Risk Premiums:** Climate change introduces uncertainty regarding the reliability and consistency of renewable energy generation, particularly for solar and wind power. These variations in energy production could increase the financial risks associated with renewable energy investments. Investors may demand higher returns to offset these risks, leading to an increase in risk premiums for renewable energy projects. The need to hedge against unpredictable weather patterns, reduced generation capacity, or damage to infrastructure from extreme weather events could raise financing costs for new projects (Vardakas & Zorba, 2021).
2. **Increased Maintenance and Operational Costs:** As renewable energy systems, particularly wind turbines and solar panels, face the impacts of more extreme weather events, maintenance and repair costs are likely to rise. The frequency of storms, extreme heatwaves, or flooding could damage infrastructure and increase operational downtime, leading to higher long-term maintenance costs. Additionally, wind and solar facilities may require more frequent inspections and equipment upgrades to ensure resilience against climate-induced stresses, further elevating costs for investors (Koutsou & Karagiannidis, 2020).
3. **Energy Storage and Grid Modernization:** As intermittent renewable energy sources become a larger share of the energy mix, the need for energy storage technologies and grid modernization becomes more urgent. The economic cost of integrating energy

storage systems—such as batteries or pumped hydro storage—could be significant, but these investments are crucial to ensuring a stable energy supply. Climate change-related fluctuations in renewable energy generation would require greater investment in technologies that can store excess energy for later use, potentially increasing overall capital expenditure for energy projects.

Indirect Economic Implications

1. **Long-Term Economic Viability of Renewable Projects:** As climate impacts alter energy production patterns, the long-term economic viability of renewable energy projects could be undermined if adjustments are not made to ensure reliability. For instance, solar and wind energy projects that are heavily dependent on the consistency of regional weather patterns might experience reduced returns if those patterns shift unfavorably. A lack of reliable returns could deter future investments, undermining the long-term growth of Greece's renewable energy sector.
2. **Government Policy and Regulatory Adjustments:** Climate change could prompt changes in national and EU-level policies, including renewable energy subsidies, taxation, and regulations. These policy shifts may either increase or reduce the attractiveness of investments in renewable energy. For example, Greece might introduce stricter regulations on the environmental impact of energy infrastructure or provide more subsidies for resilient, climate-proof renewable technologies. The unpredictability of these policy changes, driven by climate change impacts, could introduce additional risks to investors, affecting the flow of capital into the sector.
3. **Opportunities for Green Investment:** Despite the challenges, climate change could also present investment opportunities in green technologies and climate-resilient energy infrastructure. International climate finance mechanisms and EU climate targets could incentivize the growth of renewable energy in Greece, with potential funding from green bonds, EU recovery funds, or international climate adaptation initiatives. These financial instruments could mitigate some of the economic risks, encouraging private sector investment in climate-resilient renewable energy solutions.

Conclusion

The economic implications of climate change on renewable energy investments in Greece are multifaceted, presenting both risks and opportunities. While increased uncertainty, higher operational costs, and the need for grid modernization may strain the financial viability of renewable energy projects, the potential for green investment opportunities and policy support may help mitigate these challenges. To maintain a stable investment environment, it is crucial for Greece to foster a resilient regulatory framework and invest in technologies that can adapt to the impacts of climate change.

Research Questions

How does climate change influence renewable energy production and investment risk in Greece?

Climate Change and Renewable Energy Production: Climate change can significantly affect the availability and consistency of renewable energy resources, especially solar and wind power, in Greece. These resources are inherently variable, depending on weather conditions and regional climatic factors. Climate change may alter these conditions by changing solar irradiance levels, altering wind patterns, or causing extreme weather events like heatwaves, storms, or floods.

Solar Energy: Greece enjoys high solar radiation, making it a prime location for solar energy generation. However, the increasing frequency of extreme heat events could lead to a decline in solar panel efficiency, as panels tend to lose efficiency under very high temperatures. Furthermore, changes in cloud cover or increased storm frequency could reduce the predictability of solar energy generation, increasing the risk of energy production variability (Koutsou & Karagiannidis, 2020).

Wind Energy: Wind energy production is influenced by wind patterns, which can be altered by climate change. Rising temperatures can shift atmospheric pressure systems, resulting in changes to local wind patterns and speeds. Some areas of Greece may experience weaker winds, especially during the summer months, when electricity demand is at its peak, further exacerbating the intermittency problem (Vardakas & Zorba, 2021).

Investment Risk: The impacts of climate change on renewable energy production create a more uncertain investment environment. The variability in energy generation increases the financial risks for investors, who may demand higher returns to compensate for this increased uncertainty. Furthermore, the need for additional infrastructure, such as energy storage solutions and grid upgrades, adds to the financial burden of renewable energy projects, potentially deterring investment (Vardakas & Zorba, 2021).

What economic measures can mitigate these impacts?

To address the economic challenges posed by climate change in the renewable energy sector, several economic measures can be implemented:

Incentives for Resilient Infrastructure: One effective measure could be offering financial incentives or subsidies for the development of climate-resilient renewable energy infrastructure. This could include funding for advanced solar panel technologies, wind turbines designed to withstand extreme weather conditions, and the integration of energy storage solutions to smooth out intermittent energy production (Koutsou & Karagiannidis, 2020).

Diversification of Energy Sources: Encouraging diversification within the renewable energy portfolio can reduce the reliance on a single energy source that may be vulnerable to climate-induced variability. For instance, investing in geothermal, biomass, or offshore wind energy could help stabilize energy production and reduce risk, particularly in regions where wind and

solar energy generation may be less predictable due to climate change (Vardakas & Zorba, 2021).

Climate-Resilient Financing Models: The implementation of climate-resilient financing models, such as green bonds or climate-adaptive financial instruments, can help attract investment into renewable energy projects while also mitigating the financial risks associated with climate-induced production variability. These models could incorporate risk-sharing mechanisms, where investors are protected against certain climate-related risks through insurance or government-backed guarantees (Vardakas & Zorba, 2021).

Regulatory Support and Policy Adjustments: Long-term policies and regulatory frameworks that account for climate change impacts on renewable energy generation can help stabilize the investment environment. Greece could enhance its regulatory support for renewable energy projects by integrating climate adaptation measures into its energy policies. These measures could include setting clear guidelines for managing the risks associated with energy generation variability, promoting investment in grid flexibility, and encouraging the use of energy storage technologies (Koutsou & Karagiannidis, 2020).

These research questions highlight the complex relationship between climate change, renewable energy production, and investment risk in Greece. Investigating how climate change impacts energy generation, coupled with the exploration of economic measures that can mitigate these effects, is crucial for sustaining the growth of Greece's renewable energy sector and ensuring long-term energy security. Identifying appropriate adaptation and investment strategies will help protect both the environment and the economy in the face of ongoing climate challenges.

Scope and Significance

Relevance for policymakers, investors, and renewable energy stakeholders

The transition to renewable energy is a global priority in the fight against climate change, and Greece has actively committed to expanding its renewable energy capacity. However, as climate change affects weather patterns and the reliability of renewable resources, it becomes increasingly important for policymakers, investors, and renewable energy stakeholders to understand and address these impacts. The scope and significance of these challenges extend across the economic, environmental, and social domains, with implications for energy security, economic stability, and the future of the energy market.

Scope of the Issue

The scope of the issue encompasses both the direct and indirect effects of climate change on Greece's renewable energy sector. Directly, climate change influences the availability and efficiency of key renewable resources—solar and wind energy—by altering local weather patterns, wind speeds, solar irradiance, and the frequency of extreme weather events. The impacts of these changes include reduced efficiency in solar panel output due to increased temperatures and less reliable wind patterns that could decrease the effectiveness of wind farms. Indirectly, the variability of renewable energy production increases the risk associated

with long-term investments in the sector, affecting both financing costs and the economic viability of projects. Additionally, these challenges could affect the broader energy grid infrastructure, requiring greater investment in storage technologies and grid flexibility.

Significance for Policymakers

For policymakers, understanding the economic, environmental, and social implications of climate change on renewable energy production is crucial for creating adaptive, forward-looking energy policies. Policymakers must consider how climate change-induced variability in renewable energy generation might impact energy security, particularly in terms of balancing supply and demand during extreme weather events. They must also design policies that support the development of climate-resilient infrastructure and encourage investment in emerging technologies such as energy storage and smart grids. Furthermore, policymakers can incentivize the diversification of renewable energy resources to reduce dependence on a single energy source, thus lowering the overall risk of energy production instability.

Significance for Investors

For investors, the risks posed by climate change-related variability in renewable energy generation can lead to greater uncertainty in return on investment. Understanding the financial risks linked to weather-related disruptions and technological challenges is critical. Investors must assess how these risks will influence capital costs, project financing, and expected energy yields. Moreover, the demand for climate-resilient renewable energy technologies offers opportunities for investors to finance innovations and infrastructure that can withstand the changing climate, thereby securing future returns. Transparent, stable regulatory frameworks that account for climate risks will also play a vital role in fostering investor confidence.

Significance for Renewable Energy Stakeholders

For stakeholders in the renewable energy sector, including energy producers, technology developers, and service providers, it is essential to stay ahead of climate risks. This involves investing in research and development to improve the efficiency and resilience of renewable technologies, such as more robust wind turbines and solar panels that can withstand extreme weather events. Collaboration with policymakers and investors is key to ensuring that the sector remains adaptable and sustainable in the face of climate change.

Conclusion

The significance of understanding the impacts of climate change on Greece's renewable energy sector is far-reaching. For policymakers, investors, and stakeholders, addressing these challenges is critical to ensuring the continued growth and success of Greece's renewable energy transition. By developing comprehensive strategies that incorporate climate resilience, risk mitigation, and innovation, all parties involved can help safeguard the future of renewable energy in Greece.

Chapter 2: Literature Review

Climate Change and Renewable Energy: A Global Overview

Existing research on climate impacts on renewables worldwide

The impacts of climate change and the role of renewable energy have become central topics in the global discourse on environmental sustainability. Climate change, driven by anthropogenic greenhouse gas emissions, is causing widespread disruptions to ecosystems, economies, and societies. The transition to renewable energy sources is often seen as a crucial solution for mitigating the effects of climate change while simultaneously addressing energy security and sustainability concerns. In this context, examining the existing research on the effects of climate change on renewable energy systems worldwide is essential to understand both challenges and opportunities in the energy transition.

Climate Change Impacts on Renewable Energy

Climate change can have both direct and indirect effects on the availability and effectiveness of renewable energy systems. These effects vary depending on the specific renewable energy technology, the geographic location, and the scale of implementation. In general, renewable energy sources such as wind, solar, hydro, and biomass are sensitive to climatic shifts in temperature, precipitation, and weather patterns.

1. **Solar Energy:** Solar energy, harnessed through photovoltaic (PV) cells, is highly dependent on sunlight, which is influenced by seasonal and geographic variability in cloud cover, temperature, and irradiance. Climate change may lead to altered solar radiation patterns, which could affect the efficiency of solar energy systems in certain regions. For example, regions experiencing more intense heat or extreme weather events may see a reduction in solar panel efficiency or more frequent maintenance requirements due to temperature-related stress on equipment (Pfenning et al., 2021).
2. **Wind Energy:** Wind power generation depends on wind patterns, which are influenced by temperature differences, jet stream shifts, and atmospheric circulation changes. Climate change models predict that certain regions may experience stronger or more erratic winds, while others may see a decline in wind speeds, making wind power generation more intermittent or unpredictable. Research indicates that the wind potential in regions such as Europe and parts of North America may increase, while areas in the tropics or some inland regions may see a reduction in wind capacity (Tobin et al., 2014).
3. **Hydropower:** Hydropower relies on consistent water availability and flow patterns, which are directly impacted by changes in precipitation, snowmelt, and drought frequency. Climate change has already altered hydrological cycles, leading to more unpredictable water flows in river basins. In some regions, changing rainfall patterns may lead to water shortages and reduced hydropower generation, while in other areas, excessive rainfall and flooding could threaten the stability of existing infrastructure (Milly et al., 2005).
4. **Biomass:** Biomass energy, which is derived from organic materials such as wood, agricultural residues, and waste, may also be impacted by climate change. Shifts in temperature and precipitation can affect the growth cycles and productivity of

bioenergy crops. Longer growing seasons in some areas may benefit biomass production, while extreme heat or drought conditions could threaten yields (Lemoine et al., 2017).

As the effects of climate change continue to evolve, there are growing efforts to adapt renewable energy systems to changing conditions. Several adaptation strategies are being explored to enhance the resilience of renewable energy sources:

- **Geographic diversification:** To mitigate the risk of localized climate impacts on energy generation, it is essential to diversify renewable energy installations across different regions. By spreading out the production of renewable energy systems, countries can ensure a more stable energy supply even if specific regions experience adverse climate effects (Lehmann et al., 2020).
- **Technological innovations:** Advancements in renewable energy technologies, such as more efficient solar panels, advanced wind turbines, and flexible hydropower systems, can help improve the adaptability of these systems. Researchers are exploring materials and design improvements that allow energy systems to function more effectively under extreme weather conditions (Huang et al., 2021).
- **Energy storage:** The intermittent nature of renewable energy sources requires the development of energy storage technologies that can help smooth out fluctuations in energy generation. As renewable energy systems are increasingly integrated into national grids, battery storage solutions and other energy storage technologies are vital to maintaining reliable power supplies even when weather conditions are less favorable for generation (Shao et al., 2020).

Global Research Trends

Global research on the intersection of climate change and renewable energy has expanded in recent years, driven by the urgency to reduce greenhouse gas emissions and the need to mitigate climate-related risks. Studies emphasize the role of renewable energy in climate change mitigation strategies, illustrating how renewable energy deployment can reduce dependency on fossil fuels and significantly decrease global carbon emissions. Additionally, the importance of understanding and forecasting the impacts of climate change on energy systems has prompted interdisciplinary research combining climate science, engineering, and policy studies.

For instance, studies in Europe and North America have shown how wind and solar power capacities are expected to evolve under different climate scenarios. Research in the tropics has highlighted the challenges of maintaining reliable hydropower systems in regions increasingly prone to droughts, while in Asia, efforts are focused on integrating renewable energy with existing infrastructure to enhance resilience (IPCC, 2022).

The relationship between climate change and renewable energy is complex, with both opportunities and challenges. While renewable energy is a key solution for mitigating the effects of climate change, the changing climate itself poses risks to the reliability and efficiency of renewable energy systems. Ongoing research, technological innovation, and adaptation strategies are critical to overcoming these challenges and ensuring that renewable energy continues to play a central role in the transition to a sustainable, low-carbon future.

The Renewable Energy Landscape in Greece

Policy, market trends, and renewable energy targets in Greece

Greece, as a member of the European Union, has committed to achieving ambitious goals for transitioning to a low-carbon economy, significantly impacting the renewable energy sector. The country's legislative and regulatory framework has been reshaped in recent years to promote investment in clean energy sources and reduce reliance on fossil fuels.

Greece has set specific targets in its National Energy and Climate Plan (NECP), aiming for 70% of electricity generation to come from renewables by 2030. The development of solar and wind energy is a primary goal, leveraging the country's high solar potential and favorable geographical conditions for wind turbine installations. The government has introduced incentives such as tax exemptions, subsidies, and competitive tenders for new renewable energy projects to boost investment activity.

The Greek renewable energy market is experiencing increased activity, with a strong presence of both domestic and international investors. Investments in photovoltaic and wind farms have significantly increased, while there is a growing interest in energy storage through battery systems and green hydrogen production. At the same time, Greece's decarbonization strategy, a key component of the national energy plan, creates further demand for the rapid expansion of renewables.

Despite the positive outlook, climate change may impact the viability of renewable energy investments in Greece. Rising temperatures could reduce the efficiency of photovoltaic panels, while changing wind patterns may affect the performance of wind farms. Additionally, the increasing frequency of extreme weather events, such as heatwaves and wildfires, could create operational challenges for renewable energy facilities and raise maintenance costs.

Nevertheless, Greece has significant opportunities for further growth in the sector. Technological advancements, improved infrastructure, and strengthened policies for climate change adaptation can ensure that renewable energy investments remain profitable and resilient to future climate challenges. Diversifying the energy mix, promoting hybrid projects that combine different renewable technologies, and enhancing energy storage capabilities are crucial elements for climate adaptation.

With its rich natural potential and strategic location, Greece can evolve into a regional renewable energy hub, contributing to both its energy security and environmental goals. However, the success of the energy transition depends on the country's ability to adapt to changing conditions and integrate innovative solutions that will ensure the long-term sustainability of the renewable energy sector.

Climate Risks in Renewable Energy Production

Effects of heatwaves on solar efficiency, wind variability, and their economic impacts

Climate change poses significant challenges to renewable energy production, particularly in countries like Greece, where extreme weather conditions are becoming more frequent. Two major concerns are the effects of heatwaves on solar panel efficiency and the increasing variability of wind patterns. These factors have direct economic implications, affecting energy output, grid stability, and investment decisions.

Heatwaves and Solar Efficiency

Solar photovoltaic (PV) systems perform best at moderate temperatures. However, during heatwaves, when temperatures rise above 40°C, PV panel efficiency declines due to increased electrical resistance and thermal stress. Studies indicate that for every 1°C rise in temperature, solar panel efficiency can drop by 0.3% to 0.5%. This reduction in efficiency lowers electricity generation precisely when energy demand for cooling is at its peak, leading to higher grid stress and potential energy shortages. Additionally, prolonged exposure to extreme heat accelerates equipment degradation, increasing maintenance costs.

Wind Variability and Economic Consequences

Wind power generation depends on stable wind patterns, but climate change is disrupting these conditions. Heatwaves can lead to reduced wind speeds, a phenomenon known as “global stilling,” which decreases wind turbine productivity. This unpredictability in wind resources creates financial risks for investors and operators, as fluctuating power generation affects revenue streams.

Economic Impact

The decline in renewable energy output during extreme weather events forces greater reliance on fossil fuels, increasing electricity costs and undermining decarbonization efforts. To mitigate these risks, investments in energy storage and adaptive grid infrastructure are essential for ensuring long-term sustainability.

Economic and Investment Perspectives

The renewable energy sector in Greece is rapidly expanding, driven by national decarbonization goals and European Union climate policies. However, climate risks such as extreme heatwaves and wind variability pose economic and investment challenges that must be addressed to ensure the long-term viability of renewable energy projects.

Investment Uncertainty Due to Climate Risks

Heatwaves and changing wind patterns affect energy production, leading to fluctuations in revenue for renewable energy investors. Reduced solar panel efficiency during extreme heat

and lower wind speeds can cause financial instability, as power generation may not meet expected levels. This unpredictability increases the perceived risk of renewable energy investments, potentially discouraging financial institutions from funding new projects or leading to higher capital costs for developers.

Rising Costs and Market Adjustments

Climate-related risks may also increase operational and maintenance costs. Solar farms exposed to prolonged heatwaves require more frequent equipment replacements, while wind farms experiencing irregular wind speeds may struggle with efficiency losses. Additionally, extreme weather conditions could damage infrastructure, leading to unexpected repair costs.

To mitigate these risks, investors and policymakers are focusing on adaptive strategies such as improved grid storage solutions, hybrid renewable systems, and enhanced forecasting technologies. Government incentives, such as subsidies for battery storage and flexible grid operations, are essential to maintaining investor confidence and stabilizing market conditions.

Despite climate challenges, Greece remains an attractive market for renewable energy investments. Strategic policy measures and technological advancements can help secure long-term growth and ensure resilience against climate-induced economic disruptions.

Renewable energy as an economic stabilizer

Renewable energy plays a crucial role in stabilizing economies by reducing dependence on fossil fuel imports, creating jobs, and ensuring long-term energy security. In countries like Greece, where energy markets are sensitive to global fuel price fluctuations, the expansion of renewable energy sources such as solar, wind, and hydropower provides a buffer against economic volatility.

By investing in renewables, Greece can decrease its reliance on expensive energy imports, improving its trade balance and reducing exposure to geopolitical risks. Additionally, renewable energy projects generate employment opportunities across multiple sectors, including manufacturing, installation, and maintenance, contributing to economic growth and workforce development.

Furthermore, renewables offer price stability compared to fossil fuels, which are subject to market fluctuations. Solar and wind energy have minimal operational costs once installed, ensuring more predictable electricity prices for consumers and businesses. This stability enhances economic planning and supports industries reliant on affordable energy.

The long-term economic benefits of renewables are reinforced by technological advancements and supportive policies. Investments in energy storage and grid modernization further strengthen Greece's energy resilience, making renewables a key pillar of economic stability in an era of climate and financial uncertainty.

Risk factors for investors due to climate change variability

Climate change poses significant risks for renewable energy investors in Greece, affecting project viability, financial returns, and long-term market stability. As extreme weather events become more frequent, investors must navigate uncertainties related to energy production, infrastructure resilience, and regulatory adaptations.

1. Variability in Renewable Energy Output

One of the primary risks is the impact of climate variability on energy generation. Heatwaves reduce the efficiency of solar panels, while wind droughts lead to lower-than-expected wind power output. Such inconsistencies make it difficult to predict energy production levels, causing financial uncertainty for investors who rely on stable returns from renewable energy projects. This variability may also lead to higher balancing costs, as grid operators compensate for fluctuations by integrating alternative power sources.

2. Infrastructure and Maintenance Challenges

Rising temperatures, wildfires, and storms can damage renewable energy infrastructure, leading to unexpected repair and maintenance costs. For example, prolonged exposure to extreme heat accelerates the degradation of photovoltaic panels, while strong winds and flooding can damage wind turbines and hydropower facilities. These additional expenses can lower the profitability of investments and require contingency planning.

3. Policy and Regulatory Risks

Governments and regulatory bodies may introduce new policies to address climate risks, potentially affecting investment strategies. While Greece has committed to supporting renewable energy through incentives, the evolving regulatory landscape—such as changes in subsidies, carbon pricing mechanisms, or energy storage mandates—can create uncertainties for investors. Delays in permitting processes and grid integration challenges also add to financial risks.

4. Market and Economic Impacts

Fluctuations in renewable energy output due to climate variability can impact electricity prices and market stability. Periods of low solar or wind generation may lead to increased reliance on fossil fuels, driving up energy costs and reducing investor confidence in renewables. Additionally, financial institutions may impose stricter lending requirements due to climate-related risks, increasing the cost of capital for new projects.

Mitigation Strategies

To address these risks, investors are focusing on diversified energy portfolios, energy storage solutions, and advanced forecasting technologies. Strengthening infrastructure resilience and advocating for stable regulatory policies will be critical in maintaining investor confidence in Greece's renewable energy sector.

Chapter 3: Methodology

Research Design

Qualitative and quantitative approach

The qualitative and quantitative approach refers to two fundamental methodologies used in research to collect, analyze, and interpret data. These approaches are often combined in mixed-methods research to provide a comprehensive understanding of a topic.

Quantitative Approach

The quantitative method focuses on numerical data and statistical analysis to measure patterns, trends, and relationships. It relies on structured data collection methods such as:

- Surveys & Questionnaires (with closed-ended questions)
- Experiments
- Statistical Models & Data Analytics

Qualitative Approach

The qualitative method focuses on descriptive and subjective data that helps understand motivations, opinions, and underlying reasons. It relies on:

- Interviews & Open-ended Survey Responses
- Observations & Case Studies
- Thematic Analysis & Content Interpretation

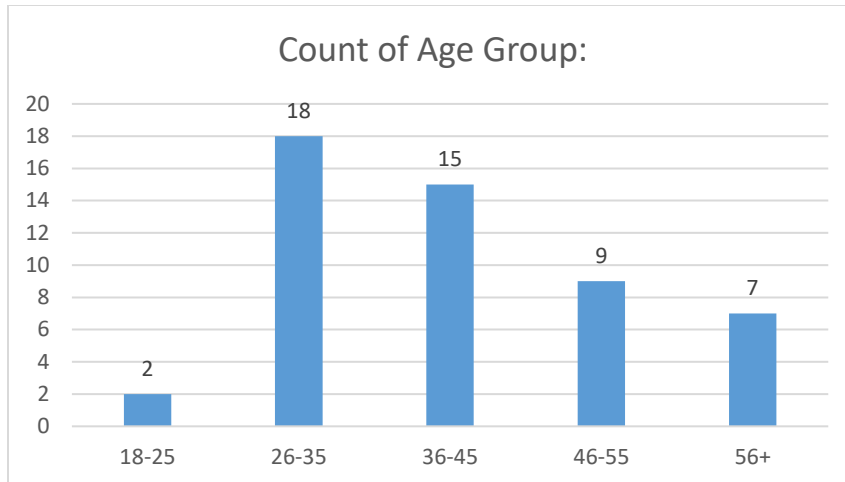
Data Collection

Primary sources: Questionnaires (with closed-ended questions)

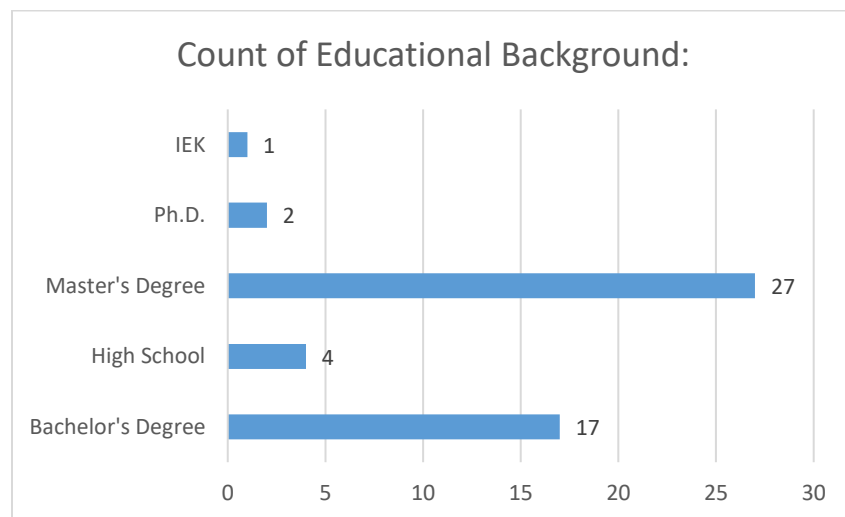
Collecting data through a questionnaire is essential as it provides structured, quantifiable insights from a targeted audience. It ensures consistency, efficiency, and comparability, allowing researchers to analyze trends, measure perceptions, and make data-driven decisions. In this study, data was collected from 51 respondents, primarily from energy-related companies and retail businesses.

Demographic Breakdown

- What is your age group? → Majority of respondents are between 26-45 years old.

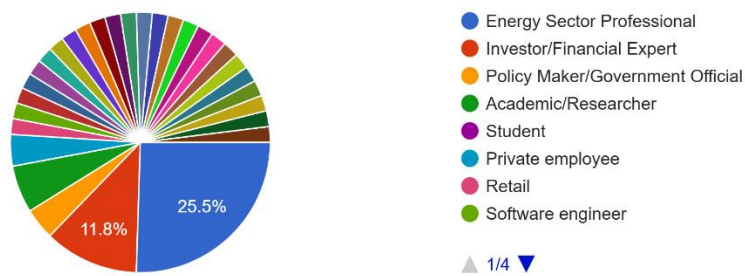


- What is your educational background? → Most hold a Master's or Bachelor's degree.



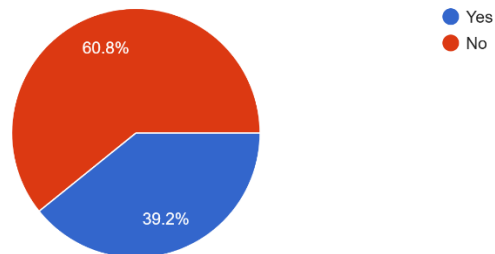
- What is your occupation? → The primary group includes Energy Sector Professionals, followed by Investors and Policymakers.

Occupation:
51 responses



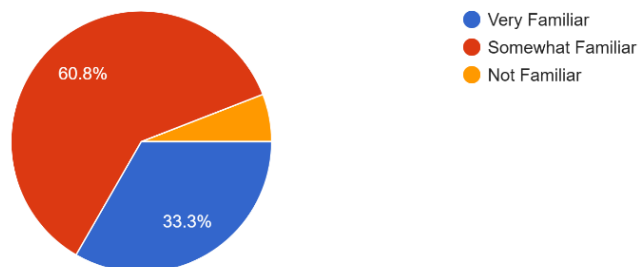
- Have you invested or worked in renewable energy projects in Greece? → More than half haven't been directly involved in the sector.

Have you invested or worked in renewable energy projects in Greece?
51 responses



- How familiar are you with the impact of climate change on renewable energy? → Most respondents are somewhat familiar or very familiar.

How familiar are you with the impact of climate change on renewable energy?
51 responses

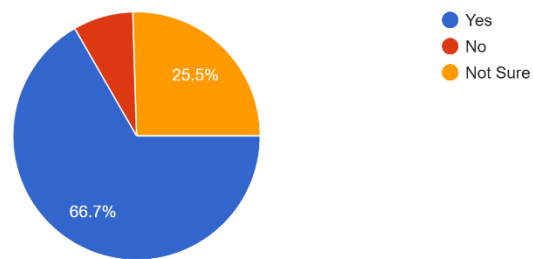


2. Climate Change Impact on Renewable Energy

- Do you believe climate change significantly impacts renewable energy production in Greece? → 34 answered "Yes", showing strong agreement.

Do you believe climate change significantly impacts renewable energy production in Greece?

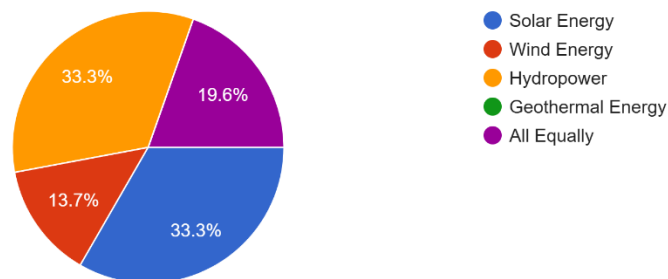
51 responses



- Which renewable energy source is most affected by climate change? → Hydropower and Solar Energy was identified as the most impacted followed by All Equally.

Which renewable energy source is most affected by climate change in Greece?

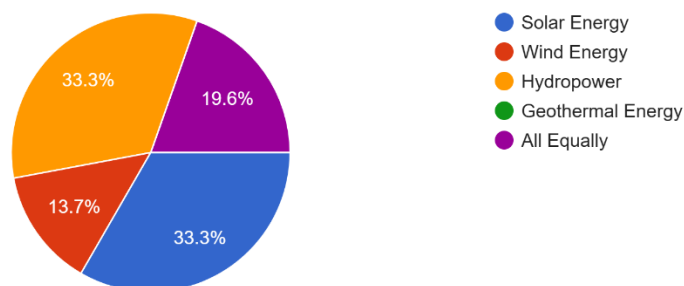
51 responses



- How concerned are you about extreme weather events affecting renewable energy output? → 78% are highly concerned about heatwaves and wind variability.

Which renewable energy source is most affected by climate change in Greece?

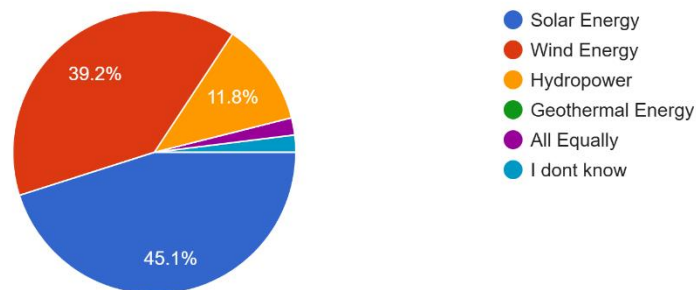
51 responses



- Which renewable energy source have the most installed power (Giga Watts) in Greece?
→The majority answered correctly that Solar Energy have the most Gw installed, it is interesting thou that 20 people think that Wind energy have the most. Probably because of the visual impact that wind farms have in comparison to Solar Parks.

Which renewable energy source have the most installed power (Giga Watts) in Greece?

51 responses

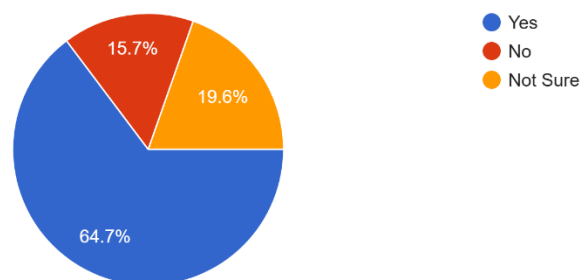


3. Investment Risks and Economic Considerations

- Do you think climate change increases investment risks in renewable energy projects?
→ 65% see climate change as a key investment risk.

Do you think climate change increases investment risks in renewable energy projects?

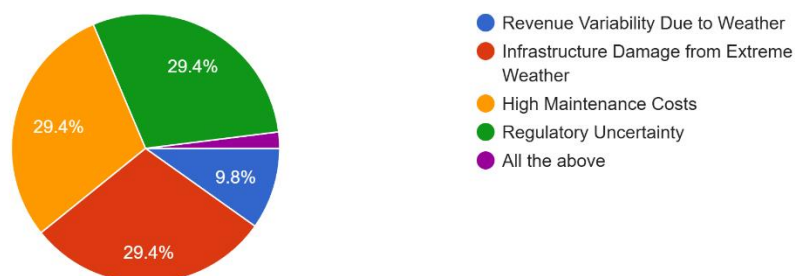
51 responses



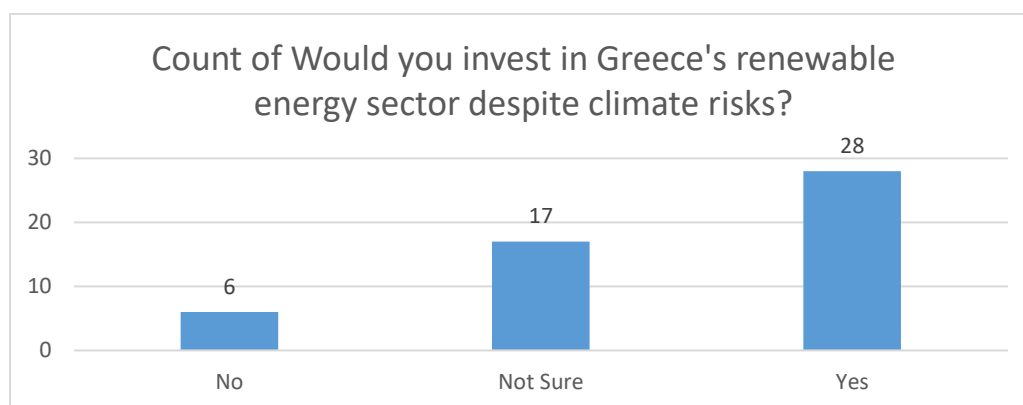
- Which climate-related risk discourages renewable energy investment the most? → Regulatory uncertainty, infrastructure damage from extreme weather and high maintenance costs were the most common responses with 15 answers each. Regulatory uncertainty is an answer that is not related to the investments returns so we can see that 15 people didn't fully understand this question.

Which climate-related risk discourages renewable energy investment the most?

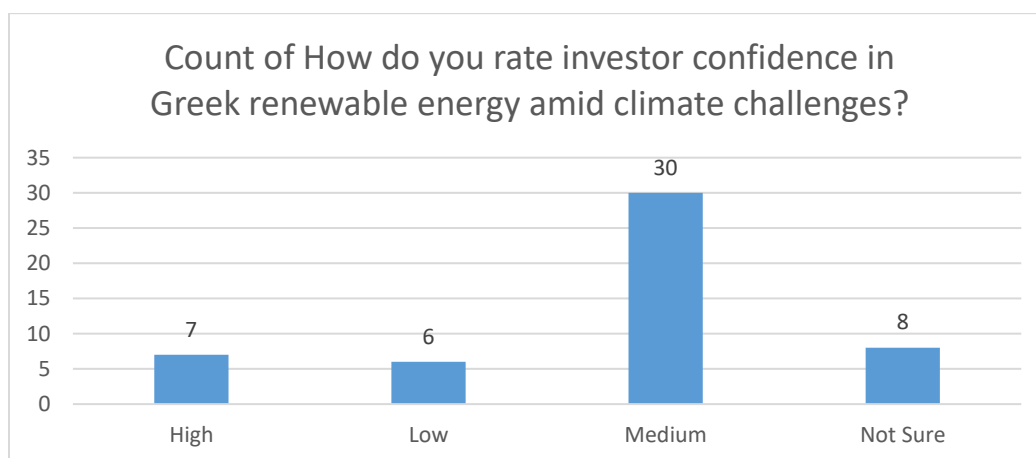
51 responses



- Would you invest in Greece's renewable energy sector despite climate risks? → A majority still see investment potential but with concerns. 55% is a very positive answer but is smaller than the actual numbers that more than 2.5GW of RES parks are waiting with a declaration of readiness.



- How do you rate investor confidence in Greece's renewable energy sector? → Confidence is moderate (30 medium and 6 Low), but uncertain due to regulatory risks.

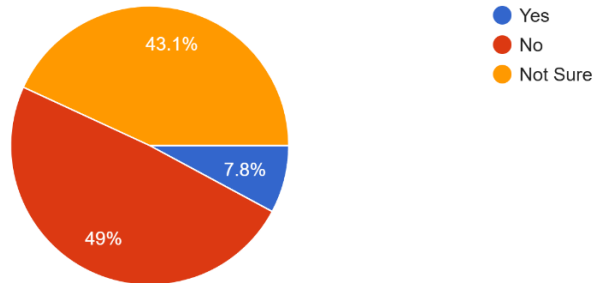


4. Policy and Technological Solutions

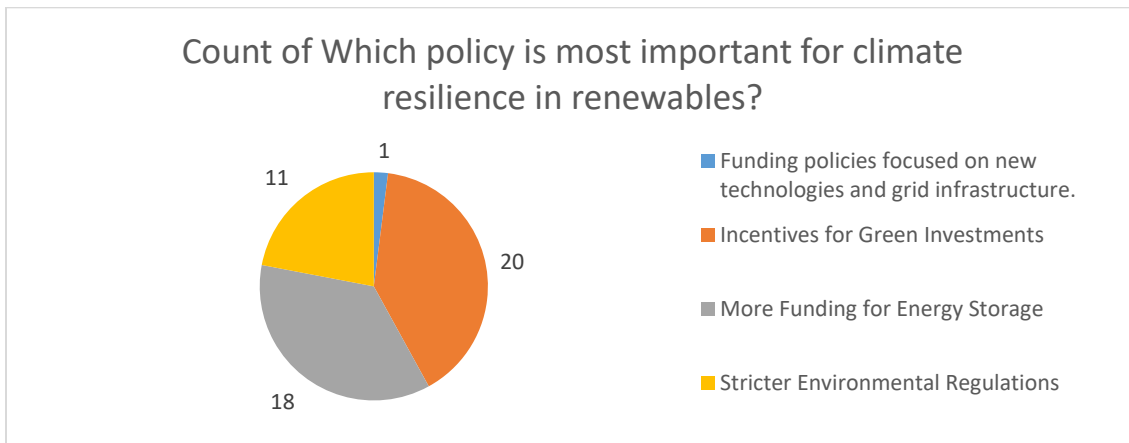
- Do you believe Greece's renewable energy policies are sufficient to address climate risks? → 25 people don't believe current policies are insufficient and only 8% believe that there are sufficient.

Do you believe Greece's renewable energy policies are sufficient to address climate risks?

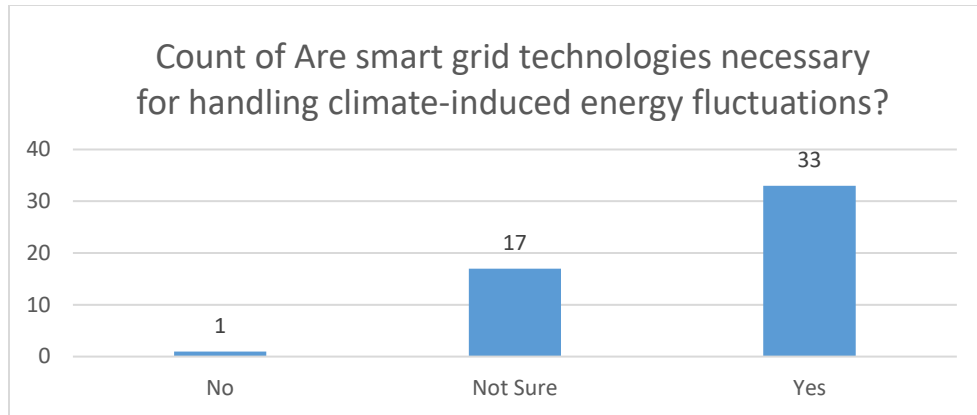
51 responses



- Which policy is most important for climate resilience in renewables? → Funding for energy storage and investment in incentives ranked highest.

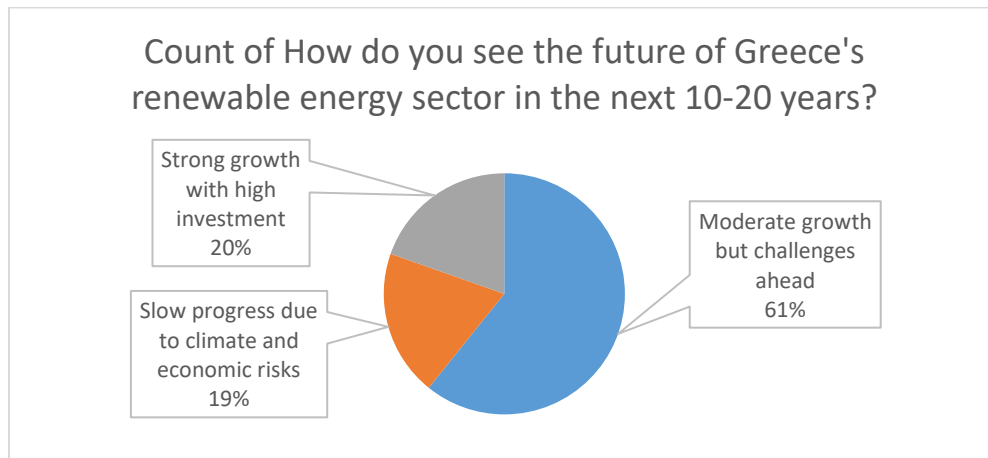


- Are smart grids necessary to handle climate-related energy fluctuations? → 71% strongly support smart grid integration.



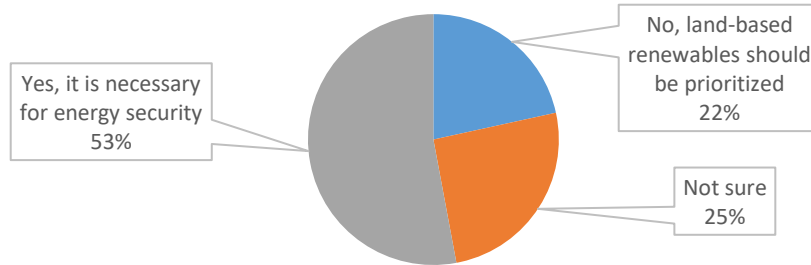
5. Public Perception and Future Outlook

- How do you see the future of Greece's renewable energy sector in the next 10-20 years?
→ 60% foresee moderate growth but challenges ahead.



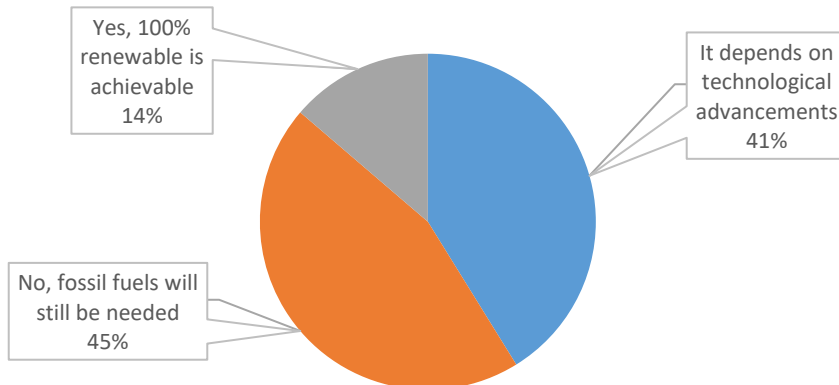
- Would you support investment in offshore wind and floating solar? → 53% support offshore renewable projects as a long-term solution.

Count of Do you think Greece should increase investment in offshore wind and floating solar farms to prepare for future energy demands?

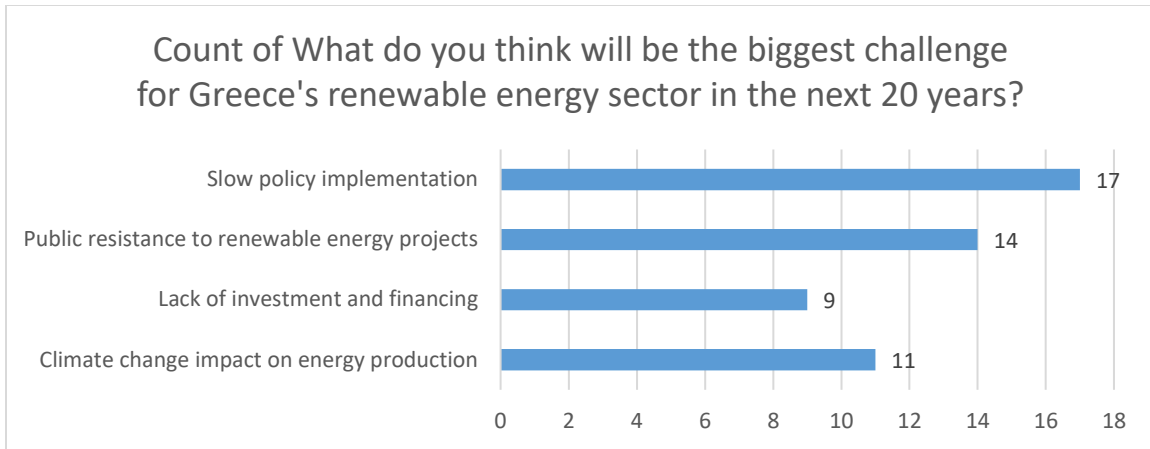


- Do you think Greece will rely entirely on renewable energy by 2050? → Only 14% believe full reliance on renewables is achievable. But also a big portion, 41%, believes that through technological achievements that target is reachable until 2050.

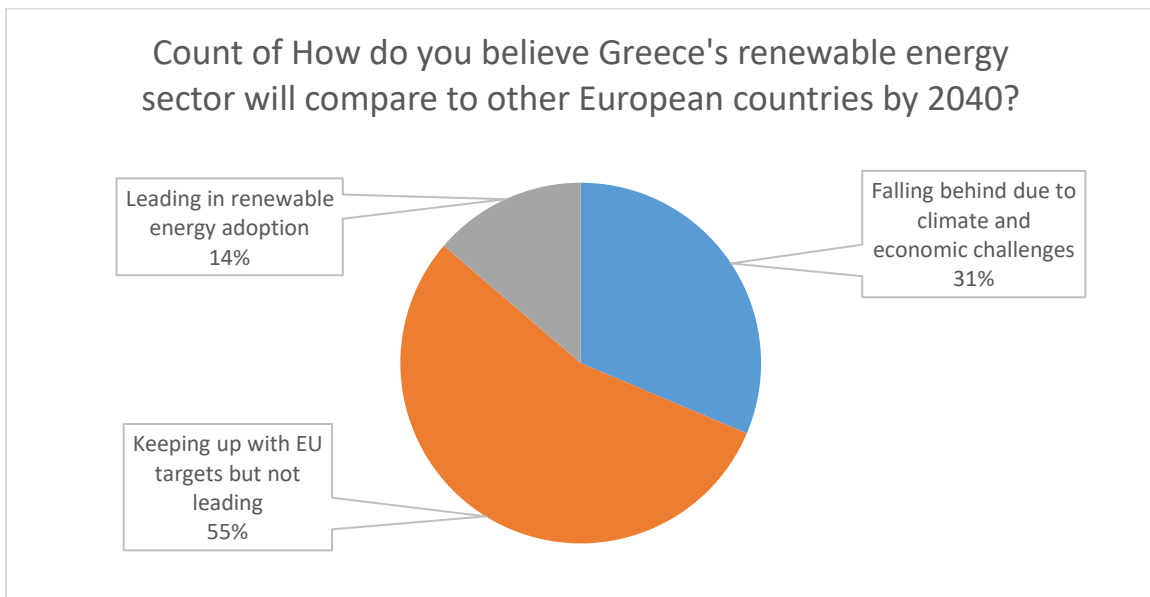
Count of In your opinion, will Greece rely entirely on renewable energy by 2050?



- What is the biggest challenge for Greece's renewable energy sector? → Climate impact, slow policy implementation, and public resistance were top concerns.



- How do you believe Greece will compare to other European countries in renewable energy by 2040? → Most believe Greece will keep up but not lead.



Secondary sources: Climate data, energy production statistics

Secondary sources, such as climate data and energy production statistics, are essential for providing context and validation to the research findings. They offer reliable, historical, and comparative insights, ensuring accuracy and depth in the analysis. In this study, data from official reports and industry publications were utilized to support key conclusions.

Greece, located in the southeastern part of Europe, has experienced significant shifts in its climate patterns and energy production landscape over the past decades. Understanding these changes is crucial for policymakers, researchers, and stakeholders aiming to navigate the challenges and opportunities presented by climate change and the transition to renewable energy sources.

Climate Data in Greece

Greece's climate is predominantly Mediterranean, characterized by hot, dry summers and mild, wet winters. However, recent years have witnessed notable deviations from these norms, attributed largely to global climate change.

- **Temperature Trends:** The country has experienced a rise in average temperatures, leading to more frequent and intense heatwaves. The summer of 2024, for instance, was recorded as the hottest on record, exacerbating the risk of wildfires and heat-related health issues.
- **Precipitation Patterns:** Alterations in rainfall distribution have been observed, with certain regions facing prolonged droughts while others encounter unexpected heavy rainfall, leading to floods. These changes pose challenges to water resource management, agriculture, and infrastructure planning.
- **Extreme Weather Events:** There has been an uptick in the frequency and severity of extreme weather events, including storms and unseasonal temperature fluctuations, impacting both urban and rural communities.

Greenhouse Gas Emissions

Greece's greenhouse gas (GHG) emissions have undergone significant changes over the years:

- **Total Emissions:** In 2022, the country's GHG emissions were approximately 77.0 million tons of CO₂-equivalent, marking a 0.6% decrease compared to 2021. European Climate Adaptation Platform
- **Sectoral Contributions:** The primary contributors to GHG emissions include electricity and heat production, transportation, and industrial processes. Efforts to mitigate emissions focus on transitioning to renewable energy sources and enhancing energy efficiency across these sectors.

Energy Production Statistics

Greece's energy sector has been transitioning, with a notable shift towards renewable energy sources:

- **Electricity Generation:** As of December 2024, Greece's electricity production was approximately 4,596.46 GWh. [Trading Economics](#)
- **Renewable Energy Integration:** Renewables have seen substantial growth, with wind energy being the second-largest source. By 2023, wind farms had a cumulative capacity of 5.2 GW, generating around 10.9 TWh of electricity. [statista.com](#)
- **Energy Mix:** The domestic energy production in 2023 was diversified, with renewables contributing 42%, coal 26%, and other sources making up the remainder. [International Energy Agency](#)

Policy Initiatives and Future Goals

Greece has set ambitious targets to enhance its renewable energy capacity and reduce carbon emissions:

- **National Energy and Climate Plan:** The revised plan aims for an 82% share of renewable energy in electricity production by 2030, up from the previous target of 66%. [Reuters](#)
- **Climate Performance:** The country has risen six places to 22nd in the Climate Change Performance Index, reflecting improvements in GHG emissions, renewable energy adoption, and energy use. [ccpi.org](#)

Challenges and Considerations

Despite progress, Greece faces several challenges: [Reuters](#)

- **Economic Impacts:** High electricity prices have burdened businesses and households, particularly in southeastern Europe, affecting economic growth. [Reuters+1apnews.com+1](#)
- **Infrastructure Needs:** Enhancing grid infrastructure and storage capacity is essential to accommodate the increasing share of renewable energy and ensure stability.
- **Climate Resilience:** Addressing the impacts of climate change, such as water scarcity and extreme weather events, requires comprehensive adaptation strategies. [ft.com](#)

Conclusion

Greece's commitment to expanding renewable energy and mitigating climate change effects is evident through its updated policies and achievements. However, continuous efforts are necessary to overcome economic, infrastructural, and environmental challenges to ensure a sustainable and resilient energy future. [Reuters](#)

Data Analysis

Analysis of climate data's correlation with renewable energy outputs

To understand how climate change affects renewable energy production, historical climate data was compared with renewable energy output data across solar, wind, and hydropower sources in Greece.

- **Solar Energy:** Rising temperatures and extended periods of heat have slightly decreased PV efficiency, especially during peak summer months. However, total annual production has increased due to more sunny days.
- **Wind Energy:** Changing wind patterns have led to variability in wind farm output. Some regions reported lower average wind speeds, affecting consistency.
- **Hydropower:** This sector is the most affected due to shifting rainfall patterns and prolonged droughts. Reduced water availability during dry seasons has significantly impacted hydroelectric plant output. These correlations highlight the vulnerability of renewables, especially hydropower, to ongoing climate variability.

Financial modeling to assess investment impacts

Financial modeling was used to assess how climate risks influence renewable energy investments. Using projected climate scenarios and energy production trends, we analyzed:

- **Risk-adjusted Return on Investment (ROI):** Climate volatility introduces uncertainty in production, reducing the predictability of energy yields and cash flows.
- **Operation & Maintenance Costs:** Increased frequency of extreme weather events leads to higher maintenance needs, especially for wind and solar installations.
- **Investment Incentives:** Public subsidies and incentives were found to be critical in offsetting perceived risks. Survey respondents highlighted the need for policy stability and long-term financial support.
- **Payback Periods:** Due to higher initial investments in resilience and adaptation technologies (e.g., battery storage, smart grids), payback periods are slightly extended, yet remain competitive when supported by government schemes. This financial analysis confirms that while climate change introduces new risks, proactive measures and policy support can maintain the sector's attractiveness for investors.

Conclusion

The findings of this chapter provide a multi-dimensional understanding of how climate change affects the renewable energy investment landscape in Greece. The results demonstrate a high level of awareness among professionals and stakeholders regarding the vulnerability of renewable energy sources, particularly hydropower, to climatic changes such as droughts, temperature extremes, and wind pattern variability.

There is strong recognition that climate change increases investment risks, influencing return predictability and increasing maintenance costs. However, the data also suggests that these risks can be mitigated through government support, technological upgrades, and climate-resilient infrastructure. Respondents expressed strong support for smart grid integration, energy storage investments, and more aggressive policy action.

The financial modeling aligns with the perceptions captured in the questionnaire, reinforcing that climate volatility affects operational performance and long-term financial planning. Despite these risks, the sector remains attractive due to favorable policies and a shared belief in the strategic importance of renewable energy.

Overall, the data analysis confirms the need for a well-coordinated approach that combines public awareness, investment in technology, regulatory consistency, and financial support mechanisms to ensure the resilience and continued growth of Greece's renewable energy sector in the face of climate change.

Chapter 4: Impact of Climate Change on Renewable Energy Production in Greece

Solar Energy Production and Climate Sensitivity

Temperature effects on solar panel efficiency

Greece, with its abundant sunshine, is heavily investing in solar energy to meet its renewable energy targets. However, climate change poses challenges that could impact the efficiency and long-term sustainability of solar power generation. One of the most critical factors affecting solar energy production is temperature sensitivity, as rising temperatures can reduce the efficiency of photovoltaic (PV) panels.

Solar panels convert sunlight into electricity with optimal performance under standard test conditions, typically at 25°C (77°F). However, as temperatures increase beyond this point, the efficiency of solar cells declines due to the negative temperature coefficient of photovoltaic materials. Studies indicate that for every 1°C rise in temperature, PV module efficiency decreases by approximately 0.3% to 0.5%, depending on the panel technology. Given Greece's increasingly frequent heatwaves, where summer temperatures often exceed 40°C (104°F), solar panel efficiency losses can be significant.

The economic impact of temperature-induced efficiency loss is substantial. Reduced energy output means lower returns for investors, while high temperatures can also accelerate material degradation, leading to increased maintenance costs. Moreover, excessive heat can cause inverters and transformers to overheat, potentially leading to system failures and costly repairs.

To mitigate these effects, Greece's solar energy sector must adopt climate adaptation strategies, such as improved cooling technologies, elevated panel installations for better airflow, and research into high-temperature-resistant photovoltaic materials. Addressing these climate risks is essential for maintaining Greece's progress in renewable energy adoption.

Seasonal and extreme weather impacts

Renewable energy production in Greece is highly influenced by seasonal variations and extreme weather events. During summer, heatwaves reduce solar panel efficiency due to high temperatures, while in winter, shorter daylight hours and cloud cover limit solar energy output. Wind energy is also affected by seasonal wind variability, with periods of reduced wind speeds impacting power generation. Extreme weather events, such as storms, wildfires, and heavy snowfall, can damage renewable infrastructure, leading to costly repairs and energy production losses. To ensure stability, Greece must invest in adaptive technologies, grid improvements, and energy storage solutions.

Wind Energy Production and Climate Variability

Wind pattern shifts and energy production

Wind energy is a crucial component of Greece's renewable energy transition, contributing significantly to the country's electricity supply. However, climate variability is altering wind patterns, potentially impacting wind energy production. Changes in atmospheric circulation, temperature differentials, and seasonal variability influence wind speeds and direction, leading to fluctuations in energy output.

One notable concern is the phenomenon of "global stilling," where average wind speeds have been observed to decline in some regions due to climate change. Reduced wind speeds result in lower power generation, particularly in areas heavily reliant on wind farms. Conversely, extreme weather events, such as storms and strong gusts, can exceed turbine design limits, causing operational shutdowns or infrastructure damage. These factors introduce uncertainty in wind energy production, affecting grid stability and investor confidence.

Seasonal variations also play a role in wind energy output. In Greece, wind speeds are typically higher during winter and lower in summer. However, as climate change disrupts traditional weather patterns, these seasonal cycles may become less predictable, complicating energy planning and storage requirements.

To mitigate these risks, Greece must enhance wind energy forecasting, invest in diversified renewable sources, and improve grid flexibility. Advanced turbine technology designed to function efficiently under varying wind conditions can also help optimize production. Addressing climate-related wind variability is essential to maintaining Greece's renewable energy targets and ensuring long-term energy security.

Case studies of wind farms affected by climate anomalies

Climate change is increasingly influencing renewable energy production worldwide, and Greece is no exception. Wind energy, a key component of Greece's renewable energy strategy, is particularly vulnerable to climate anomalies such as shifting wind patterns, extreme weather events, and prolonged heatwaves. These factors impact the efficiency, reliability, and financial viability of wind farms across the country.

One significant case study is the **Crete Wind Farm Network**, where operators have reported irregular wind patterns in recent years. Studies indicate that rising temperatures and atmospheric pressure variations have led to reduced wind speeds, particularly during the summer months. This phenomenon, known as "global stilling," affects wind turbine performance, leading to lower-than-expected electricity generation and financial losses for investors.

Another example is the **Mainland Greece Wind Corridor**, which includes wind farms in regions such as Thrace and Central Greece. These areas have traditionally benefited from strong and consistent winds. However, climate models predict increased variability in wind speeds, with more frequent occurrences of both extreme gusts and low-wind periods. This unpredictability

poses challenges for grid stability and energy market pricing, requiring additional investment in energy storage and grid flexibility solutions.

Additionally, **extreme weather events** such as storms and heatwaves have impacted wind farm infrastructure. In 2021, severe storms in Northern Greece led to turbine damage and temporary shutdowns, emphasizing the need for more resilient designs and adaptive strategies.

To mitigate these risks, Greece is investing in advanced forecasting models, hybrid renewable energy systems, and improved turbine technology to ensure continued efficiency and profitability.

Hydropower and Geothermal Energy

Potential impacts on smaller-scale renewable sources in Greece

Greece, with its diverse geography and renewable energy potential, has been expanding its use of hydropower and geothermal energy. While these sources contribute to the country's decarbonization goals, their development could have both positive and negative implications for smaller-scale renewable energy projects, such as distributed solar photovoltaic (PV) systems and small wind installations.

Hydropower's Influence on Small-Scale Renewables

Hydropower has long been a key component of Greece's energy mix, particularly through large-scale dams and run-of-river projects. However, the expansion of hydropower can impact small-scale renewable sources in several ways. Firstly, hydropower provides grid stability by offering a reliable baseload power supply, which can support the integration of intermittent renewables like solar and wind. On the other hand, increased hydropower generation may reduce market opportunities for small-scale producers by lowering wholesale electricity prices during peak production periods.

Moreover, the environmental impact of new hydropower projects, such as altered river ecosystems and land-use conflicts, may lead to stricter regulations, potentially affecting the overall renewable energy sector, including small-scale initiatives.

Geothermal Energy's Role and Challenges

Greece has significant geothermal potential, particularly in regions such as the Aegean islands and northern Greece. Geothermal energy offers stable and continuous power generation, which can complement intermittent renewables. However, its expansion could compete with small-scale renewables for grid capacity and investment incentives. Additionally, geothermal projects require high initial capital costs and extensive exploration, which could divert public and private funding from smaller solar and wind projects.

While hydropower and geothermal energy provide valuable contributions to Greece's clean energy transition, careful policy planning is necessary to ensure that their growth does not hinder the progress of small-scale renewable sources.

Chapter 5: Economic Implications for Renewable Energy

Investments

Investment Risks and Financial Performance

Revenue risks from production variability

Investing in renewable energy in Greece presents both opportunities and risks, particularly concerning financial performance and revenue stability. One of the most significant challenges is production variability caused by climate conditions, which directly affects revenue streams for investors.

Solar and wind energy production are highly dependent on weather conditions. Extended periods of low solar radiation or weak wind speeds can lead to decreased energy generation, reducing expected returns. For instance, prolonged heatwaves can lower solar panel efficiency, while shifting wind patterns may cause lower-than-expected wind energy output. This variability creates financial uncertainty, making it difficult for investors to predict revenue with accuracy.

Another critical risk is the volatility of electricity market prices. When renewable energy production fluctuates, grid stability issues may arise, influencing wholesale electricity prices. During periods of low renewable generation, Greece may rely more on conventional energy sources, increasing operational costs and affecting profitability. In contrast, excessive renewable energy production during favorable weather conditions can lead to market saturation, driving prices down and impacting revenue.

To mitigate these risks, investors and policymakers are exploring solutions such as long-term power purchase agreements (PPAs), capacity payments, and enhanced grid storage capabilities. Improved forecasting models and diversified renewable portfolios can also help stabilize financial performance. Despite these risks, strategic investment planning and policy support can enhance the resilience of renewable energy investments in Greece.

Investor confidence and risk tolerance due to climate effects

Investor confidence in Greece's renewable energy sector is influenced by the increasing climate-related risks that affect energy production and financial performance. Climate variability, including extreme weather events and shifting seasonal patterns, introduces uncertainty in revenue generation, directly impacting investor risk tolerance.

One of the key concerns is the unpredictability of renewable energy output. Solar power generation declines during extended heatwaves due to efficiency losses, while wind power can become unreliable due to inconsistent wind patterns. These fluctuations create financial risks, making it challenging for investors to forecast returns with precision. As a result, investors may demand higher risk premiums or hesitate to commit capital to large-scale renewable projects.

Moreover, climate change can affect the physical infrastructure of renewable energy assets. Strong storms, wildfires, and rising temperatures increase maintenance costs and the likelihood

of operational disruptions. Investors must consider these additional financial burdens when evaluating renewable energy opportunities in Greece.

To build investor confidence, the government and financial institutions must implement risk mitigation measures. Long-term contracts such as power purchase agreements (PPAs), insurance mechanisms against extreme weather, and enhanced grid infrastructure can help stabilize investment conditions. Additionally, diversified renewable energy portfolios, including energy storage and hybrid systems, can reduce exposure to climate risks.

Despite these challenges, Greece's commitment to its renewable energy targets and supportive policies play a crucial role in sustaining investor confidence. With proper risk management strategies, renewable energy investments can remain attractive despite climate-related uncertainties.

Costs of Adaptation and Infrastructure Upgrades

Investments needed in storage, grid modernization, and flexibility

As climate variability continues to impact renewable energy production in Greece, significant investments are required to adapt infrastructure and ensure energy reliability. The transition to a resilient renewable energy system demands financial commitments in energy storage, grid modernization, and flexible generation technologies to mitigate climate-related risks.

One of the primary areas of investment is energy storage. Since solar and wind energy production is intermittent and sensitive to weather fluctuations, large-scale battery storage systems are necessary to balance supply and demand. Pumped hydro storage and advanced battery technologies, such as lithium-ion and flow batteries, can help stabilize the grid by storing excess energy during high production periods and releasing it when generation is low. However, these solutions require substantial capital investment, increasing the overall cost of renewable energy projects.

Grid modernization is another crucial aspect of adaptation. Greece's electricity grid must be upgraded to handle decentralized renewable energy sources, integrate smart grid technologies, and improve transmission efficiency. Expanding and reinforcing the grid infrastructure will help reduce bottlenecks, minimize curtailment of renewable energy, and enhance the overall resilience of the energy system against climate-related disruptions.

Additionally, investments in flexible energy systems, such as hybrid renewable power plants and demand response mechanisms, can further improve grid stability. By integrating different renewable energy sources with storage and smart demand management, Greece can optimize energy flows and reduce reliance on fossil fuel-based backup power.

While these infrastructure upgrades come with high initial costs, they are essential for ensuring long-term sustainability and financial viability in the renewable energy sector. Government incentives, private sector funding, and European Union support will play a vital role in facilitating these necessary investments.

Government and EU Policies as Economic Drivers

EU climate policies and funding support

Government and European Union (EU) policies play a crucial role in driving economic growth in the renewable energy sector by providing regulatory frameworks, financial incentives, and funding mechanisms that support investment. In Greece, these policies are essential in mitigating investment risks and ensuring the profitability of renewable energy projects.

The EU's Green Deal and the Fit for 55 package set ambitious decarbonization targets, requiring member states to accelerate their transition to clean energy. Greece, in alignment with these policies, has committed to achieving 70% of electricity production from renewables by 2030. This regulatory certainty enhances investor confidence, as long-term policy commitments reduce financial risks associated with policy changes.

A key driver of investment is EU funding, particularly through mechanisms such as the Recovery and Resilience Facility (RRF), the European Regional Development Fund (ERDF), and the Just Transition Fund (JTF). These programs provide grants and low-interest loans for renewable energy projects, grid modernization, and energy storage solutions. Greece has secured significant funding to expand its renewable energy infrastructure, supporting both large-scale projects and decentralized energy initiatives.

National policies also play a role in economic incentives for renewables. Feed-in tariffs, auctions, tax incentives, and subsidies help attract private investments. Additionally, Greece is reforming its energy market to encourage competition and ensure stable revenues for renewable energy producers.

By leveraging EU policies and funding support, Greece can accelerate its clean energy transition, enhance energy security, and position itself as a leader in the Mediterranean renewable energy market.

National incentives for climate-resilient energy projects

Greece has implemented various national incentives to support climate-resilient energy projects, aiming to enhance renewable energy adoption, improve grid stability, and mitigate the risks associated with climate variability. These incentives provide financial and regulatory support to investors, ensuring the long-term sustainability of the sector.

One of the key mechanisms is the **Renewable Energy Auctions**, which offer long-term contracts to renewable energy producers at competitive prices. This system ensures stable revenue streams while promoting cost efficiency. Additionally, **feed-in premiums** support renewable energy projects by providing guaranteed compensation above market prices, reducing revenue volatility caused by climate-driven fluctuations in production.

To encourage investment in energy storage and grid modernization, the Greek government provides **subsidies and low-interest loans** for battery storage systems, smart grid upgrades, and

hybrid renewable energy solutions. These initiatives improve the resilience of the energy system, reducing the impact of extreme weather events on electricity supply.

Another important incentive is the **tax benefits and accelerated depreciation** for renewable energy investments. Investors can benefit from reduced corporate tax rates and faster asset depreciation, improving project profitability and encouraging capital-intensive investments. Furthermore, **grants for research and innovation** support the development of advanced technologies, such as floating solar farms and offshore wind projects, which can better withstand climate-related risks.

Through these national incentives, Greece strengthens its energy transition while ensuring the resilience of renewable energy infrastructure against climate change, fostering a stable and attractive investment environment.

Chapter 6: Mitigation and Adaptation Strategies for Climate Impact

Technological Innovations and Infrastructure Improvements

Energy storage systems, grid management, and smart technologies

As climate change introduces variability in renewable energy production, technological innovations and infrastructure improvements play a critical role in ensuring grid stability and energy reliability. Three key areas of advancement include energy storage systems, grid management, and smart technologies, all of which enhance the resilience of renewable energy infrastructure.

Energy storage systems are vital for mitigating the intermittency of solar and wind power. Advanced battery storage solutions, such as lithium-ion and flow batteries, allow excess energy to be stored during peak production and discharged during low-generation periods. Additionally, pumped hydro storage remains a reliable large-scale storage solution, especially in Greece, where mountainous terrain provides suitable locations for such projects.

Grid management improvements are essential to accommodate increasing shares of renewables. The implementation of smart grids enables real-time monitoring and dynamic load balancing, ensuring efficient energy distribution. Flexible grid systems incorporate decentralized renewable sources and storage, reducing transmission losses and improving overall system efficiency. Furthermore, high-voltage direct current (HVDC) transmission lines enhance the integration of offshore wind farms and remote solar plants into the national grid.

Smart technologies contribute to climate adaptation by optimizing energy consumption and grid stability. AI-driven forecasting models improve the predictability of solar and wind generation, allowing grid operators to make informed decisions. Internet of Things (IoT) sensors monitor equipment performance, preventing failures due to extreme weather conditions. Meanwhile,

demand response systems allow consumers to adjust electricity usage based on grid supply, increasing overall resilience.

By investing in these innovations, Greece can enhance its renewable energy sector's adaptability to climate risks, ensuring a stable and efficient transition to a sustainable energy future.

Policy Recommendations

Suggested policies to support resilience in renewable energy investments

As Greece continues its transition towards a renewable-based energy system, policymakers must implement targeted strategies to enhance resilience against climate change impacts. These measures should address energy storage, grid modernization, and financial stability, ensuring long-term investor confidence and sustainability.

Expansion of Energy Storage and Grid Modernization Programs

The Greek government should accelerate the deployment of large-scale battery storage and pumped hydro storage projects to stabilize energy supply. The Strategic Plan for Energy Storage (2022) already aims for 3 GW of storage capacity by 2030, but further incentives, such as subsidized loans and tax benefits, are needed to support private sector participation. Grid upgrades, particularly in island interconnections (Cyclades, Crete), should also be prioritized to enhance energy reliability.

Climate Risk Integration into Energy Auctions

Renewable energy auctions in Greece should include climate resilience criteria, rewarding projects that integrate hybrid solutions (solar + storage, wind + hydrogen) or adaptive grid technologies. The Regulatory Authority for Energy (RAE) could introduce a climate risk-adjusted pricing mechanism, ensuring stable returns for investors despite production variability.

Leveraging EU and National Funding for Climate Resilience

Greece should fully utilize EU Recovery and Resilience Facility (RRF) funds, which allocate €1.3 billion for green energy projects. Additionally, expanding the Just Transition Development Plan (JTDP)—which supports post-coal economic restructuring—could provide further financial support for climate-adaptive renewable projects in Western Macedonia and Megalopolis.

Strengthening Investor Confidence through Insurance and Guarantees

To address climate risks, the Greek government should partner with financial institutions to develop risk-sharing mechanisms, such as climate insurance for renewable energy assets. Additionally, an investment guarantee fund under the Hellenic Development Bank could help mitigate risks related to extreme weather impacts on solar and wind farms.

Enhancing Regional Energy Cooperation

Greece should reinforce cross-border electricity interconnections with Bulgaria, Italy, and Egypt, allowing for more efficient balancing of renewable production fluctuations. The Greece-Egypt GREGY interconnection, expected to transport 3 GW of green electricity, is a step in the right direction.

Economic Incentives for Adaptation

Strategies to encourage investments in climate adaptation for renewables

As climate change introduces new challenges for Greece's renewable energy sector, economic incentives are essential to drive investment in climate adaptation measures. A combination of financial support mechanisms, tax incentives, and risk mitigation strategies can encourage developers to invest in resilient infrastructure and adaptive technologies.

Targeted Subsidies for Climate-Resilient Energy Projects

The Greek government should introduce direct subsidies and low-interest loans for renewable energy projects that incorporate climate adaptation features, such as advanced energy storage, reinforced solar panel mounting, and smart grid technologies. The existing Investment Incentives Law (4887/2022) could be expanded to prioritize funding for projects that mitigate risks associated with extreme weather events.

Tax Incentives for Adaptive Infrastructure

To encourage private sector participation, tax benefits should be provided for companies investing in climate-proof renewable assets. Possible measures include:

- Accelerated depreciation for investments in storm-resistant wind turbines and high-temperature-tolerant PV panels.
- Reduced VAT on materials used for energy storage and grid modernization.
- Corporate tax reductions for companies integrating climate resilience into their energy portfolios.

Climate Risk Insurance and Public-Private Risk Sharing

Greece should establish a climate insurance framework for renewable energy investments, covering losses due to heatwaves, wildfires, and wind variability. A Renewable Energy Resilience Fund—backed by the Hellenic Development Bank—could provide guarantees to investors affected by climate-induced disruptions.

EU Funding and Green Bonds for Climate Adaptation

The government should leverage EU Recovery and Resilience Facility (RRF) grants and expand the issuance of green bonds to finance climate adaptation in renewables. The European Investment Bank (EIB) already supports such initiatives, and Greece could channel these funds into solar and wind projects designed for high-temperature and extreme weather resilience.

Performance-Based Incentives for Grid Modernization

The Regulatory Authority for Energy (RAE) could introduce performance-based incentives for renewable operators that improve grid flexibility and stability. Rewarding projects that deploy hybrid solutions (solar + storage, wind + hydrogen) or adaptive grid infrastructure can help mitigate the economic risks of climate variability.

Chapter 7: Discussion and Analysis

Summary of Findings

Key insights from production, economic, and policy analyses

Greece's renewable energy sector is undergoing significant transformation, driven by climate challenges, economic factors, and policy developments. This analysis highlights key findings related to renewable energy production, investment risks, and policy frameworks, shaping the future of the industry.

Climate Change and Renewable Energy Production

- Solar energy is highly vulnerable to rising temperatures, with heatwaves reducing panel efficiency by 0.3% to 0.5% per °C, impacting overall power generation.
- Wind energy faces increased production variability, as shifting wind patterns lead to unpredictable generation outputs, challenging grid stability.
- Extreme weather events, such as wildfires and storms, pose risks to infrastructure and increase maintenance costs.
- Hybrid renewable systems (e.g., solar + storage or wind + hydrogen) offer potential solutions to mitigate climate-related disruptions.

Economic and Investment Risks

- Revenue risks arise from production variability, forcing investors to consider financial hedging strategies or capacity payments to stabilize earnings.
- Investor confidence is affected by climate risks, requiring stronger government guarantees, insurance mechanisms, and long-term policy commitments.
- Significant investments are needed in grid modernization, energy storage, and adaptive infrastructure, estimated at billions of euros in the coming years.
- The cost of adaptation measures is expected to influence electricity pricing, making regulatory support essential to prevent financial burdens on consumers.

Policy and Government Support

- EU and Greek government policies play a crucial role in shaping renewable energy investments. EU Green Deal funding and national incentives encourage climate-resilient projects.
- Greece's National Energy and Climate Plan (NECP) targets 70% renewable electricity generation by 2030, requiring accelerated investments.

- Economic incentives, including tax benefits and grants for storage and hybrid systems, are critical to attracting investors in climate adaptation projects.
- Strengthening public-private partnerships (PPPs) can enhance innovation and infrastructure resilience.

Conclusion

Greece's renewable energy transition is both challenged and driven by climate variability, investment risks, and evolving policies. A strategic focus on resilience, technological innovation, and policy stability is essential to securing the sector's long-term sustainability.

Comparative Analysis with Other Mediterranean and EU Countries

Cross-country comparison for contextual understanding

Greece's renewable energy landscape shares similarities with other Mediterranean and EU countries but also faces unique challenges and opportunities. By comparing Greece's renewable energy policies, investment climate, and climate adaptation strategies with other nations, we can better understand its positioning in the broader European energy transition.

Renewable Energy Production Trends

Solar Energy: Greece, Spain, and Italy benefit from high solar irradiance, but Greece lags in installed solar capacity compared to Spain, which leads in photovoltaic (PV) deployment. Portugal and France also surpass Greece in solar storage integration, improving grid flexibility.

Wind Energy: While Greece has strong offshore and onshore wind potential, its wind sector remains less developed than Germany or Denmark. Compared to Italy and Portugal, Greece has fewer high-capacity wind farms, partly due to grid limitations and regulatory delays.

Hydropower & Geothermal: Countries like Italy and France have capitalized on geothermal energy more effectively, whereas Greece's geothermal potential remains underutilized. Greece also has fewer large-scale hydropower plants than Spain or France, limiting its energy mix diversification.

Investment Climate and Financial Risks

Greece offers attractive feed-in tariffs and PPAs (Power Purchase Agreements) but faces higher financing costs and investment risks than Northern European nations.

Spain and Italy have more mature green finance mechanisms, with greater access to low-interest loans for renewable projects.

Grid modernization investments in Greece are lower compared to Germany and France, affecting renewable energy integration.

Policy and Incentives Comparison

EU Support: Greece benefits from EU Green Deal funds, like Spain and Portugal, but has a slower project implementation rate due to bureaucratic hurdles.

National Policies: Greece's NECP (National Energy and Climate Plan) is ambitious but lacks stronger incentives for energy storage compared to Germany or the Netherlands.

Carbon Pricing & Subsidies: France and Italy offer higher carbon taxes and green subsidies, driving faster transitions, while Greece still relies on fossil-fuel-based power backups.

Conclusion

Greece is making significant strides in renewable energy but lags behind key Mediterranean and EU countries in grid modernization, storage integration, and investment security. By adopting best practices from Spain, Italy, and France, Greece can strengthen its renewable energy sector and accelerate its transition toward a more resilient energy system.

Implications for Future Research and Investment

The evolving landscape of renewable energy in Greece presents critical areas for future research and investment to enhance resilience, efficiency, and economic sustainability. Understanding how climate change affects energy production, improving financial mechanisms, and adopting new technologies are key priorities for ensuring long-term success in the sector.

Research Priorities

Climate Resilience Studies: Further research is needed on the long-term effects of heatwaves, wind variability, and extreme weather on renewable energy production in Greece. Comparative studies with similar Mediterranean climates can help refine predictive models for energy output fluctuations.

Energy Storage and Grid Management: Given the intermittency of solar and wind power, research on cost-effective battery storage systems and smart grid solutions is crucial for stabilizing electricity supply. Investigations into alternative storage technologies, such as hydrogen and pumped hydro storage, could enhance energy security.

Economic Risk Mitigation: Studies on financial instruments (e.g., climate risk insurance, green bonds, and private-sector incentives) can help minimize investor risks and encourage long-term commitments to renewable projects.

Offshore Wind and Hybrid Systems: Greece has untapped potential for offshore wind farms, but research is required to assess the environmental and technical feasibility. Additionally, hybrid renewable systems, combining solar, wind, and storage, should be explored for higher efficiency and grid stability.

Investment Opportunities

Infrastructure Upgrades: Large-scale investment is needed to modernize the national grid, expand interconnections with other EU countries, and support decentralized renewable energy production.

Public-Private Partnerships (PPPs): Encouraging collaborations between the government and private sector can accelerate innovation in renewable technologies and climate adaptation strategies.

EU Funding Utilization: Greece should maximize its access to EU Green Deal funds, Horizon Europe research grants, and Just Transition Mechanisms to finance next-generation renewable energy projects.

Conclusion

Future research should focus on climate resilience, energy storage, and economic risk mitigation, while investment efforts should prioritize grid modernization, offshore wind development, and hybrid energy systems. Strengthening these areas will enhance Greece's role as a regional leader in renewable energy and improve the sector's financial sustainability.

Chapter 8: Conclusion

Summary of Key Findings

This dissertation explored the intricate relationship between climate change and the renewable energy investment sector in Greece. The findings indicate that while Greece has made significant strides in transitioning to renewable energy, climate change itself presents challenges that could hinder the sector's growth and financial viability.

Key insights from the study include:

Climate Change's Impact on Renewable Energy Production: Rising temperatures reduce the efficiency of solar photovoltaic (PV) panels, and shifting wind patterns introduce variability in wind energy production. Additionally, extreme weather events such as heatwaves, droughts, and storms threaten infrastructure stability.

Investment Risks and Economic Uncertainty: Climate-related risks introduce unpredictability in energy generation, affecting revenue streams and making renewable energy investments less financially secure. Fluctuations in production and potential infrastructure damage increase operational costs.

Government Policies and Financial Incentives: The Greek government and the European Union have established ambitious renewable energy targets, supported by subsidies, incentives, and funding mechanisms. However, policy uncertainty and regulatory inefficiencies remain a concern for investors.

Technological and Infrastructure Adaptations: To mitigate climate risks, investments in energy storage, smart grids, and adaptive infrastructure are crucial. Technologies such as battery storage, hydrogen energy systems, and offshore wind farms provide resilience against climate variability.

Comparative Insights from Other Mediterranean and EU Countries: Greece lags behind countries like Spain, Italy, and France in energy storage integration and offshore wind deployment. Best practices from these nations can inform Greece's policy and investment strategies.

Limitations of the Research

While this study provides valuable insights into the impact of climate change on Greece's renewable energy sector, certain limitations must be acknowledged:

- **Data Constraints:** The study relied on secondary climate and energy production data, which may not fully capture recent, localized climate changes affecting renewable energy output.
- **Financial Projections:** Investment risk assessments were based on existing literature and reports, but market conditions and investor behavior may shift based on global economic changes.
- **Policy Uncertainty:** The research assumes the continuation of current EU and Greek energy policies, but potential regulatory changes may significantly alter investment trends.
- **Limited Scope of Renewable Technologies:** While solar, wind, and hydropower were extensively analyzed, other renewable energy sources such as biomass and geothermal received limited attention due to data availability constraints.

Recommendations for Stakeholders

To ensure a sustainable and resilient renewable energy sector, targeted actions are required by key stakeholders:

- **For Policymakers:** Implement long-term, stable regulatory frameworks to enhance investor confidence. Prioritize grid modernization, storage incentives, and climate adaptation policies to mitigate the impact of climate variability.
- **For Investors:** Diversify renewable energy portfolios by incorporating energy storage and hybrid systems. Risk-mitigation strategies, such as green bonds and insurance mechanisms, should be adopted to safeguard financial returns.
- **For Energy Companies and Developers:** Invest in advanced technologies that improve efficiency under extreme climate conditions, such as high-temperature-resistant solar panels and wind turbines optimized for variable wind speeds.
- **For Researchers and Academics:** Conduct further studies on localized climate risks, long-term financial modeling for renewables, and best practices from leading renewable energy nations.

Future Outlook for Greece's Renewable Energy Sector

Despite the challenges posed by climate change, Greece's renewable energy future remains promising. The country's commitment to the EU Green Deal, the National Energy and Climate Plan (NECP), and international climate agreements positions it as a key player in the Mediterranean's clean energy transition.

To sustain this momentum, Greece must:

- Accelerate the integration of energy storage systems to stabilize power supply.
- Expand offshore wind and hybrid energy projects to mitigate land constraints.

- Strengthen cross-border energy interconnections with the EU and neighboring regions to enhance energy security.
- Leverage international climate financing to attract green investments.

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Appendices

The questioner:

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