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Optimizing the spatial allocation of wind and solar energy production

SCM Thesis

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I would like to thank each one of the professors that have helped me growing educationally and specifically Dr. Nikolaos Thomaidis for trusting me and his very helpful and fruitful collaboration.

I would like to dedicate my thesis to my family for supporting me in every single step and to a special and beloved person, that unfortunately I could no longer share my life with.

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Abstract

The increasing reliance on renewable energy sources has become a global necessity to address climate change and meet the growing energy demand. Among these, wind and solar energy play a crucial role due to their sustainability and environmental benefits. However, the inherent intermittency of these sources poses significant challenges in ensuring a stable and reliable energy supply. This study investigates the optimization of spatial allocation for wind and solar power generation, utilizing Modern Portfolio Theory (MPT) as a framework to enhance efficiency and mitigate risk. By analyzing production patterns, capacity factors, and risk diversification strategies, this research provides insights into optimizing resource allocation for investors, policymakers, and grid operators. The findings contribute to advancing a resilient and sustainable energy infrastructure.

Keywords: Renewable Energy, Wind Power, Solar Energy, Modern Portfolio Theory, Energy Optimization, Risk Diversification, Capacity Factor.

Περίληψη

Η αυξανόμενη εξάρτηση από τις ανανεώσιμες πηγές ενέργειας αποτελεί βασικό πυλώνα της παγκόσμιας ενεργειακής μετάβασης, συμβάλλοντας στην αντιμετώπιση της κλιματικής αλλαγής και στην κάλυψη της αυξανόμενης ζήτησης ενέργειας. Η αιολική και η ηλιακή ενέργεια είναι δύο βασικοί πυλώνες αυτής της μετάβασης, παρέχοντας βιώσιμες λύσεις με χαμηλό περιβαλλοντικό αντίκτυπο. Ωστόσο, η διακύμανση της παραγωγής τους λόγω των φυσικών συνθηκών δημιουργεί προκλήσεις στη διασφάλιση σταθερού ενεργειακού εφοδιασμού. Στην παρούσα μελέτη εξετάζεται η βελτιστοποίηση της χωρικής κατανομής της αιολικής και ηλιακής παραγωγής, εφαρμόζοντας τη Θεωρία Σύγχρονου Χαρτοφυλακίου (MPT) ως μέσο βελτίωσης της απόδοσης και μείωσης του κινδύνου. Μέσα από την ανάλυση προτύπων παραγωγής, συντελεστών χωρητικότητας και στρατηγικών διαφοροποίησης κινδύνου, η έρευνα παρέχει χρήσιμες πληροφορίες για τη βέλτιστη κατανομή πόρων, απευθυνόμενη σε επενδυτές, υπεύθυνους χάραξης πολιτικής και διαχειριστές δικτύων. Τα αποτελέσματα συνεισφέρουν στην ενίσχυση ενός ανθεκτικού και βιώσιμου ενεργειακού συστήματος.

Λέξεις-Κλειδιά: Ανανεώσιμες Πηγές Ενέργειας, Αιολική Ενέργεια, Ηλιακή Ενέργεια, Θεωρία Σύγχρονου Χαρτοφυλακίου, Βελτιστοποίηση Ενέργειας, Διαφοροποίηση Κινδύνου, Συντελεστής Χωρητικότητας.

1. Introduction

The global energy landscape is undergoing a profound transformation as countries seek to transition away from fossil fuels toward sustainable, low-carbon alternatives. Renewable energy sources, particularly wind and solar power, have emerged as essential components of this transition due to their abundant availability, declining costs, and environmental benefits. However, a key challenge associated with these energy sources is their intermittency and variability, which complicates grid stability and energy supply reliability.

The unpredictability of wind and solar energy production arises from natural fluctuations in weather patterns, making it difficult to ensure a steady electricity supply. In response to this challenge, researchers and policymakers have explored various methods to enhance energy system stability. One of the most effective strategies is spatial diversification, which involves optimizing the geographic distribution of wind and solar power plants to reduce overall production volatility.

This study applies Modern Portfolio Theory (MPT)—a well-established financial optimization framework—to the field of renewable energy planning. MPT demonstrates that diversification across assets with low or negative correlation reduces overall portfolio risk while maintaining expected returns. In the context of energy production, this principle suggests that a carefully allocated mix of wind and solar farms across different locations can enhance energy reliability and efficiency.

The research aims to address the following key questions:

- Which regions exhibit the highest and lowest renewable energy production over time?
- Which locations have the most stable or volatile energy output?
- How do inter-regional correlations affect overall energy yield and risk?
- What is the optimal spatial distribution of wind and solar energy installations to maximize efficiency and minimize risk?

To answer these questions, we employ a quantitative, data-driven approach using historical energy production data, statistical analysis, and portfolio optimization techniques. Several portfolio configurations are examined, including:

- Minimum Variance Portfolio (MVP) – for risk-averse investors prioritizing stability.
- Maximum Yield Portfolio (MYP) – for investors seeking maximum energy production.
- Equally Weighted Portfolio – for a neutral, unbiased allocation strategy.
- Maximum Information Ratio Portfolio – optimizing the yield-to-risk tradeoff.
- Information Ratio-Sorted Portfolio – prioritizing locations based on efficiency.

By systematically evaluating these portfolio strategies, this study contributes valuable insights into how spatially optimized renewable energy allocation can improve system resilience, attract investment, and support the global energy transition. The findings are particularly relevant for energy policymakers, investors, and grid operators, who must navigate the complexities of integrating large-scale renewable energy projects into national and regional grids.

The subsequent chapters explore the theoretical background of renewable energy production and risk management, the research methodology, and the empirical results of the optimization models. Ultimately, this study aims to provide a comprehensive framework for optimizing wind and solar energy investments, ensuring a more sustainable, stable, and economically viable energy future.

2. Theoretical Background

2.1 Renewable Energy Sources

The global population has been steadily increasing. By the end of 2024, this number had risen to approximately 8.1 billion, marking an increase of 71 million people within two years. Projections indicate that by 2030, the global population could reach 8.5 billion, with further increases pushing it to nearly 10 billion by the end of the century. As the population grows, so does the demand for energy, making energy supply a critical factor in sustaining modern societies. (Shahzad, 2015)

Energy sources are broadly classified into two categories: **renewable and nonrenewable**. **Nonrenewable sources**, such as coal, oil, and natural gas, are limited in supply as they take millions of years to develop and will eventually be exhausted. In contrast, **renewable energy sources** are naturally replenished over short time scales and have a much lower environmental footprint. Examples of these include **solar power, wind energy, hydropower, geothermal energy, and biomass**. (Shahzad, 2015).

Despite the increasing awareness of environmental concerns, over 60% of the world's electricity production still comes from nonrenewable sources. This overreliance accelerates resource depletion and intensifies climate change due to greenhouse gas emissions. (Rajput et al., 2022) The negative consequences of nonrenewable energy dependence have become increasingly evident in recent years, with extreme weather events and global temperature rises underscoring the urgency of transitioning to sustainable energy solutions. By the end of 2024, global temperatures had reached an alarming milestone, with the year becoming the hottest on record, surpassing the critical threshold of 1.5°C above pre-industrial levels for the first time. (Fortune, 2024)

The consequences of rising temperatures are already visible, particularly in the rapid melting of glaciers. Studies suggest that even under optimistic climate scenarios, 50% of the world's glaciers could disappear by 2100. This accelerated ice loss contributes to rising sea levels and threatens water supplies for millions of people. (Euronews, 2023) Additionally, the geopolitical risks associated with fossil fuel dependency have further highlighted the need for energy diversification. As seen in recent conflicts, fossil fuel-exporting nations can leverage their energy supplies for political and economic advantage, creating instability in global energy markets. (NewMoney, 2024)

A significant development affecting global climate efforts is the decision of the United States to withdraw from the Paris Agreement once again, with the process set to take effect by January 27, 2026. This marks the second time the U.S. has exited the agreement, the first being

during President Donald Trump's tenure (Naftemporiki, 2024). This decision poses several risks:

1. **Increased greenhouse gas emissions:** The U.S., being the second-largest emitter globally, could contribute to rising global emissions, making it harder to achieve the targets set by the Paris Agreement. (NewMoney, 2024)
2. **Financial implications:** The withdrawal may lead to reduced funding for developing nations in their climate adaptation efforts, as the U.S. had previously committed substantial financial support. (NewMoney, 2024)
3. **Geopolitical consequences:** The exit could weaken global cooperation on climate action, undermining collective efforts to combat climate change. (NewMoney, 2024)

In stark contrast, the European Union continues to uphold the Paris Agreement, setting ambitious goals to reduce greenhouse gas emissions by at least 55% by 2030. (Consilium.europa.eu) The EU has maintained its commitment to investing in renewable energy and implementing policies that drive decarbonization, solidifying its role as a global leader in climate action.

The withdrawal of a major global player like the U.S. raises concerns about the stability of the Paris Agreement itself. If more countries follow suit, the agreement's effectiveness could be significantly weakened, delaying necessary climate action. The reduction in funding and policy support could slow progress toward meeting emissions reduction targets, ultimately exacerbating climate-related disasters. (NewMoney, 2024)

By 2050, renewable energy is expected to dominate global electricity generation, significantly reducing dependence on fossil fuels. With continuous technological advancements and strong policy initiatives, countries worldwide are working toward ambitious climate targets to prevent severe environmental consequences. As we move closer to 2080 and beyond, the emphasis will remain on fostering long-term sustainability, strengthening energy security, and mitigating the adverse impacts of climate change.

These global commitments have driven nations to accelerate investments in clean energy infrastructure, cutting-edge technologies, and enhanced energy efficiency. As a result, the renewable energy sector is expanding at an unprecedented rate, with wind and solar power playing a crucial role in the shift toward a sustainable and self-sufficient energy future.

2.2 Wind Energy

Renewable energy sources, particularly wind and solar, have become central to global electricity generation strategies. In recent years, wind energy has gained significant attention, with numerous countries, including Greece, actively promoting investments in this sector. Major companies are investing in wind farms, competing to secure a share in the wind energy market.

Wind power stands as one of the most substantial and impactful renewable energy sources. Unlike conventional energy sources, wind energy requires no fuel and produces no pollutant

emissions, rendering it environmentally friendly. Technological advancements have matured wind power into a competitive energy source.

2.2.1 Wind Energy in Greece

Greece has made significant strides in wind energy development. As of 2023, the country achieved record highs in wind, solar, and hydroelectric energy production. The installed wind capacity reached approximately 4.7 gigawatts (GW), reflecting substantial growth from previous years (Trade.gov, 2024; Statista, 2024).

Looking ahead, Greece plans to add roughly 400 megawatts (MW) of onshore wind capacity annually from 2024 to 2030, aiming to further bolster its renewable energy infrastructure. Furthermore, offshore wind projects are being developed, aligning with the national energy transition goals. Greece's first Offshore Wind Law, passed in 2022, is expected to facilitate at least 2 GW of offshore wind energy by 2030 (Statista, 2024).

2.2.2 Wind Energy in the European Union

The European Union (EU) has made significant progress in its transition to renewable energy. During the first half of 2024, wind and solar energy together supplied 30% of the EU's electricity, surpassing fossil fuels, which contributed 27% (Ember, 2024). This shift highlights the EU's dedication to reducing dependency on fossil fuels while strengthening energy security.

In 2023, the EU achieved a record-breaking expansion in wind power, adding 16.2 GW of new capacity, with onshore wind accounting for 82% of the total increase. However, to successfully meet its 2030 climate and energy objectives, the EU must accelerate its wind power development, requiring the installation of 33 GW annually (WindEurope, 2024).

2.2.3 Wind Energy in the United States

As of 2023, the United States had an installed wind power capacity of approximately 141.3 GW (Statista 2024). The country continues to invest in both onshore and offshore wind projects, contributing to its renewable energy portfolio. However, recent political decisions and policy shifts, including a reduced emphasis on climate agreements, have created uncertainty regarding future investments and expansion.

2.2.4 Challenges and Future Outlook

Although wind energy is a promising solution for sustainable electricity production, its intermittent nature poses challenges. The fluctuation in wind speeds makes it difficult for wind power to function as a consistent baseload energy source. To address these limitations, advancements in energy storage technologies, grid optimization, and hybrid renewable systems are crucial for maximizing the effectiveness of wind energy.

In conclusion, wind power is set to become a key component of the global shift toward clean energy solutions. Ongoing investments, supportive regulatory frameworks, and continuous technological innovation will be vital in overcoming current obstacles and unlocking the full potential of wind energy.

2.3 Solar Energy

Solar energy has emerged as one of the fastest-growing renewable energy sources worldwide, playing a crucial role in the transition toward a low-carbon energy system. Its rapid expansion is driven by advancements in photovoltaic (PV) technology, declining installation costs, and supportive government policies. As concerns about climate change intensify, solar energy is becoming an essential component of national and regional energy strategies.

One of the key advantages of solar energy is its abundance. The sun delivers an estimated 173,000 terawatts of solar energy to the Earth continuously—more than 10,000 times the world's total energy use (IEA, 2023). This vast potential has led to widespread investments in solar power generation, with many countries setting ambitious targets for expanding their solar capacity.

In recent years, solar energy has experienced exponential growth. According to the International Energy Agency (IEA, 2024), solar PV capacity increased by over 190 gigawatts (GW) in 2023 alone, setting a new record for annual additions. The total global installed capacity now exceeds 1.3 terawatts (TW), with projections indicating that solar will become the dominant source of electricity generation in many countries by 2050.

Recent breakthroughs in solar panel technology have significantly improved efficiency and performance. Traditional silicon-based PV panels, which once had efficiency rates of 12-15%, now regularly exceed 22%, with some cutting-edge designs reaching up to 30% in laboratory conditions (NREL, 2024). Innovations such as bifacial solar panels, which capture sunlight from both sides, and perovskite solar cells, which promise higher efficiency at lower costs, are further driving the industry forward.

Storage solutions are also evolving to address solar energy's intermittency. The increasing integration of battery storage systems, such as lithium-ion and flow batteries, allows for more reliable solar energy use, ensuring electricity supply even during nighttime or cloudy periods (IEA, 2024).

The declining cost of solar installations has made solar energy more competitive with traditional fossil fuels. The levelized cost of electricity (LCOE) for utility-scale solar projects has

fallen by more than 80% since 2010, making it one of the most cost-effective energy sources globally (BloombergNEF, 2024). Governments are incentivizing further growth through policies such as feed-in tariffs, tax credits, and net metering programs, which encourage residential and commercial adoption of solar PV systems (IRENA, 2024).

2.3.1 Solar Energy in Greece

Greece has significantly expanded its solar energy capacity. From 2018 to 2022, the country's solar capacity increased from 2.6 gigawatts (GW) to 5.3 GW. In 2024, Greece installed an additional 400 megawatts (MW) of net-metered photovoltaic (PV) systems, bringing its cumulative distributed solar capacity to 850 MW. This growth aligns with Greece's broader renewable energy initiatives, which also include substantial investments in wind energy (PV Magazine, 2024).

2.3.2 Solar Energy in the European Union

The European Union (EU) has made remarkable progress in solar energy adoption. In 2023, the EU connected an additional 55.9 GW of photovoltaic systems to the grid, increasing the cumulative capacity to 263 GW. This expansion contributed to wind and solar energy generating 30% of the EU's electricity in the first half of 2024, surpassing fossil fuels, which accounted for 27% (Ember, 2024).

2.3.3 Solar Energy in the United States

The United States continues to expand its solar energy production, with a cumulative installed capacity surpassing 140 GW in 2024. Large-scale solar farms and residential photovoltaic installations are key contributors to this rapid expansion. Despite policy uncertainties, solar power remains a dominant renewable energy source in the country (WindEurope, 2024).

2.3.4 Challenges and Future Outlook

Despite its potential, solar energy faces challenges, including intermittency, land use concerns, and supply chain constraints. Improvements in battery storage, grid integration, and panel efficiency will be crucial in overcoming these hurdles. As technology advances and costs continue to decline, solar energy is expected to play a dominant role in achieving global climate targets by 2050 (Statista, 2024).

2.4 Wind Turbines

Wind turbines are the backbone of wind energy generation, converting kinetic energy from wind into mechanical power, which is then transformed into electricity. The fundamental components of a wind turbine include the rotor blades, nacelle, generator, tower, and foundation. The rotor blades capture wind energy, causing them to spin and drive a shaft connected to a generator that produces electricity (WindEurope, 2024).

2.4.1 Types of Wind Turbines

Wind turbines are categorized based on their axis of rotation:

- **Horizontal-Axis Wind Turbines (HAWTs):** The most common type, featuring three blades mounted on a horizontal shaft.
- **Vertical-Axis Wind Turbines (VAWTs):** Less common, with blades rotating around a vertical axis, suitable for urban and offshore environments (Statista, 2024).

2.4.2 Wind Turbine Capacity and Efficiency

Wind turbine capacity varies significantly, with modern onshore turbines ranging from 2 MW to 6 MW, while offshore turbines can exceed 15 MW. The efficiency of a wind turbine depends on factors such as blade length, wind speed, and turbine placement. Generally, turbines operate efficiently at wind speeds between 12-25 m/s, with a cut-in speed around 3-4 m/s and a cut-out speed around 25 m/s for safety reasons (Ember, 2024).

2.4.3 Challenges and Future Developments

Despite their benefits, wind turbines face challenges, including intermittency, noise pollution, and environmental impact on bird populations. Ongoing research focuses on improving turbine aerodynamics, increasing energy capture at lower wind speeds, and advancing floating wind turbine technology to unlock deeper offshore potential (WindEurope, 2024).

Wind turbines continue to evolve, with advancements in materials, automation, and artificial intelligence enhancing their performance and efficiency. As global demand for renewable energy rises, wind turbines will play a crucial role in achieving sustainability goals and reducing dependence on fossil fuels.

2.5 Solar Panels

Solar panels serve as the core technology for capturing solar energy, utilizing photovoltaic (PV) cells to transform sunlight into electricity. These cells, predominantly composed of silicon, absorb photons from sunlight, generating direct current (DC) electricity, which is subsequently converted into alternating current (AC) to power households, businesses, and the electrical grid (*PV Magazine, 2024*).

2.5.1 Types of Solar Panels

Solar panels come in three main types, each with distinct characteristics that affect efficiency, cost, and suitability for different applications. Below is an overview of these three primary types:

- **Monocrystalline Solar Panels.** Made from a single, continuous crystal structure of silicon, giving them a uniform black appearance. Offer the highest efficiency rates (typically 20-22%) and excellent durability. It is more expensive but space-efficient, making them ideal for rooftops and limited-space applications. According to its functioning mechanism, electrons are mobilized within the silicon crystal when exposed to sunlight, generating direct current (DC) electricity. Its connection is in series or parallel to form modules, linked to an inverter that converts DC to alternating current (AC) for use.
- **Polycrystalline Solar Panels.** Manufactured from multiple silicon crystal fragments melted together, resulting in a blue, speckled appearance. It has slightly lower efficiency (15-18%) but more affordable than monocrystalline panels. It is suitable for residential and commercial installations where space is not a constraint. According to its functioning mechanism, it is similar to monocrystalline, photons from sunlight knock electrons loose within the silicon structure to produce electricity. Concerning the connection, it is wired together in modules, connected to charge controllers and inverters to ensure efficient power distribution.
- **Thin-Film Solar Panels.** It is comprised of layers of photovoltaic material deposited onto a substrate (e.g., glass, plastic, or metal). It is more flexible and lightweight but generally less efficient (**10-12%**) than crystalline silicon panels. It is ideal for large-scale solar farms and portable applications due to their adaptability. According to its functioning mechanism, photovoltaic layers absorb sunlight, exciting electrons to produce electricity. Concerning the connection, it is typically connected with integrated bypass diodes, reducing power loss due to shading. Often paired with battery storage systems for standalone applications.

These three types of solar panels each serve different needs based on efficiency, cost, and installation conditions. Choosing the right panel depends on factors such as available space, budget, and energy requirements. Proper electrical connections and inverters are essential for integrating solar panels into functional energy systems.

2.5.2 Solar Panel Efficiency and Capacity

Modern solar panels achieve efficiencies ranging from 15% to over 22%, with research focused on pushing this limit further. A standard residential solar panel has a capacity of 300-400 watts, while commercial and utility-scale panels can exceed 500 watts per module (Ember, 2024).

2.5.3 Challenges and Future Developments

Despite their advantages, solar panels face challenges such as efficiency losses due to shading, temperature variations, and material degradation over time. Innovations in perovskite solar cells, bifacial panels, and solar tracking systems aim to enhance efficiency and energy yield (WindEurope, 2024).

As global energy demand rises, solar panels remain at the forefront of renewable energy solutions, driving the transition towards a cleaner, more sustainable future.

2.6 Risk Dimensions

Despite significant advancements in wind and solar power technologies, both energy sources still face multiple risk dimensions that affect their efficiency, financial viability, and reliability.

2.6.1 Wind Energy Risks

The most critical risk associated with wind energy is volumetric risk, which stems from the high variability and limited predictability of wind patterns. This unpredictability makes it difficult for investors and system operators to accurately forecast power generation levels (Cunha & Ferreira). One widely adopted strategy to mitigate this risk is spatial diversification, which involves distributing wind farms across different geographical areas to ensure a more stable energy supply (Thomaidis 2012).

Additionally, technological and maintenance risks impact wind turbine efficiency. Issues such as blade degradation, mechanical failures, and grid integration challenges can reduce the overall performance of wind energy systems (WindEurope, 2024). Moreover, extreme weather conditions, including hurricanes and freezing events, pose a significant threat to wind farm operations (Ember, 2024).

2.6.2 Solar Energy Risks

Solar energy also faces volumetric risk, primarily due to cloud cover variability, seasonal changes, and its diurnal cycle. Unlike wind, solar energy is entirely unavailable at night, necessitating the use of storage solutions such as battery systems to ensure energy supply consistency (Statista, 2024).

Another major risk is land availability and efficiency limitations. Solar farms require large land areas for deployment, and land-use conflicts with agricultural and urban development projects can hinder expansion (PV Magazine, 2024). Additionally, extreme temperatures can impact photovoltaic (PV) efficiency, reducing their energy output in very hot or cold climates (Ember, 2024).

Both wind and solar energy require ongoing innovation, grid enhancements, and supportive policies to mitigate these risks and enhance their long-term viability as primary energy sources for a sustainable future.

2.7 Modern Portfolio Theory

2.7.1 Basic Characteristics

Modern Portfolio Theory (MPT) was introduced by Harry Markowitz in the 1950s as a mathematical approach to optimizing investment portfolios through diversification. The key principle of MPT is to invest in assets with low cross-correlation, thereby reducing overall risk while maintaining or increasing expected returns. This theory is widely applied in finance and has found practical applications in the renewable energy sector, particularly in wind and solar energy investments.

2.7.2 Risk Profiles

Investing in renewable energy, whether wind or solar, comes with inherent risks. These risks impact project viability and return on investment. Investors in wind and solar energy projects can be categorized into three risk profiles:

- **Profit-seeking investors:** These investors are willing to undertake high levels of risk in pursuit of higher returns.
- **Risk-averse investors:** These investors prioritize stability and lower risk, often accepting lower returns for greater predictability.
- **Risk-neutral investors:** These investors balance risk and return, optimizing for medium levels of profitability and security.

The level of risk tolerance determines the optimal energy portfolio mix, which will be explored further in later chapters.

2.7.3 Mean-Variance Analysis

A central concept in MPT is **Mean-Variance (MV) Analysis**, which aims to identify the optimal balance between expected returns and risk. Investors seek to maximize returns for a given level of risk or minimize risk for a targeted return level. MV analysis emphasizes the benefits

of diversification—when assets (or energy sources) exhibit low correlation, the overall portfolio risk decreases while maintaining high returns.

In the context of renewable energy production, the two key measures in MV analysis are:

- **Portfolio Yield:** In this application, yield refers to the expected **energy output** over a given period rather than financial return. It represents the total expected electricity generation (MWh) from a combination of renewable sources (e.g., wind and solar) in an optimized energy portfolio.
- **Portfolio Risk:** Here, risk is quantified as the variability (standard deviation) of the energy output rather than financial volatility. It reflects the fluctuations in renewable energy production due to factors such as weather conditions, seasonal variations, and geographic dispersion of energy sources.

By applying MV analysis to renewable energy portfolios, we aim to minimize the variability of energy production while maintaining high energy output. This approach enhances grid stability and ensures a more predictable supply of electricity, supporting the integration of renewables into the energy mix effectively.

These calculations will be elaborated in Chapter 3.

2.7.4 Renewable Energy Portfolios

Applying MPT to wind and solar energy portfolios enables investors and policymakers to optimize energy mix decisions. Studies have demonstrated that geographically dispersed wind and solar projects can enhance energy reliability while reducing overall production risk.

A diversified renewable energy portfolio provides multiple advantages:

- **Risk mitigation:** Combining wind and solar assets with different variability patterns minimizes exposure to single-source volatility.
- **Increased stability:** Hybrid energy portfolios help stabilize aggregate production, ensuring a more reliable supply.
- **Investment appeal:** Optimized portfolios attract institutional investors seeking balanced risk-adjusted returns.

2.7.5 Capacity Allocation and Policy Implications

For policymakers and private investors, the application of MPT to energy investments can enhance energy security and economic viability. With the liberalization of energy markets, the ability to effectively manage risk and return has become increasingly critical (Cunha & Ferreira).

In Greece, major wind and solar companies hold capacities exceeding 700 MW each. The allocation of these resources across multiple locations can significantly impact portfolio

performance. The concept of **capacity factor**, defined as the ratio of actual energy output to theoretical maximum output, plays a crucial role in assessing the efficiency of renewable installations. This factor will be explored in the following chapters as part of our methodology for optimizing wind and solar energy investments.

2.8 Literature Review

A thorough literature review is essential in understanding the current state of research regarding wind and solar energy, their associated risks, and the application of Modern Portfolio Theory (MPT) in energy optimization.

2.8.1 Renewable Energy Developments

Recent studies have extensively analyzed the role of renewable energy in mitigating climate change and securing a sustainable energy future. According to Ember (2024), wind and solar energy have surpassed fossil fuel-based electricity production in several regions. Thomaidis et al. (2022) highlight the increasing reliance on renewable sources as governments worldwide strive to meet their carbon neutrality goals by 2050.

2.8.2 Risks and Challenges in Wind and Solar Energy

A key aspect of renewable energy deployment is the volatility and intermittency associated with wind and solar power. Cunha & Ferreira explore the concept of **volumetric risk**, emphasizing how spatial diversification can mitigate production fluctuations. Similarly, Santos-Alamillos et al. discuss the importance of geospatial distribution in stabilizing energy output, reinforcing findings from previous studies on energy security and system resilience.

2.8.3 Application of Modern Portfolio Theory (MPT) in Energy

The integration of MPT in the energy sector has been widely researched in recent years. Markowitz (1952) originally introduced the theory to optimize financial assets, but recent studies have adapted it to energy portfolio management. Thomaidis & Moukas (2022) successfully applied MPT to optimize wind energy portfolios in Europe, demonstrating how diversified wind locations can reduce aggregate volatility. Cunha & Ferreira extend this approach to mixed renewable portfolios, combining wind and solar to enhance energy reliability and minimize financial risk.

2.8.4 Capacity Factor and Investment Strategies

Another crucial metric in renewable energy assessment is the **capacity factor**, which is set as the energy output divided by the theoretical output. Studies by WindEurope (2024) and Statista (2024) indicate that offshore wind projects tend to have higher capacity factors than onshore wind, making them a more stable investment despite higher installation costs. Meanwhile, advancements in solar panel efficiency, as discussed in PV Magazine (2024), are improving the feasibility of solar investments in regions with high irradiance.

3. Research Methodology

In this chapter, we outline the purpose of our research and formulate key questions that arise from it. We then detail the process of selecting and acquiring the dataset, followed by the necessary preprocessing steps. Additionally, we present and analyze the descriptive statistics of our dataset, incorporating relevant visualizations to illustrate key insights. Finally, we discuss significant observations derived from the data analysis.

3.1 Research Objective and Key Questions

The previous chapter addressed the challenges stemming from the variability and unpredictability of renewable energy sources, specifically wind and solar power production. One widely recognized approach to mitigating these uncertainties is spatial diversification. Our study aims to evaluate the effectiveness of spatial diversification as a strategy to reduce investment risks associated with fluctuations in wind and solar energy production while maintaining high production levels.

To achieve this goal, our research seeks to answer the following questions:

- Which regions exhibit the highest and lowest levels of renewable energy production over the years?
- Which regions demonstrate the highest and lowest variability in their average energy output?
- Which regions show strong positive correlations in energy production, and which exhibit negative correlations?
- How do these correlations impact their combined energy output over time?
- What portfolio configurations are optimal for different investor risk profiles?
- Which regions contribute the most to the optimal portfolios?

- Which regions are underrepresented in the optimal portfolios?
- What alternative portfolio structures exist, and what are their expected returns and associated risks?
- How do these alternative portfolios compare to the identified optimal configurations?

By addressing these questions, we aim to provide a comprehensive assessment of the impact of spatial diversification on the reliability and efficiency of renewable energy investments.

3.2 Sample Data

The dataset used in this study originates from the EMHIRES (European Meteorological-derived High-resolution RES dataset) project. EMHIRES is the first publicly available dataset containing wind and solar energy data for the 28 European Union countries and neighboring regions. Specifically, EMHIRES provides wind and solar power-related data at the NUTS2 level for Greece, derived from meteorological sources. (*Gonzalez-Aparicio et al., 2017*).

For our empirical analysis, we utilize hourly wind and solar capacity factors across multiple Greek regions. The dataset spans 30 years, covering the period from January 1, 1986, to December 31, 2015.

The **13 Greek regions** included in the dataset are as follows:

- **EL30:** Attica
- **EL41:** North Aegean
- **EL42:** South Aegean
- **EL43:** Crete
- **EL51:** Eastern Macedonia and Thrace
- **EL52:** Central Macedonia
- **EL53:** Western Macedonia
- **EL54:** Epirus
- **EL61:** Thessaly
- **EL62:** Ionian Islands
- **EL63:** Western Greece
- **EL64:** Central Greece
- **EL65:** Peloponnese



Figure 1 : NUTS2 level region of Greece (Eurostat, 2020)

3.3 Research Design

This section outlines the initial data analysis, and the criteria used for data selection in our research. Next, we present the statistical measures derived from the dataset. Finally, we discuss the portfolio optimization methodology, including the key equations that will be applied in the empirical analysis of the following chapter.

3.3.1 Preliminary Data Analysis

Given the extensive dataset, our analysis is conducted on a daily basis to facilitate better interpretation of the results. This required transforming the hourly wind and solar capacity factors into total daily renewable energy production for each region.

Appendix A presents the total daily wind energy production per region, **Appendix B** presents the total daily solar energy production per region, while **Appendix C** is the combination of wind and solar energy.

Following this, we conducted a descriptive statistical analysis to gain deeper insights into the renewable energy production patterns for each region. The statistical measures—such as mean, median, standard deviation, skewness, kurtosis, and variance—were computed using Python’s Pandas library and validated through Excel’s Data Analysis Tool. The results of this analysis are shown in **Appendix D, E and F** for wind energy, solar energy and the combination of these two, respectively.

Examining the statistics, we observed that region EL42 (South Aegean) recorded the highest total wind energy production, whereas region EL53 (Western Macedonia) had the lowest. Additionally, EL42 exhibited the highest average daily wind production, while EL53 had the lowest average wind production. Regarding variability, EL30 (Attica) displayed the highest standard deviation for wind energy, suggesting significant fluctuations in yearly production, while EL53 (Thessaly) had the lowest, indicating stable production levels over time.

Figures below illustrate key findings:

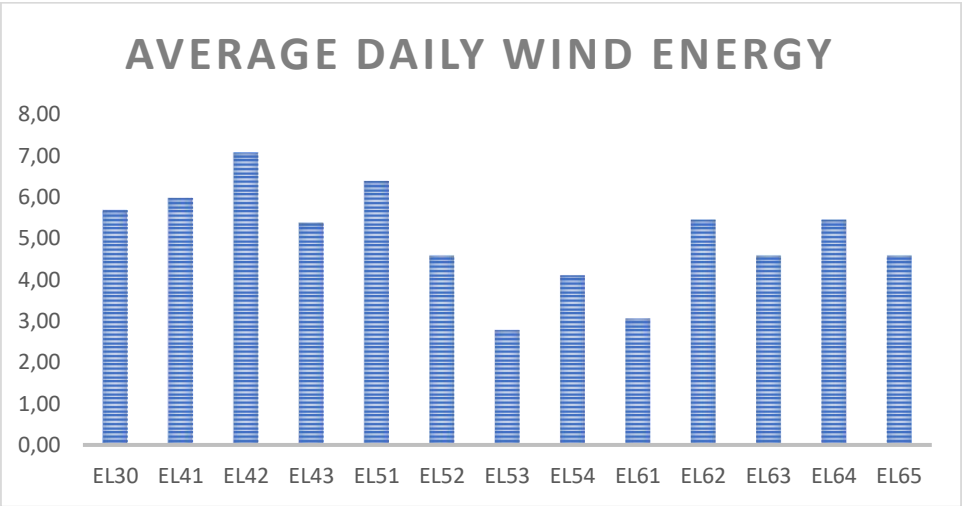
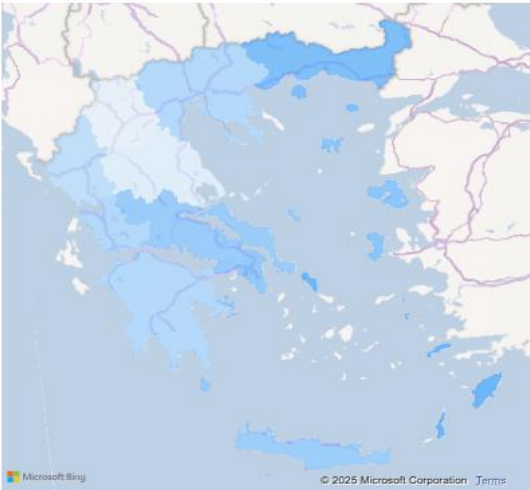


Figure 2: The average total wind production per region



Wind production heatmap

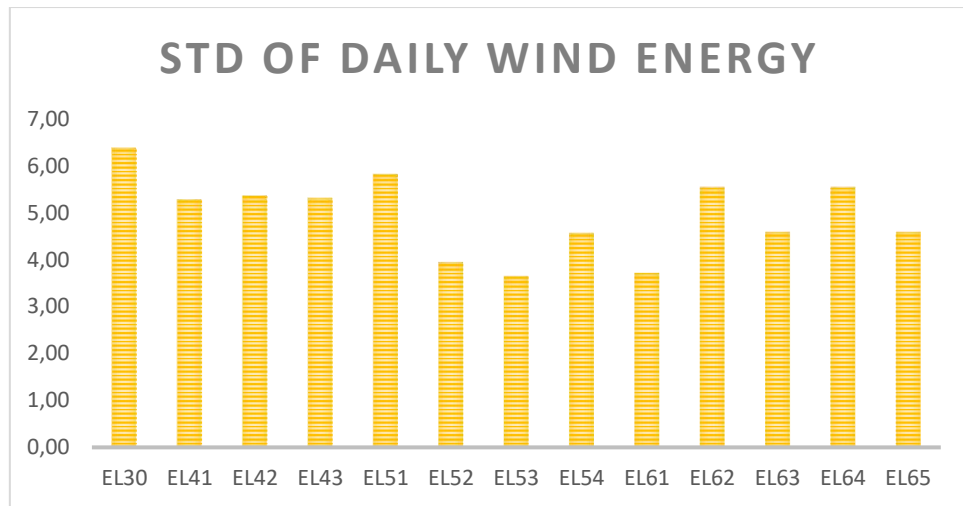
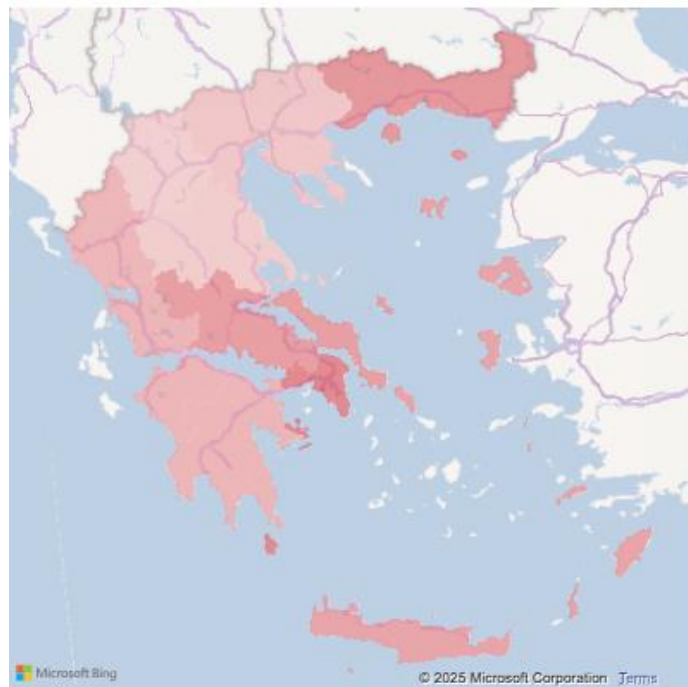


Figure 3: The standard deviation of production per region.



Wind Standard Deviation heatmap

According to solar energy, examining the statistics, we observed that region EL42 (South Aegean) recorded the highest total wind energy production, whereas region EL53 (Western Macedonia) had the lowest. Additionally, EL42 exhibited the highest average annual solar production, while EL53 had the lowest average solar production. Regarding variability, EL53 (Western Macedonia) displayed the highest standard deviation for solar energy, suggesting significant fluctuations in yearly production, while EL42 (South Aegean) had the lowest, indicating stable production levels over time.

Figures below illustrate key findings:

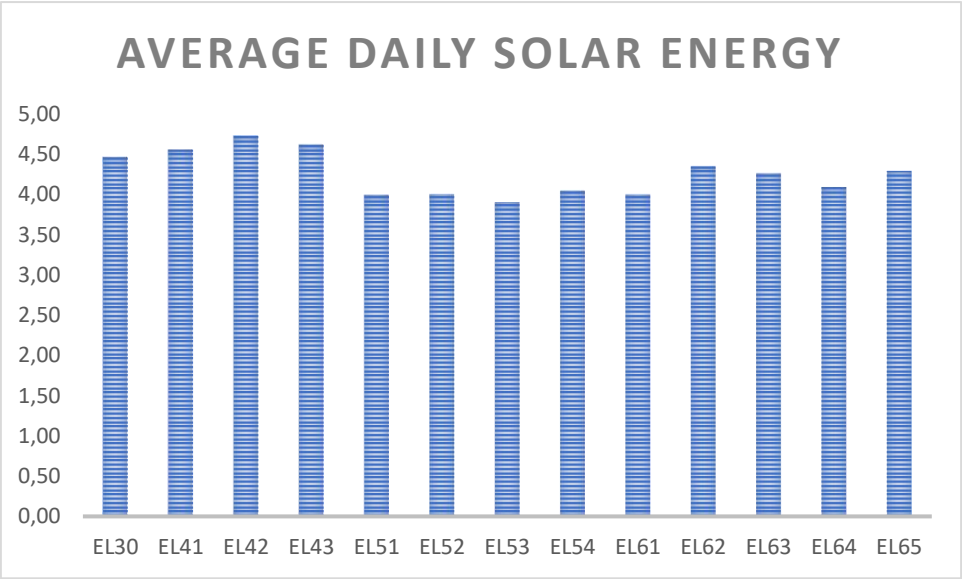


Figure 4: The average total solar production per region



Solar production heatmap

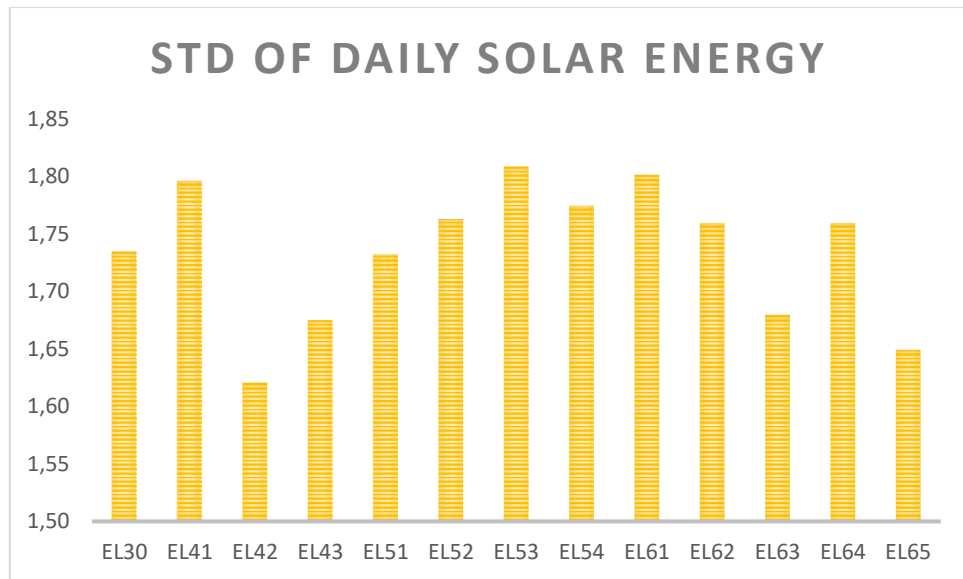


Figure 5: The standard deviation of solar production per region



Solar Standard Deviation heatmap

Lastly, to assess inter-regional dependencies, we computed the correlation matrix for wind and solar energy production across all regions (**Appendix G, H, I** for wind energy, solar energy and its combination, respectively). This matrix provides insights into how production levels in different regions move relative to each other. For instance, regarding wind production, EL42 (South Aegean) and EL53 (Western Macedonia) exhibit the weakest correlation, indicating their energy outputs are largely independent. Conversely, EL63 (Western Greece) and EL65 (Peloponnese) have the highest correlation, implying their energy production trends follow a similar pattern.

Concerning the solar production, EL43 (Crete) and EL54 (Epirus) exhibit the weakest correlation, indicating their energy outputs are largely independent. Conversely, EL61 (Thessaly) and EL64 (Central Greece) have the highest correlation, implying their energy production trends follow a similar pattern.

Understanding these relationships is crucial, as strong positive correlations suggest regions experience similar production patterns, making them less suitable for diversification in an optimal energy portfolio. Conversely, negatively correlated regions provide better diversification potential by balancing fluctuations in energy output.

By leveraging these statistical insights and correlations, we can move forward with optimizing energy portfolios, ensuring minimal risk and maximum stability for investors in the renewable energy sector.

3.3.2 Portfolio Optimization

In this section, we describe the portfolio optimization methodology, which determines the optimal renewable energy portfolios based on specific objectives and constraints. This process utilizes mean-variance optimization, which is fundamental in investment theory and applied here to renewable energy capacity allocation.

The portfolio's expected return (mean total annual production) is calculated as:

$$\mu_p = \mu'w = \sum_{i=1}^N \mu_i w_i$$

Where:

- μ' is the transpose vector of the mean annual production per region: $\mu' = (\mu_{EL30}, \mu_{EL41}, \mu_{EL42}, \mu_{EL43}, \dots, \mu_{EL63}, \mu_{EL64}, \mu_{EL65})$
- w represents the weight of each region in the overall capacity plan.
- N is the number of regions (13 in our case).

The standard deviation (risk) of the portfolio is calculated using the covariance matrix (Σ):

$$\sigma_p = \sqrt{w' \Sigma w}$$

where Σ is the covariance matrix of energy production across regions, derived from **Appendix J** for wind energy, **Appendix K** for solar energy and **Appendix L** for the combination of the two.

Constraints Applied:

- Each region's weight is constrained between 0 and 1: $0 \leq w_i \leq 1$
- The total capacity sum must equal 100%: $\sum_{i=1}^N w_i = 1$

Using these calculations and constraints, we identify **efficient portfolios**, including:

- **Minimum Variance Portfolio (MVP):** The portfolio with the lowest risk.
- **Maximum Yield Portfolio:** The portfolio maximizing expected energy production.
- **Equally Weighted Portfolio:** Allocating equal capacity across regions.
- **Maximum Information Ratio Portfolio:** Optimizing return-to-risk tradeoff.

This methodology ensures a robust assessment of spatial diversification in renewable energy investments, balancing risk and return effectively.

3.3.3 Minimum Variance Portfolio

This portfolio represents the lowest possible risk configuration. The objective function minimizes the portfolio's standard deviation, ensuring stability in energy production.

$$\sigma_p = \sqrt{\mathbf{w}' \Sigma \mathbf{w}}$$

The constraints applied:

- Each region's weight is between 0 and 1. $0 \leq w_i \leq 1$
- The total portfolio weight sums to 100%. $\sum_{i=1}^N w_i = 1$

3.3.4 Maximum Yield Portfolio

This portfolio aims to maximize expected energy production, disregarding risk constraints. It is useful for investors prioritizing maximum return.

$$\mu_p = \mu' \mathbf{w} = \sum_{i=1}^N \mu_i w_i$$

The optimization constraints remain the same:

- Weights must be between 0 and 1. $0 \leq w_i \leq 1$
- The sum of weights must equal 100%. $\sum_{i=1}^N w_i = 1$

3.4 Alternative Portfolios

Beyond the above two portfolios, we explore additional configurations.

3.4.1 Equally Weighted Portfolio

The Equally Weighted Portfolio (EWP) assumes an equal allocation of renewable energy capacity across all regions. This approach allows us to analyze the implications of an evenly distributed investment strategy without considering individual regional performance or risk factors.

Methodology

In this portfolio, each region is assigned an equal weight such that:

$$w_i = \frac{1}{N}$$

where N is the total number of regions (13 in the case of wind or solar energy, 26 in the combination of these).

- $w_{EL30} = w_{EL41} = w_{EL42} = w_{EL43} = w_{EL51} = w_{EL52} = w_{EL53} = w_{EL54} = w_{EL61} = w_{EL62} = w_{EL63} = w_{EL64} = w_{EL65}$
- The sum of weights is equal to 100%. $\sum_{i=1}^N w_i = 1$

3.4.2 Maximum Information Ratio Portfolio

This portfolio optimizes the information ratio (IR), which quantifies yield per unit of risk. The objective is to maximize:

$$IR_p = \frac{\mu_p}{\sigma_p}$$

We solve for the portfolio weights that maximize the IR.

The optimization constraints remain the same:

- Weights must be between 0 and 1. $0 \leq w_i \leq 1$
- The sum of weights must equal 100%. $\sum_{i=1}^N w_i = 1$

3.4.3 Information Ratio-Sorted Portfolio

Here, regions are ranked by their individual IR values, and weights are assigned proportionally to their ranking. This ensures higher allocation to regions offering the best risk-return tradeoff.

$$w_i = \frac{IR_i}{\sum_{i=1}^N IR_i}$$

IR_i is the IR ratio of region $i = 1, 2, \dots, N = 13$

Each of these portfolio strategies provides a unique perspective on capacity allocation and risk management, forming the foundation of our empirical analysis.

4. Research Findings-Discussion

This chapter presents the results of the portfolio optimization process, addressing the research questions established in Chapter 3. The empirical analysis is based on the sample data and optimization methodologies described earlier. The findings derived from this analysis are then compared with the performance of alternative portfolio configurations, providing a comprehensive discussion on the implications of spatial diversification strategies in renewable energy investment.

4.1 Minimum Variance Portfolio

In this section, we execute the optimization process using the equations and constraints outlined in Section 3.3.3. using Excel's solver for optimizing the problem, ensuring accuracy and efficiency.

The objective is to minimize the standard deviation of the portfolio, which represents the overall risk. The optimization process determines the proportion of installed capacity for each region that results in the lowest possible risk.

4.1.1 Minimum Variance Portfolio for Wind Energy

The resulting Minimum Variance Portfolio (MVP) for just wind production is structured as follows:

REGION	MVP WEIGHT (%)
EL30	0,0%
EL41	5,1%
EL42	17,5%
EL43	1,2%
EL51	0,1%
EL52	0,0%
EL53	40,4%
EL54	0,0%
EL61	35,8%
EL62	0,0%
EL63	0,0%
EL64	0,0%
EL65	0,0%
TOTAL	100%

Table 1: Synthesis of the Minimum Variance Portfolio Wind Production



Synthesis of the Minimum Variance Portfolio Wind Production heatmap

The portfolio composition indicates that more than one region could compete in the optimization. The maximum of the installed capacity must be allocated to the Western Macedonia region (EL53) with 40.4%, as it exhibits the lowest standard deviation in daily wind energy production and to the Thessaly region (EL61) with 35.8%. The remaining capacity is mainly distributed in South Aegean (17.5%), North Aegean (5.1%), Crete (4.3%) and Eastern Macedonia & Thrace (0.1%).

The expected return and associated risk level of the Minimum Variance Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	3.83
RISK (σp)	3.02

Table 2: Wind Expected Return and Risk of the Minimum Variance Portfolio

Thus, the expected daily energy production of the minimum variance portfolio is 3.29 MWh, with a standard deviation of 3.02 MWh.

These results confirm that, for a risk-averse investor, allocating most of the installed capacity in Western Macedonia (EL53) is optimal, as it has the lowest standard deviation in energy production. This observation aligns with the descriptive statistical analysis conducted earlier, which identified Western Macedonia as the most stable energy-producing region over the years.

4.1.2 Minimum Variance Portfolio for Solar Energy

The resulting Minimum Variance Portfolio (MVP) for just solar production is structured as follows:

REGION	MVP WEIGHT (%)
EL30	0,0%
EL41	0,0%
EL42	19,8%
EL43	26,9%
EL51	17,1%
EL52	0,1%
EL53	0,0%
EL54	25,2%

EL61	0,0%
EL62	0,0%
EL63	0,0%
EL64	0,0%
EL65	11,0%
TOTAL	100%

Table 3: Synthesis of the Minimum Variance Portfolio Solar Production



Synthesis of the Minimum Variance Portfolio Solar Production heatmap

The portfolio composition indicates that more than one region could compete in the optimization. The maximum of the installed capacity must be allocated to the Crete region (EL43) with 26.9% and Epirus (EL54) with 25.2%, as it exhibits the lowest standard deviation in daily energy production. The remaining capacity is mainly distributed in South Aegean (19.8%), Eastern Macedonia & Thrace (17.1%) and Central Macedonia (0.1%).

The expected return and associated risk level of the Minimum Variance Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.36
RISK (σp)	1.49

Table 4: Solar Expected Return and Risk of the Minimum Variance Portfolio

Thus, the expected daily energy production of the minimum variance portfolio for solar production is 4.36 MWh, with a standard deviation of 1.49 MWh.

These results confirm that, for a risk-averse investor, allocating most of the installed capacity in Crete (EL43) is optimal, as it has the lowest standard deviation in energy production. This observation aligns with the descriptive statistical analysis conducted earlier, which identified Crete as the most stable energy-producing region over the years.

4.1.3 Minimum Variance Portfolio for Wind & Solar Energy

The resulting Minimum Variance Portfolio (MVP) for both wind and solar production is structured as follows:

REGION	MVP WEIGHT (%)
EL30_WIND	0,0%
EL41_WIND	0,0%
EL42_WIND	0,0%
EL43_WIND	3,0%
EL51_WIND	0,1%
EL52_WIND	8,5%
EL53_WIND	0,2%
EL54_WIND	0,0%
EL61_WIND	14,0%
EL62_WIND	0,0%
EL63_WIND	0,0%
EL64_WIND	0,0%
EL65_WIND	0,0%
EL30_SOLAR	0,0%

EL41_SOLAR	0,0%
EL42_SOLAR	11,5%
EL43_SOLAR	18,8%
EL51_SOLAR	9,9%
EL52_SOLAR	0,0%
EL53_SOLAR	10,3%
EL54_SOLAR	0,0%
EL61_SOLAR	0,0%
EL62_SOLAR	0,0%
EL63_SOLAR	13,0%
EL64_SOLAR	0,0%
EL65_SOLAR	10,6%
TOTAL	100%

Table 5: Synthesis of the Minimum Variance Portfolio Wind & Solar Production



Synthesis of the Minimum Variance Portfolio Wind & Solar Production heatmap

The portfolio composition indicates that more than one region could compete in the optimization. The main resource that is used in this case is Solar Energy, with more than 70%. There are 3 regions, Crete, Eastern Macedonia & Thrace and Western Macedonia, where both wind and solar energy are used, with just 3.3% the wind production and 40% the solar energy. North Aegean, Western Greece and Peloponnese compete in the optimization with the

installation of solar energy for 35.1%. Central Macedonia and Thessaly compete as wind energy.

The expected return and associated risk level of the Minimum Variance Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μ_p)	4.22
RISK (σ_p)	1.05

Table 6: Wind & Solar Expected Return and Risk of the Minimum Variance Portfolio

Thus, the expected daily energy production of the minimum variance portfolio for combined production is 1624.71 MWh, with a standard deviation of 32.04 MWh.

These results confirm that, for a risk-averse investor, allocating most of the installed capacity in Crete (EL43) is optimal, as it has the lowest standard deviation in energy production. This observation aligns with the descriptive statistical analysis conducted earlier, which identified Crete as the most stable energy-producing region over the years.

Concerning the Minimum Variance Portfolio, it seems that between the Wind and Solar Energy, the second one has a much smaller variance. So, it is expected that for the combination portfolio, solar energy will be higher. Indeed, in this case solar energy has a weight above 70%, producing the best-case scenario for Minimum Variance Portfolio.

4.2 Maximum Yield Portfolio

In this section, we execute the optimization process using the methodology outlined in Section 3.3.4. The objective is to maximize the expected energy production without considering risk constraints. Using Excel's Solver optimization to determine the best allocation.

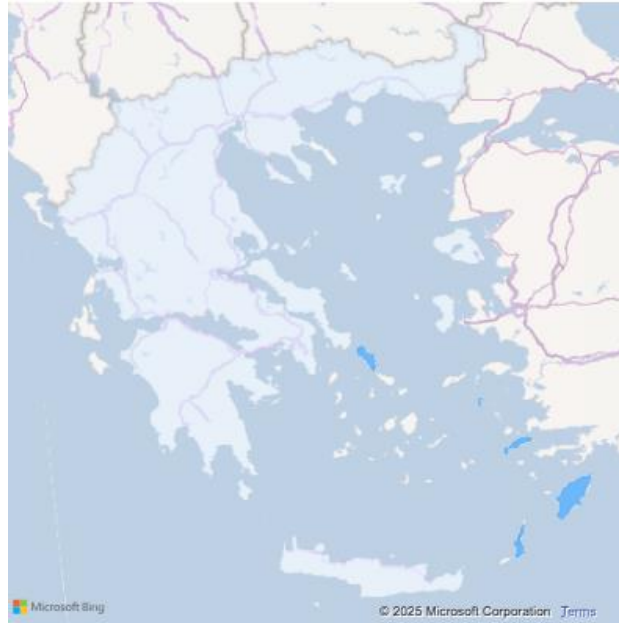
4.2.1 Maximum Yield Portfolio for Wind Energy

The results for the Maximum Yield Portfolio (MYP) wind production are as follows:

REGION	MYP WEIGHT (%)
EL30	0,0%
EL41	0,0%
EL42	100,0%
EL43	0,0%
EL51	0,0%
EL52	0,0%
EL53	0,0%

EL54	0,0%
EL61	0,0%
EL62	0,0%
EL63	0,0%
EL64	0,0%
EL65	0,0%
TOTAL	100.00%

Table 7: Synthesis of the Maximum Yield Portfolio Wind Production



Synthesis of the Maximum Yield Portfolio Wind Production heatmap

The MYP allocates 100% of the installed capacity to the South Aegean region (EL42), as it demonstrates the highest expected wind energy production.

The expected return and risk level of the Maximum Yield Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	7.08
RISK (σp)	5.36

Table 8: Expected Return and Risk of the Maximum Yield Portfolio Wind Production

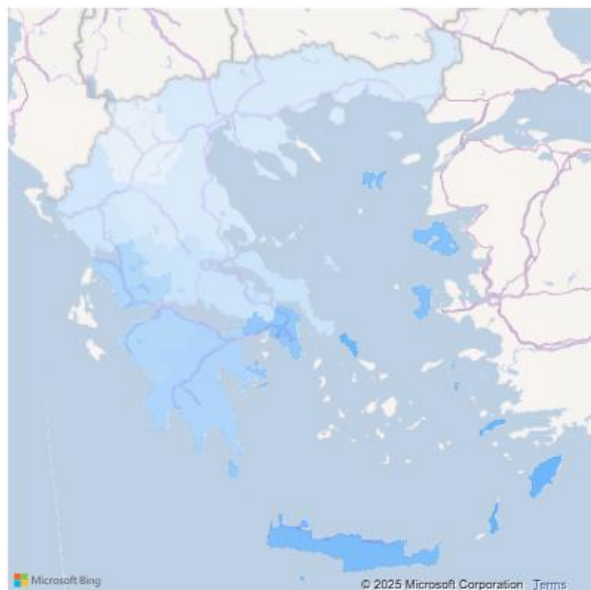
Thus, the expected daily wind energy production of the maximum yield portfolio is 7.08 MWh, with a higher standard deviation of 5.36 MWh, indicating increased variability.

4.2.2 Maximum Yield Portfolio for Solar Energy

The results for the Maximum Yield Portfolio (MYP) solar production are as follows:

REGION	MYP WEIGHT (%)
EL30	0,0%
EL41	0,0%
EL42	100,0%
EL43	0,0%
EL51	0,0%
EL52	0,0%
EL53	0,0%
EL54	0,0%
EL61	0,0%
EL62	0,0%
EL63	0,0%
EL64	0,0%
EL65	0,0%
TOTAL	100.00%

Table 9: Synthesis of the Maximum Yield Portfolio Solar Production



Synthesis of the Maximum Yield Portfolio Solar Production heatmap

The MYP allocates 100% of the installed capacity to the South Aegean region (EL42), as it demonstrates the highest expected solar energy production.

The expected return and risk level of the Maximum Yield Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.74
RISK (σp)	1.62

Table 10: Expected Return and Risk of the Maximum Yield Portfolio Solar Production

Thus, the expected annual solar energy production of the maximum yield portfolio is 4.74 MWh, with a higher standard deviation of 1.62 MWh, indicating not an increased variability.

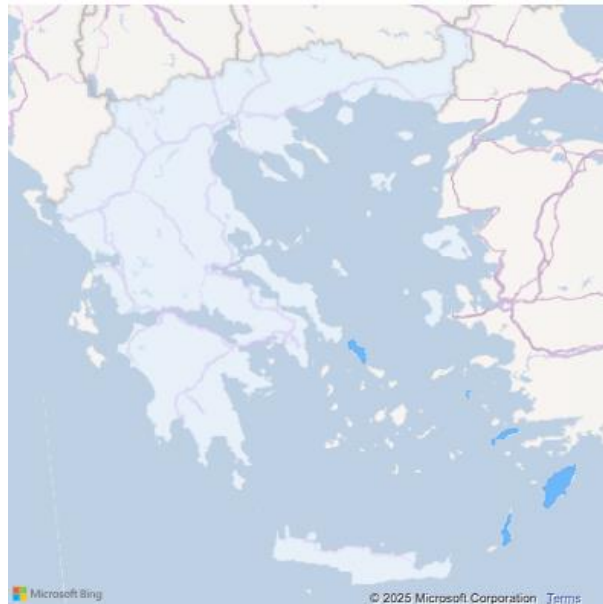
4.2.3 Maximum Yield Portfolio for Wind & Solar Energy

The resulting Maximum Yield Portfolio (MYP) for both wind and solar production is structured as follows:

REGION	MYP WEIGHT (%)
EL30_WIND	0,0%
EL41_WIND	0,0%
EL42_WIND	100,0%
EL43_WIND	0,0%
EL51_WIND	0,0%
EL52_WIND	0,0%
EL53_WIND	0,0%
EL54_WIND	0,0%
EL61_WIND	0,0%
EL62_WIND	0,0%
EL63_WIND	0,0%
EL64_WIND	0,0%
EL65_WIND	0,0%
EL30_SOLAR	0,0%
EL41_SOLAR	0,0%
EL42_SOLAR	0,0%
EL43_SOLAR	0,0%
EL51_SOLAR	0,0%
EL52_SOLAR	0,0%

EL53_SOLAR	0,0%
EL54_SOLAR	0,0%
EL61_SOLAR	0,0%
EL62_SOLAR	0,0%
EL63_SOLAR	0,0%
EL64_SOLAR	0,0%
EL65_SOLAR	0,0%
TOTAL	100%

Table 11: Synthesis of the Maximum Yield Portfolio Solar Production



Synthesis of the Maximum Yield Portfolio Solar Production heatmap

As it is expected, the portfolio composition indicates that just one region could compete in the optimization, South Aegean. The only resource that is used in this case is Wind Energy.

The expected return and associated risk level of the Minimum Variance Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μ_p)	7.08
RISK (σ_p)	5.36

Table 12: Wind & Solar Expected Return and Risk of the Maximum Yield Portfolio

Thus, the expected daily energy production of the maximum yield portfolio for combined production is 7.08 MWh, with a standard deviation of 5.36 MWh.

These results confirm that, for a risk-averse investor, allocating most of the installed capacity in South Aegean (EL42) is optimal, as it has the maximum expected return in energy production.

Concerning the Maximum Yield Portfolio, it seems that between the Wind and Solar Energy, the first one has a much higher expected return, while both refer to the same region at 100%. So, it is expected that for the combination portfolio, the same region would have 100%. As wind energy has a higher expected return, the combination portfolio is optimizing using just Wind Energy in South Aegean.

4.3 Equally Weighted Portfolio

In this section, we compute the Equally Weighted Portfolio using the methodology outlined in Section 3.4.1. This portfolio assigns equal weights to all regions to explore how a fully diversified investment would perform.

4.3.1 Equally Weighted Portfolio for Wind Production

The results for the Equally Weighted Portfolio (EWP) for wind production are as follows:

REGION	EWP WEIGHT (%)
EL30	7.69%
EL41	7.69%
EL42	7.69%
EL43	7.69%
EL51	7.69%
EL52	7.69%
EL53	7.69%
EL54	7.69%
EL61	7.69%
EL62	7.69%
EL63	7.69%
EL64	7.69%
EL65	7.69%
TOTAL	100.00%

Table 13: Synthesis of the Equally Weighted Portfolio for Wind production



Synthesis of the Equally Weighted Portfolio for Wind production heatmap

The expected return and risk of the Equally Weighted Portfolio for wind production are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μ_p)	5.01
RISK (σ_p)	3.98

Table 14: Wind Expected Return and Risk of the Equally Weighted Portfolio

Key Insights

- The EWP has a higher expected return than the MVP but lower than the MYP.
- The risk level is higher than the MVP but lower than the MYP.

4.3.2 Equally Weighted Portfolio for Solar Production

The results for the Equally Weighted Portfolio (EWP) for solar production are as follows:

REGION	EWP WEIGHT (%)
EL30	7.69%
EL41	7.69%
EL42	7.69%
EL43	7.69%
EL51	7.69%
EL52	7.69%
EL53	7.69%
EL54	7.69%

EL61	7.69%
EL62	7.69%
EL63	7.69%
EL64	7.69%
EL65	7.69%
TOTAL	100.00%

Table 15: Synthesis of the Equally Weighted Portfolio for solar production



Synthesis of the Equally Weighted Portfolio for Solar production heatmap

The expected return and risk of the Equally Weighted Portfolio for solar production are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.26
RISK (σp)	1.56

Table 16: Solar Expected Return and Risk of the Equally Weighted Portfolio

Key Insights

- The EWP has the lowest expected return than the MVP and the MYP.
- The risk level is higher than the MVP and the MYP.

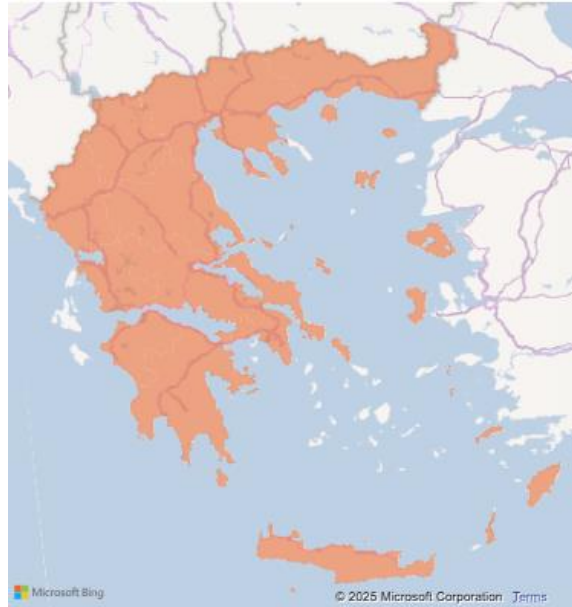
4.3.3 Equally Weighted Portfolio for Wind & Solar Energy

The resulting Equally Weighted Portfolio (EWP) for both wind and solar production is structured as follows:

REGION	EWP WEIGHT (%)
EL30_WIND	3,85%
EL41_WIND	3,85%
EL42_WIND	3,85%
EL43_WIND	3,85%
EL51_WIND	3,85%
EL52_WIND	3,85%
EL53_WIND	3,85%
EL54_WIND	3,85%
EL61_WIND	3,85%
EL62_WIND	3,85%
EL63_WIND	3,85%
EL64_WIND	3,85%
EL65_WIND	3,85%
EL30_SOLAR	3,85%
EL41_SOLAR	3,85%
EL42_SOLAR	3,85%
EL43_SOLAR	3,85%
EL51_SOLAR	3,85%
EL52_SOLAR	3,85%
EL53_SOLAR	3,85%
EL54_SOLAR	3,85%
EL61_SOLAR	3,85%
EL62_SOLAR	3,85%
EL63_SOLAR	3,85%
EL64_SOLAR	3,85%
EL65_SOLAR	3,85%

TOTAL	100%
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Table 17: Synthesis of the Equal Weighted Portfolio Wind & Solar Production



Synthesis of the Equally Weighted Portfolio for Wind & Solar production heatmap

The expected return and associated risk level of the Minimum Variance Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μ_p)	4.63
RISK (σ_p)	1.87

Table 18: Wind & Solar Expected Return and Risk of the Minimum Variance Portfolio

Thus, the expected daily energy production of the equal weighted portfolio for combined production is 4.63 MWh, with a standard deviation of 1.87 MWh.

Key Insights

- The EWP has a lower expected return than the MYP and a higher expected return than the MVP.
- The risk level is higher than the MVP and lower than the MYP.

4.4 Maximum Information Ratio Portfolio

In this section, we compute the Maximum IR Portfolio using the methodology outlined in Section 3.4.2. This portfolio maximizes the expected return per unit of risk.

4.4.1 Maximum Information Ratio Portfolio for Wind Production

The results for the Maximum Information Ratio Portfolio (IR Portfolio) for wind production are as follows:

REGION	IR PORTFOLIO WEIGHT (%)
EL30	0,0%
EL41	0,0%
EL42	46,6%
EL43	0,0%
EL51	11,0%
EL52	6,1%
EL53	13,2%
EL54	0,0%
EL61	10,6%
EL62	0,0%
EL63	3,4%
EL64	0,0%
EL65	9,0%
TOTAL	100.00%

Table 19: Synthesis of the Maximum IR Portfolio for wind production



Synthesis of the Maximum IR Portfolio for wind production heatmap

The expected return and risk of the Maximum IR Portfolio are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	5.55
RISK (σp)	3.69
INFORMATION RATIO (IR)	1.50

Table 20: Expected Return, Risk, and IR of the Maximum IR Portfolio for wind production

Key Insights

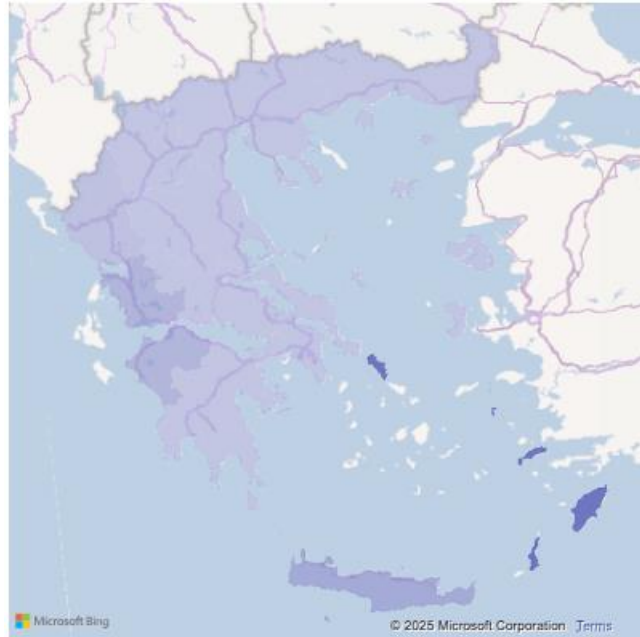
- The IR Portfolio achieves a higher return compared to the Equally Weighted Portfolio for a lower risk level.
- The risk level is lower than that of the Maximum Yield Portfolio but a higher than the Minimum Variance Portfolio.

4.4.2 Maximum Information Ratio Portfolio for Solar Production

The results for the Maximum Information Ratio Portfolio (IR Portfolio) for solar production are as follows:

REGION	IR PORTFOLIO WEIGHT (%)
EL30	0,0%
EL41	0,0%
EL42	53,7%
EL43	18,8%
EL51	0,0%
EL52	0,0%
EL53	0,0%
EL54	3,6%
EL61	0,0%
EL62	13,1%
EL63	10,9%
EL64	0,0%
EL65	0,0%
TOTAL	100.00%

Table 21: Synthesis of the Maximum IR Portfolio for solar production



Synthesis of the Maximum IR Portfolio for solar production heatmap

The solar expected return and risk of the Maximum IR Portfolio are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.59
RISK (σp)	1.53
INFORMATION RATIO (IR)	3.01

Table 22: Expected Return, Risk, and IR of the Maximum IR Portfolio for solar production

Key Insights

- The IR Portfolio achieves a higher return compared to the Equally Weighted Portfolio for a similar risk level.
- The risk level is lower than that of the Maximum Yield Portfolio but a bit higher than the Minimum Variance Portfolio.

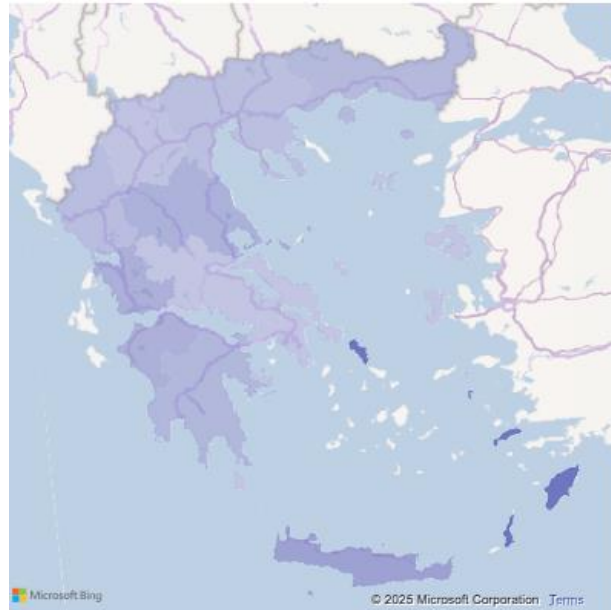
4.4.3 Maximum Information Ratio Portfolio for Wind & Solar Energy

The results for the Maximum Information Ratio Portfolio (IR Portfolio) for solar production are as follows:

REGION	IR PORTFOLIO WEIGHT (%)
EL30_WIND	0,0%

EL41_WIND	0,0%
EL42_WIND	1,4%
EL43_WIND	3,1%
EL51_WIND	6,0%
EL52_WIND	1,5%
EL53_WIND	1,4%
EL54_WIND	0,0%
EL61_WIND	10,1%
EL62_WIND	0,0%
EL63_WIND	0,8%
EL64_WIND	0,0%
EL65_WIND	0,0%
EL30_SOLAR	0,0%
EL41_SOLAR	0,0%
EL42_SOLAR	37,8%
EL43_SOLAR	14,7%
EL51_SOLAR	0,0%
EL52_SOLAR	1,6%
EL53_SOLAR	0,0%
EL54_SOLAR	4,4%
EL61_SOLAR	0,0%
EL62_SOLAR	0,0%
EL63_SOLAR	9,5%
EL64_SOLAR	0,0%
EL65_SOLAR	7,7%
TOTAL	100%

Table 23: Synthesis of the Maximum Information Ratio Portfolio Wind & Solar Production



Synthesis of the Maximum Information Ratio Portfolio Wind & Solar Production heatmap

The expected return and associated risk level of the Maximum Information Ratio Portfolio are presented in the table below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.55
RISK (σp)	1.09
IR	4.17

Table 24: Wind & Solar Expected Return and Risk of the Minimum Variance Portfolio

Thus, the expected daily energy production of the Maximum Information Ratio portfolio for combined production is 4.55 MWh, with a standard deviation of 1.09 MWh and Information Ratio of 4.17.

It seems that solar production has a much higher contribution than the wind production. There are four regions, South Aegean, Crete, Central Macedonia and Western Greece, that compete in the optimization with both solar and wind production. Western Macedonia and Eastern Macedonia & Thrace has also a small contribution with wind production, while Epirus and Peloponnese contribute to the optimization with solar production.

Key Insights

- The IR portfolio has a lower expected return than the MYP and a higher expected return than the MVP.
- The risk level is higher than the MVP and lower than the MYP.

4.5 Information Ratio-Sorted Portfolio

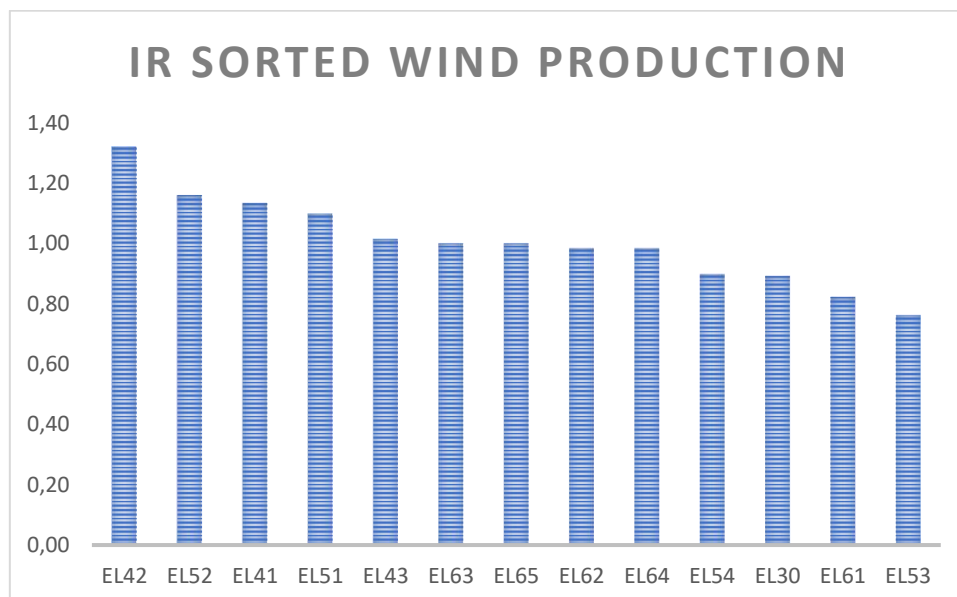
In this section, we compute the IR-Sorted Portfolio using the methodology outlined in Section 3.4.3. This portfolio assigns weights to regions based on their relative IR values.

4.5.1 Information Ratio-Sorted Portfolio for Wind Production

The results for the Information Ratio-Sorted Portfolio (IR-Sorted Portfolio) for wind production are as follows:

	MEAN	STD	IR
EL42	7,08	5,36	1,32
EL52	4,59	3,95	1,16
EL41	5,98	5,28	1,13
EL51	6,39	5,82	1,10
EL43	5,39	5,31	1,01
EL63	4,59	4,59	1,00
EL65	4,59	4,59	1,00
EL62	5,45	5,54	0,98
EL64	5,45	5,54	0,98
EL54	4,11	4,57	0,90
EL30	5,69	6,38	0,89
EL61	3,06	3,72	0,82
EL53	2,78	3,65	0,76

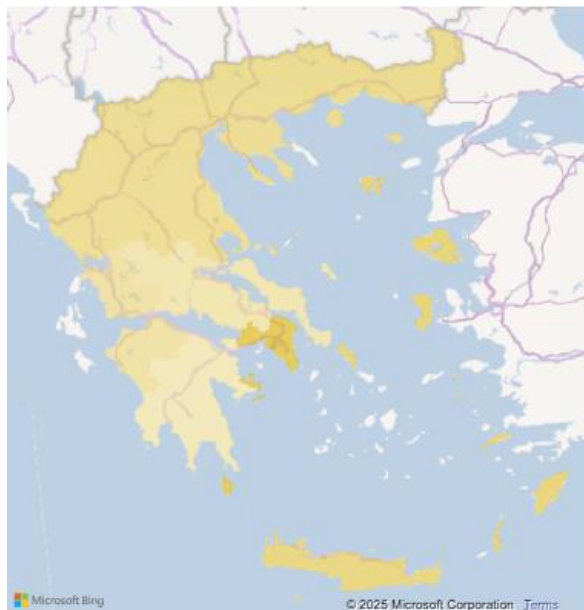
Table 25: Synthesis of the IR-Sorted Portfolio for wind production



EL42 has the highest IR, while EL53 has the lowest one. The respective weights are shown below.

	W
EL42	10.11%
EL52	8.88%
EL41	8.67%
EL51	8.40%
EL43	7.76%
EL63	7.65%
EL65	7.65%
EL62	7.53%
EL64	7.53%
EL54	6.87%
EL30	6.82%
EL61	6.29%
EL53	5.83%

Table 26: Synthesis of the IR-Sorted Portfolio weights for wind production



Synthesis of the IR-Sorted Portfolio weights for wind production heatmap

The expected return and risk of the IR-Sorted Portfolio for wind production are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	5.14
RISK (σp)	4.03

Table 27: Expected Return and Risk of the IR-Sorted Portfolio for wind production

Key Insights

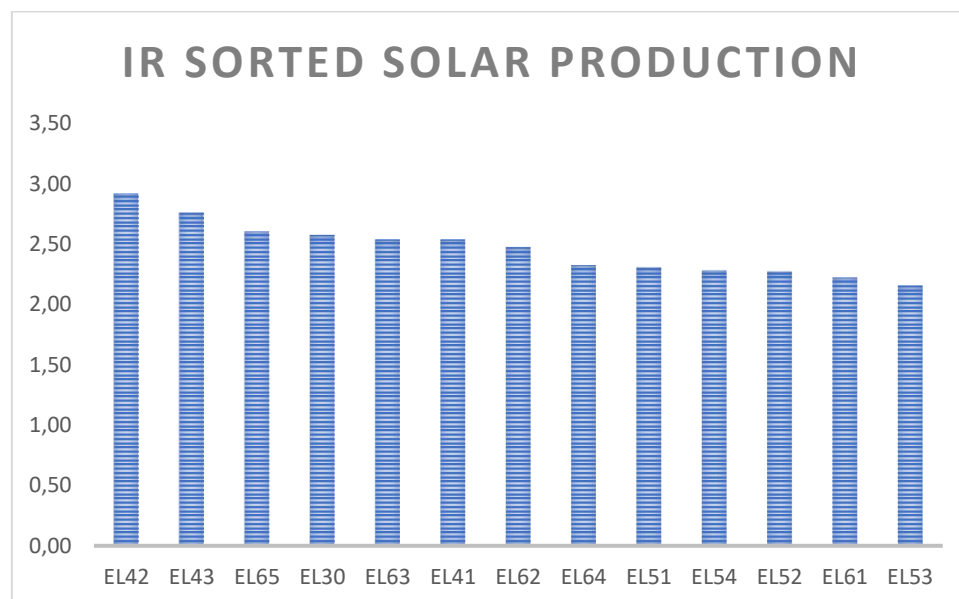
- The IR-Sorted Portfolio achieves a higher return than the Equally Weighted Portfolio for a similar risk level, proving it to be a more efficient allocation strategy.
- The risk level is lower than that of the Maximum Yield Portfolio but higher than the Minimum Variance Portfolio.

4.5.2 Information Ratio-Sorted Portfolio for Solar Production

The results for the Information Ratio-Sorted Portfolio (IR-Sorted Portfolio) for solar production are as follows:

	MEAN	STD	IR
EL42	4,74	1,62	2,92
EL43	4,62	1,68	2,76
EL65	4,29	1,65	2,60
EL30	4,47	1,74	2,58
EL63	4,27	1,68	2,54
EL41	4,56	1,80	2,54
EL62	4,35	1,76	2,47
EL64	4,09	1,76	2,33
EL51	4,00	1,73	2,31
EL54	4,05	1,77	2,28
EL52	4,01	1,76	2,27
EL61	4,00	1,80	2,22
EL53	3,90	1,81	2,16

Table 28: Synthesis of the IR-Sorted Portfolio for solar production



EL42 has the highest IR, while EL53 has the lowest one. The respective weights are shown below.

	W
EL42	9.14%
EL43	8.63%
EL65	8.14%
EL30	8.05%
EL63	7.94%
EL41	7.94%
EL62	7.73%
EL64	7.27%
EL51	7.21%
EL54	7.14%
EL52	7.11%
EL61	6.95%
EL53	6.75%

Table 29: Synthesis of the IR-Sorted Portfolio weights for solar production



Synthesis of the IR-Sorted Portfolio weights for solar production heatmap

The expected return and risk of the IR-Sorted Portfolio for wind production are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.28
RISK (σp)	1.55

Table 30: Expected Return and Risk of the IR-Sorted Portfolio for solar production

Key Insights

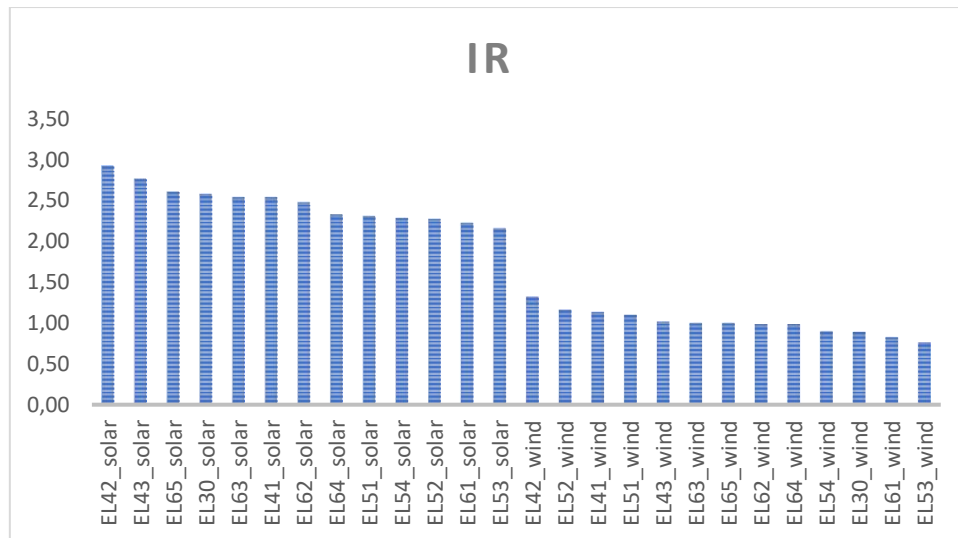
- The IR-Sorted Portfolio achieves a similar return to the Equally Weighted Portfolio for a similar risk level.
- The risk level is lower than that of the Maximum Yield Portfolio but higher than the Minimum Variance Portfolio.

4.5.3 Information Ratio-Sorted Portfolio for Wind & Solar Production

The results for the Information Ratio-Sorted Portfolio (IR-Sorted Portfolio) for solar production are as follows:

	MEAN	STD	IR
EL42_SOLAR	4,74	1,62	2,92
EL43_SOLAR	4,62	1,68	2,76
EL65_SOLAR	4,29	1,65	2,60
EL30_SOLAR	4,47	1,74	2,58
EL63_SOLAR	4,27	1,68	2,54
EL41_SOLAR	4,56	1,80	2,54
EL62_SOLAR	4,35	1,76	2,47
EL64_SOLAR	4,09	1,76	2,33
EL51_SOLAR	4,00	1,73	2,31
EL54_SOLAR	4,05	1,77	2,28
EL52_SOLAR	4,01	1,76	2,27
EL61_SOLAR	4,00	1,80	2,22
EL53_SOLAR	3,90	1,81	2,16
EL42_WIND	7,08	5,36	1,32
EL52_WIND	4,59	3,95	1,16
EL41_WIND	5,98	5,28	1,13
EL51_WIND	6,39	5,82	1,10
EL43_WIND	5,39	5,31	1,01
EL63_WIND	4,59	4,59	1,00
EL65_WIND	4,59	4,59	1,00
EL62_WIND	5,45	5,54	0,98
EL64_WIND	5,45	5,54	0,98
EL54_WIND	4,11	4,57	0,90
EL30_WIND	5,69	6,38	0,89
EL61_WIND	3,06	3,72	0,82
EL53_WIND	2,78	3,65	0,76

Table 31: Synthesis of the IR-Sorted Portfolio for wind & solar production



EL42 for Solar production has the highest IR, while EL53 for wind production has the lowest one. The respective weights are shown below.

W	
EL42_SOLAR	6,49%
EL43_SOLAR	6,13%
EL65_SOLAR	5,78%
EL30_SOLAR	5,72%
EL63_SOLAR	5,64%
EL41_SOLAR	5,63%
EL62_SOLAR	5,49%
EL64_SOLAR	5,16%
EL51_SOLAR	5,12%
EL54_SOLAR	5,07%
EL52_SOLAR	5,04%
EL61_SOLAR	4,93%
EL53_SOLAR	4,79%
EL42_WIND	2,93%
EL52_WIND	2,58%
EL41_WIND	2,52%
EL51_WIND	2,44%
EL43_WIND	2,25%
EL63_WIND	2,22%
EL65_WIND	2,22%
EL62_WIND	2,18%
EL64_WIND	2,18%
EL54_WIND	1,99%
EL30_WIND	1,98%
EL61_WIND	1,83%
EL53_WIND	1,69%

Table 32: Synthesis of the IR-Sorted Portfolio weights for wind & solar production



Synthesis of the IR-Sorted Portfolio weights for wind & solar production heatmap

The expected return and risk of the IR-Sorted Portfolio for wind and solar production are presented below:

METRIC	VALUE (MWH)
EXPECTED RETURN (μp)	4.53
RISK (σp)	1.30

Table 30: Expected Return and Risk of the IR-Sorted Portfolio for wind & solar production

Key Insights

- The IR-Sorted Portfolio achieves a lower return than the Equally Weighted Portfolio for a lower risk level.
- The risk level is lower than that of the Maximum Yield Portfolio but higher than the Minimum Variance Portfolio.

4.6 Comparison

This research has examined various portfolio strategies tailored for different investor profiles. It is important to note that no single portfolio is universally optimal—each investor must choose the one that aligns with their objectives and risk tolerance.

One of the key advantages of optimized portfolios over alternative ones is their ability to account for correlations between different regions. In the optimization process, highly correlated regions are assigned smaller shares, ensuring that the overall portfolio minimizes

risk. Alternative portfolio strategies, such as the equally weighted approach, do not consider these correlations and may achieve similar expected yields, but with significantly higher risk exposure.

Another crucial reason for strategic spatial diversification is the environmental footprint of renewable energy projects. Selecting optimal regions for wind and solar installations ensures that production is maximized while minimizing environmental impact. While renewable energy is cleaner than conventional sources, the installation, maintenance, and decommissioning of wind and solar farms still have environmental consequences. Thus, it is more beneficial to invest in a few, strategically chosen regions rather than spreading capacity across the entire country without a clear optimization plan.

In summary, our research confirms that spatial diversification enhances the reliability of a renewable energy portfolio. By applying this strategy, investors can maximize returns and minimize risks, selecting only the regions that add value to their portfolio. Furthermore, the environmental impact of renewable energy projects can be mitigated by carefully selecting optimal locations, making wind and solar power truly sustainable.

5. Conclusion

The transition to renewable energy sources has become an essential priority for ensuring energy security, reducing carbon emissions, and achieving long-term sustainability. However, the variability and intermittency of wind and solar energy introduce significant challenges in maintaining a stable and reliable electricity supply. This study focused on optimizing the spatial allocation of wind and solar energy production by applying Modern Portfolio Theory (MPT), demonstrating how diversification strategies can effectively mitigate risks and enhance overall energy yield.

The results of this research emphasize that spatial diversification is a key factor in achieving stability and maximizing efficiency in renewable energy production. By allocating capacity across different geographical regions, the study confirmed that risk can be significantly reduced without necessarily sacrificing return. The Minimum Variance Portfolio (MVP) highlighted that for risk-averse investors, prioritizing regions with low standard deviation in energy production leads to more stable and predictable output. The Maximum Yield Portfolio (MYP), on the other hand, demonstrated that if an investor prioritizes maximum expected production over stability, regions with the highest average energy yield should receive the majority of capacity allocation, despite the increased volatility that comes with this strategy.

Furthermore, the application of Information Ratio-based optimization provided additional insights into balancing risk and return. The Maximum Information Ratio (IR) Portfolio optimized the return-to-risk tradeoff, offering an effective strategy for investors seeking an optimal balance. The Information Ratio-Sorted Portfolio, which assigns weights based on the relative efficiency of each region, further demonstrated that targeting locations with superior risk-adjusted returns leads to more robust performance compared to equal-weighted allocations.

Another critical takeaway is the complementary nature of wind and solar energy. The study found that solar energy generally exhibits lower variability compared to wind energy, making it a more stable choice for diversification. Conversely, wind energy tends to have higher expected returns but with greater uncertainty, necessitating careful site selection and geographical dispersion to mitigate risks. This supports the argument that combining wind and solar resources enhances overall reliability, reinforcing the importance of hybrid renewable energy portfolios.

From a policy and investment perspective, the findings of this research have practical implications. Policymakers can leverage portfolio optimization techniques to design more efficient renewable energy infrastructure, ensuring that installed capacity is strategically allocated to maximize system reliability. Similarly, energy investors can use these insights to develop more resilient investment portfolios, minimizing financial risk while optimizing returns. Moreover, the environmental impact of renewable energy projects can be significantly reduced through optimized site selection, as concentrating production in a few strategically chosen locations minimizes land-use conflicts and improves integration into the electricity grid.

In summary, the study underscores the necessity of data-driven decision-making in renewable energy planning. By adopting modern financial optimization techniques, stakeholders can improve energy security, reduce reliance on fossil fuels, and facilitate the transition towards a sustainable and resilient energy system. The integration of advanced spatial allocation methods will be instrumental in shaping the future of renewable energy, ensuring that wind and solar resources are deployed efficiently, economically, and sustainably.

Appendix

Appendix A

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54
1/1/1986	8,87	18,49	16,15	10,38	17,42	9,48	1,55	5,86
2/1/1986	1,03	2,78	7,64	9,53	1,35	1,18	1,01	1,03
3/1/1986	0,54	1,42	1,21	1,50	5,08	5,48	5,88	3,86
4/1/1986	5,12	8,16	3,45	0,82	13,73	9,59	5,45	6,95
5/1/1986	5,28	11,19	9,00	3,12	14,32	8,02	1,71	5,05
6/1/1986	5,40	6,41	6,44	1,68	3,37	2,77	2,17	3,25
7/1/1986	12,46	15,88	15,61	9,47	15,36	10,41	5,46	10,32
...								
31/12/2015	20,27	16,75	21,39	22,27	15,38	8,26	1,14	10,41

	EL61	EL62	EL63	EL64	EL65
1/1/1986	1,25	11,05	7,08	11,05	7,08
2/1/1986	1,07	1,29	3,00	1,29	3,00

3/1/1986	1,18	1,64	2,53	1,64	2,53
4/1/1986	2,00	6,88	7,55	6,88	7,55
5/1/1986	1,34	7,48	4,26	7,48	4,26
6/1/1986	2,80	5,87	5,97	5,87	5,97
7/1/1986	4,15	13,52	9,46	13,52	9,46
...					
31/12/2015	6,01	16,36	10,86	16,36	10,86

Appendix A: Wind production

Appendix B

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54
1/1/1986	1,28	0,39	0,79	0,95	1,59	1,87	1,87	0,91
2/1/1986	3,06	1,86	2,50	2,15	2,35	3,27	3,56	2,99
3/1/1986	4,68	3,52	4,03	3,42	3,40	3,88	2,93	0,50
4/1/1986	3,82	2,58	2,98	3,19	1,96	1,64	2,04	1,04
5/1/1986	3,30	2,55	2,64	2,10	1,89	1,47	0,93	0,81
6/1/1986	2,37	1,89	2,74	2,92	1,37	2,26	2,82	2,24
7/1/1986	2,82	1,55	2,12	1,49	1,51	3,15	2,68	1,21
...								
31/12/2015	1,22	2,51	2,42	1,06	4,43	2,70	1,66	2,79

	EL61	EL62	EL63	EL64	EL65
1/1/1986	2,25	1,59	1,33	1,47	1,50
2/1/1986	3,45	2,81	3,13	2,97	3,42
3/1/1986	3,65	1,29	1,62	3,98	3,42
4/1/1986	2,21	2,06	1,29	2,67	1,80
5/1/1986	1,45	1,63	1,58	2,17	2,41
6/1/1986	2,45	2,26	2,08	2,35	2,17
7/1/1986	2,17	1,65	0,79	2,08	1,60
...					
31/12/2015	1,02	1,92	2,03	1,12	0,68

Appendix B: Solar production

Appendix C

	EL30_WIND	EL41_WIND	EL42_WIND	EL43_WIND	EL51_WIND	EL52_WIND	EL53_WIND
1/1/1986	8,87	18,49	16,15	10,38	17,42	9,48	1,55
2/1/1986	1,03	2,78	7,64	9,53	1,35	1,18	1,01
3/1/1986	0,54	1,42	1,21	1,50	5,08	5,48	5,88
4/1/1986	5,12	8,16	3,45	0,82	13,73	9,59	5,45
5/1/1986	5,28	11,19	9,00	3,12	14,32	8,02	1,71
6/1/1986	5,40	6,41	6,44	1,68	3,37	2,77	2,17
7/1/1986	12,46	15,88	15,61	9,47	15,36	10,41	5,46
...							
31/12/2015	20,27	16,75	21,39	22,27	15,38	8,26	1,14

	EL54_WIND	EL61_WIND	EL62_WIND	EL63_WIND	EL64_WIND	EL65_WIND	EL30_SOLAR
1/1/1986	5,86	1,25	11,05	7,08	11,05	7,08	1,28
2/1/1986	1,03	1,07	1,29	3,00	1,29	3,00	3,06
3/1/1986	3,86	1,18	1,64	2,53	1,64	2,53	4,68
4/1/1986	6,95	2,00	6,88	7,55	6,88	7,55	3,82
5/1/1986	5,05	1,34	7,48	4,26	7,48	4,26	3,30
6/1/1986	3,25	2,80	5,87	5,97	5,87	5,97	2,37
7/1/1986	10,32	4,15	13,52	9,46	13,52	9,46	2,82
...							
31/12/2015	10,41	6,01	16,36	10,86	16,36	10,86	1,22

	EL41_SOLAR	EL42_SOLAR	EL43_SOLAR	EL51_SOLAR	EL52_SOLAR	EL53_SOLAR	EL54_SOLAR
1/1/1986	0,39	0,79	0,95	1,59	1,87	1,87	0,91
2/1/1986	1,86	2,50	2,15	2,35	3,27	3,56	2,99
3/1/1986	3,52	4,03	3,42	3,40	3,88	2,93	0,50
4/1/1986	2,58	2,98	3,19	1,96	1,64	2,04	1,04
5/1/1986	2,55	2,64	2,10	1,89	1,47	0,93	0,81
6/1/1986	1,89	2,74	2,92	1,37	2,26	2,82	2,24
7/1/1986	1,55	2,12	1,49	1,51	3,15	2,68	1,21
...							
31/12/2015	2,51	2,42	1,06	4,43	2,70	1,66	2,79

	EL61_SOLAR	EL62_SOLAR	EL63_SOLAR	EL64_SOLAR	EL65_SOLAR
1/1/1986	2,25	1,59	1,33	1,47	1,50
2/1/1986	3,45	2,81	3,13	2,97	3,42
3/1/1986	3,65	1,29	1,62	3,98	3,42
4/1/1986	2,21	2,06	1,29	2,67	1,80
5/1/1986	1,45	1,63	1,58	2,17	2,41
6/1/1986	2,45	2,26	2,08	2,35	2,17
7/1/1986	2,17	1,65	0,79	2,08	1,60

...					
31/12/2015	1,02	1,92	2,03	1,12	0,68

Appendix C: Wind & Solar production

Appendix D

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54
MEAN	5,69	5,98	7,08	5,39	6,39	4,59	2,78	4,11
STANDARD ERROR	0,06	0,05	0,05	0,05	0,06	0,04	0,03	0,04
MEDIAN	2,96	4,39	6,07	3,65	4,51	3,46	1,37	2,35
STANDARD DEVIATION	6,38	5,28	5,36	5,31	5,82	3,95	3,65	4,57
SAMPLE VARIANCE	40,68	27,86	28,72	28,19	33,86	15,61	13,30	20,89
KURTOSIS	0,37	-0,01	-0,59	0,59	0,03	1,37	4,46	2,63
SKEWNESS	1,19	0,94	0,62	1,15	0,99	1,26	2,04	1,69
RANGE	23,94	22,75	23,24	23,40	23,86	22,34	23,78	23,96
MINIMUM	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,00
MAXIMUM	23,94	22,76	23,25	23,40	23,86	22,34	23,78	23,96
SUM	62313,75	65545,80	77591,15	59015,13	70017,55	50239,15	30460,74	44982,11
COUNT	10957	10957	10957	10957	10957	10957	10957	10957

	EL61	EL62	EL63	EL64	EL65
MEAN	3,06	5,45	4,59	5,45	4,59
STANDARD ERROR	0,04	0,05	0,04	0,05	0,04
MEDIAN	1,67	3,32	2,95	3,32	2,95
STANDARD DEVIATION	3,72	5,54	4,59	5,54	4,59
SAMPLE VARIANCE	13,82	30,73	21,06	30,73	21,06
KURTOSIS	6,27	0,16	1,27	0,16	1,27
SKEWNESS	2,31	1,08	1,33	1,08	1,33
RANGE	24,00	22,70	23,61	22,70	23,61
MINIMUM	0,00	0,00	0,00	0,00	0,00
MAXIMUM	24,00	22,70	23,61	22,70	23,61
SUM	33492,06	59734,17	50257,06	59734,17	50257,06
COUNT	10957	10957	10957	10957	10957

Appendix D: Wind statistics

Appendix E

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54
MEAN	4,47	4,56	4,74	4,62	4,00	4,01	3,90	4,05
STANDARD ERROR	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
MEDIAN	4,99	5,10	5,28	5,08	4,35	4,44	4,34	4,50
STANDARD DEVIATION	1,74	1,80	1,62	1,68	1,73	1,76	1,81	1,77
SAMPLE VARIANCE	3,01	3,23	2,63	2,81	3,00	3,11	3,27	3,15
KURTOSIS	-0,65	-0,78	-0,58	-0,84	-0,91	-0,90	-1,03	-0,87
SKEWNESS	-0,76	-0,69	-0,78	-0,63	-0,51	-0,59	-0,48	-0,60
RANGE	6,93	6,92	6,81	6,87	6,80	6,76	6,84	6,73
MINIMUM	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
MAXIMUM	6,93	6,92	6,81	6,87	6,80	6,76	6,84	6,73
SUM	48961,92	49957,60	51895,44	50670,25	43790,86	43899,71	42760,91	44379,62
COUNT	10957	10957	10957	10957	10957	10957	10957	10957

	EL61	EL62	EL63	EL64	EL65
MEAN	4,00	4,35	4,27	4,09	4,29
STANDARD ERROR	0,02	0,02	0,02	0,02	0,02
MEDIAN	4,49	4,83	4,73	4,53	4,76
STANDARD DEVIATION	1,80	1,76	1,68	1,76	1,65
SAMPLE VARIANCE	3,25	3,10	2,82	3,10	2,72
KURTOSIS	-0,97	-0,84	-0,66	-0,99	-0,70
SKEWNESS	-0,58	-0,65	-0,73	-0,55	-0,69
RANGE	6,68	6,77	6,72	6,78	6,76
MINIMUM	0,00	0,00	0,00	0,00	0,00
MAXIMUM	6,68	6,77	6,72	6,78	6,76
SUM	43869,92	47686,28	46747,93	44837,15	47054,88
COUNT	10957	10957	10957	10957	10957

Appendix E: Solar statistics

Appendix F

	<i>EL30_WIND</i>	<i>EL41_WIND</i>	<i>EL42_WIND</i>	<i>EL43_WIND</i>	<i>EL51_WIND</i>	<i>EL52_WIND</i>	<i>EL53_WIND</i>
MEAN	5,69	5,98	7,08	5,39	6,39	4,59	2,78
STANDARD ERROR	0,06	0,05	0,05	0,05	0,06	0,04	0,03
MEDIAN	2,96	4,39	6,07	3,65	4,51	3,46	1,37
STANDARD DEVIATION	6,38	5,28	5,36	5,31	5,82	3,95	3,65
SAMPLE VARIANCE	40,68	27,86	28,72	28,19	33,86	15,61	13,30
KURTOSIS	0,37	-0,01	-0,59	0,59	0,03	1,37	4,46
SKEWNESS	1,19	0,94	0,62	1,15	0,99	1,26	2,04
RANGE	23,94	22,75	23,24	23,40	23,86	22,34	23,78
MINIMUM	0,00	0,01	0,01	0,00	0,00	0,00	0,00
MAXIMUM	23,94	22,76	23,25	23,40	23,86	22,34	23,78
SUM	62313,75	65545,80	77591,15	59015,13	70017,55	50239,15	30460,74
COUNT	10957	10957	10957	10957	10957	10957	10957

	<i>EL54_WIND</i>	<i>EL61_WIND</i>	<i>EL62_WIND</i>	<i>EL63_WIND</i>	<i>EL64_WIND</i>	<i>EL65_WIND</i>	<i>EL30_SOLAR</i>
MEAN	4,11	3,06	5,45	4,59	5,45	4,59	4,47
STANDARD ERROR	0,04	0,04	0,05	0,04	0,05	0,04	0,02
MEDIAN	2,35	1,67	3,32	2,95	3,32	2,95	4,99
STANDARD DEVIATION	4,57	3,72	5,54	4,59	5,54	4,59	1,74
SAMPLE VARIANCE	20,89	13,82	30,73	21,06	30,73	21,06	3,01
KURTOSIS	2,63	6,27	0,16	1,27	0,16	1,27	-0,65
SKEWNESS	1,69	2,31	1,08	1,33	1,08	1,33	-0,76
RANGE	23,96	24,00	22,70	23,61	22,70	23,61	6,93
MINIMUM	0,00	0,00	0,00	0,00	0,00	0,00	0,00
MAXIMUM	23,96	24,00	22,70	23,61	22,70	23,61	6,93
SUM	44982,11	33492,06	59734,17	50257,06	59734,17	50257,06	48961,92
COUNT	10957	10957	10957	10957	10957	10957	10957

	<i>EL41_SOLAR</i>	<i>EL42_SOLAR</i>	<i>EL43_SOLAR</i>	<i>EL51_SOLAR</i>	<i>EL52_SOLAR</i>	<i>EL53_SOLAR</i>	<i>EL54_SOLAR</i>
MEAN	4,56	4,74	4,62	4,00	4,01	3,90	4,05
STANDARD ERROR	0,02	0,02	0,02	0,02	0,02	0,02	0,02
MEDIAN	5,10	5,28	5,08	4,35	4,44	4,34	4,50

STANDARD DEVIATION	1,80	1,62	1,68	1,73	1,76	1,81	1,77
SAMPLE VARIANCE	3,23	2,63	2,81	3,00	3,11	3,27	3,15
KURTOSIS	-0,78	-0,58	-0,84	-0,91	-0,90	-1,03	-0,87
SKEWNESS	-0,69	-0,78	-0,63	-0,51	-0,59	-0,48	-0,60
RANGE	6,92	6,81	6,87	6,80	6,76	6,84	6,73
MINIMUM	0,00	0,00	0,00	0,00	0,00	0,00	0,00
MAXIMUM	6,92	6,81	6,87	6,80	6,76	6,84	6,73
SUM	49957,60	51895,44	50670,25	43790,86	43899,71	42760,91	44379,62
COUNT	10957	10957	10957	10957	10957	10957	10957

	EL61_SOLA R	EL62_SOLA R	EL63_SOLA R	EL64_SOLA R	EL65_SOLA R
MEAN	4,00	4,35	4,27	4,09	4,29
STANDARD ERROR	0,02	0,02	0,02	0,02	0,02
MEDIAN	4,49	4,83	4,73	4,53	4,76
STANDARD DEVIATION	1,80	1,76	1,68	1,76	1,65
SAMPLE VARIANCE	3,25	3,10	2,82	3,10	2,72
KURTOSIS	-0,97	-0,84	-0,66	-0,99	-0,70
SKEWNESS	-0,58	-0,65	-0,73	-0,55	-0,69
RANGE	6,68	6,77	6,72	6,78	6,76
MINIMUM	0,00	0,00	0,00	0,00	0,00
MAXIMUM	6,68	6,77	6,72	6,78	6,76
SUM	43869,92	47686,28	46747,93	44837,15	47054,88
COUNT	10957	10957	10957	10957	10957

Appendix F: Wind & Solar statistics

Appendix G

	<i>EL30</i>	<i>EL41</i>	<i>EL42</i>	<i>EL43</i>	<i>EL51</i>	<i>EL52</i>	<i>EL53</i>	<i>EL54</i>	<i>EL61</i>	<i>EL62</i>	<i>EL63</i>	<i>EL64</i>	<i>EL65</i>
EL30	1,00	0,84	0,68	0,65	0,76	0,66	0,22	0,69	0,40	0,99	0,62	0,99	0,62
EL41	0,84	1,00	0,84	0,71	0,76	0,65	0,19	0,56	0,27	0,87	0,43	0,87	0,43
EL42	0,68	0,84	1,00	0,89	0,48	0,43	0,16	0,38	0,19	0,68	0,31	0,68	0,31
EL43	0,65	0,71	0,89	1,00	0,42	0,41	0,22	0,41	0,24	0,63	0,38	0,63	0,38
EL51	0,76	0,76	0,48	0,42	1,00	0,90	0,36	0,75	0,42	0,81	0,53	0,81	0,53
EL52	0,66	0,65	0,43	0,41	0,90	1,00	0,73	0,88	0,58	0,73	0,66	0,73	0,66
EL53	0,22	0,19	0,16	0,22	0,36	0,73	1,00	0,71	0,59	0,29	0,60	0,29	0,60
EL54	0,69	0,56	0,38	0,41	0,75	0,88	0,71	1,00	0,72	0,75	0,82	0,75	0,82
EL61	0,40	0,27	0,19	0,24	0,42	0,58	0,59	0,72	1,00	0,42	0,79	0,42	0,79
EL62	0,99	0,87	0,68	0,63	0,81	0,73	0,29	0,75	0,42	1,00	0,65	1,00	0,65
EL63	0,62	0,43	0,31	0,38	0,53	0,66	0,60	0,82	0,79	0,65	1,00	0,65	1,00
EL64	0,99	0,87	0,68	0,63	0,81	0,73	0,29	0,75	0,42	1,00	0,65	1,00	0,65
EL65	0,62	0,43	0,31	0,38	0,53	0,66	0,60	0,82	0,79	0,65	1,00	0,65	1,00

Appendix G: Wind correlation

Appendix H

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54	EL61	EL62	EL63	EL64	EL65
EL30	1,00	0,83	0,86	0,83	0,74	0,76	0,75	0,66	0,84	0,73	0,78	0,94	0,92
EL41	0,83	1,00	0,92	0,81	0,82	0,73	0,71	0,68	0,75	0,71	0,75	0,82	0,78
EL42	0,86	0,92	1,00	0,90	0,73	0,68	0,68	0,63	0,74	0,69	0,72	0,82	0,80
EL43	0,83	0,81	0,90	1,00	0,65	0,62	0,63	0,56	0,70	0,63	0,67	0,80	0,79
EL51	0,74	0,82	0,73	0,65	1,00	0,87	0,77	0,72	0,78	0,70	0,74	0,78	0,73
EL52	0,76	0,73	0,68	0,62	0,87	1,00	0,92	0,81	0,91	0,78	0,80	0,84	0,78
EL53	0,75	0,71	0,68	0,63	0,77	0,92	1,00	0,87	0,94	0,81	0,84	0,86	0,80
EL54	0,66	0,68	0,63	0,56	0,72	0,81	0,87	1,00	0,81	0,91	0,92	0,75	0,75
EL61	0,84	0,75	0,74	0,70	0,78	0,91	0,94	0,81	1,00	0,80	0,85	0,95	0,86
EL62	0,73	0,71	0,69	0,63	0,70	0,78	0,81	0,91	0,80	1,00	0,93	0,78	0,81
EL63	0,78	0,75	0,72	0,67	0,74	0,80	0,84	0,92	0,85	0,93	1,00	0,86	0,90
EL64	0,94	0,82	0,82	0,80	0,78	0,84	0,86	0,75	0,95	0,78	0,86	1,00	0,93
EL65	0,92	0,78	0,80	0,79	0,73	0,78	0,80	0,75	0,86	0,81	0,90	0,93	1,00

Appendix H: Solar correlation

Appendix I

	EL30_wind	EL41_wind	EL42_wind	EL43_wind	EL51_wind	EL52_wind	EL53_wind	EL54_wind	EL61_wind	EL62_wind	EL63_wind	EL64_wind	EL65_wind
EL30_wind	1,00	0,84	0,68	0,65	0,76	0,66	0,22	0,69	0,40	0,99	0,62	0,99	0,62
EL41_wind	0,84	1,00	0,84	0,71	0,76	0,65	0,19	0,56	0,27	0,87	0,43	0,87	0,43
EL42_wind	0,68	0,84	1,00	0,89	0,48	0,43	0,16	0,38	0,19	0,68	0,31	0,68	0,31
EL43_wind	0,65	0,71	0,89	1,00	0,42	0,41	0,22	0,41	0,24	0,63	0,38	0,63	0,38
EL51_wind	0,76	0,76	0,48	0,42	1,00	0,90	0,36	0,75	0,42	0,81	0,53	0,81	0,53
EL52_wind	0,66	0,65	0,43	0,41	0,90	1,00	0,73	0,88	0,58	0,73	0,66	0,73	0,66
EL53_wind	0,22	0,19	0,16	0,22	0,36	0,73	1,00	0,71	0,59	0,29	0,60	0,29	0,60
EL54_wind	0,69	0,56	0,38	0,41	0,75	0,88	0,71	1,00	0,72	0,75	0,82	0,75	0,82
EL61_wind	0,40	0,27	0,19	0,24	0,42	0,58	0,59	0,72	1,00	0,42	0,79	0,42	0,79
EL62_wind	0,99	0,87	0,68	0,63	0,81	0,73	0,29	0,75	0,42	1,00	0,65	1,00	0,65
EL63_wind	0,62	0,43	0,31	0,38	0,53	0,66	0,60	0,82	0,79	0,65	1,00	0,65	1,00
EL64_wind	0,99	0,87	0,68	0,63	0,81	0,73	0,29	0,75	0,42	1,00	0,65	1,00	0,65
EL65_wind	0,62	0,43	0,31	0,38	0,53	0,66	0,60	0,82	0,79	0,65	1,00	0,65	1,00
EL30_solar	-0,29	-0,18	-0,12	-0,21	-0,33	-0,34	-0,22	-0,41	-0,41	-0,28	-0,35	-0,28	-0,35
EL41_solar	-0,23	-0,18	-0,12	-0,20	-0,34	-0,40	-0,32	-0,42	-0,34	-0,25	-0,33	-0,25	-0,33
EL42_solar	-0,29	-0,21	-0,15	-0,25	-0,35	-0,38	-0,27	-0,43	-0,35	-0,30	-0,34	-0,30	-0,34
EL43_solar	-0,33	-0,23	-0,19	-0,29	-0,34	-0,35	-0,21	-0,39	-0,32	-0,32	-0,31	-0,32	-0,31
EL51_solar	-0,12	-0,09	-0,04	-0,10	-0,28	-0,34	-0,29	-0,36	-0,33	-0,15	-0,30	-0,15	-0,30
EL52_solar	-0,16	-0,10	-0,01	-0,07	-0,28	-0,31	-0,22	-0,34	-0,39	-0,18	-0,32	-0,18	-0,32
EL53_solar	-0,20	-0,14	-0,03	-0,08	-0,32	-0,34	-0,22	-0,38	-0,43	-0,22	-0,35	-0,22	-0,35
EL54_solar	-0,09	-0,08	0,03	-0,02	-0,24	-0,30	-0,28	-0,32	-0,37	-0,13	-0,32	-0,13	-0,32
EL61_solar	-0,27	-0,18	-0,07	-0,13	-0,37	-0,36	-0,20	-0,41	-0,44	-0,28	-0,37	-0,28	-0,37
EL62_solar	-0,09	-0,05	0,04	-0,02	-0,21	-0,27	-0,25	-0,31	-0,38	-0,11	-0,30	-0,11	-0,30
EL63_solar	-0,15	-0,12	-0,03	-0,08	-0,27	-0,33	-0,28	-0,36	-0,40	-0,18	-0,34	-0,18	-0,34
EL64_solar	-0,32	-0,22	-0,13	-0,21	-0,39	-0,39	-0,22	-0,44	-0,43	-0,32	-0,38	-0,32	-0,38
EL65_solar	-0,26	-0,20	-0,12	-0,17	-0,33	-0,34	-0,21	-0,39	-0,42	-0,27	-0,34	-0,27	-0,34

	EL30_solar	EL41_solar	EL42_solar	EL43_solar	EL51_solar	EL52_solar	EL53_solar	EL54_solar	EL61_solar	EL62_solar	EL63_solar	EL64_solar	EL65_solar
EL30_solar	-0,29	-0,23	-0,29	-0,33	-0,12	-0,16	-0,20	-0,09	-0,27	-0,09	-0,15	-0,32	-0,26
EL41_solar	-0,18	-0,18	-0,21	-0,23	-0,09	-0,10	-0,14	-0,08	-0,18	-0,05	-0,12	-0,22	-0,20
EL42_solar	-0,12	-0,12	-0,15	-0,19	-0,04	-0,01	-0,03	0,03	-0,07	0,04	-0,03	-0,13	-0,12
EL43_solar	-0,21	-0,20	-0,25	-0,29	-0,10	-0,07	-0,08	-0,02	-0,13	-0,02	-0,08	-0,21	-0,17
EL51_solar	-0,33	-0,34	-0,35	-0,34	-0,28	-0,28	-0,32	-0,24	-0,37	-0,21	-0,27	-0,39	-0,33
EL52_solar	-0,34	-0,40	-0,38	-0,35	-0,34	-0,31	-0,34	-0,30	-0,36	-0,27	-0,33	-0,39	-0,34
EL53_solar	-0,22	-0,32	-0,27	-0,21	-0,29	-0,22	-0,22	-0,28	-0,20	-0,25	-0,28	-0,22	-0,21
EL54_solar	-0,41	-0,42	-0,43	-0,39	-0,36	-0,34	-0,38	-0,32	-0,41	-0,31	-0,36	-0,44	-0,39
EL61_solar	-0,41	-0,34	-0,35	-0,32	-0,33	-0,39	-0,43	-0,37	-0,44	-0,38	-0,40	-0,43	-0,42
EL62_solar	-0,28	-0,25	-0,30	-0,32	-0,15	-0,18	-0,22	-0,13	-0,28	-0,11	-0,18	-0,32	-0,27
EL63_solar	-0,35	-0,33	-0,34	-0,31	-0,30	-0,32	-0,35	-0,32	-0,37	-0,30	-0,34	-0,38	-0,34
EL64_solar	-0,28	-0,25	-0,30	-0,32	-0,15	-0,18	-0,22	-0,13	-0,28	-0,11	-0,18	-0,32	-0,27
EL65_solar	-0,35	-0,33	-0,34	-0,31	-0,30	-0,32	-0,35	-0,32	-0,37	-0,30	-0,34	-0,38	-0,34
EL30_solar	1,00	0,83	0,86	0,83	0,74	0,76	0,75	0,66	0,84	0,73	0,78	0,94	0,92
EL41_solar	0,83	1,00	0,92	0,81	0,82	0,73	0,71	0,68	0,75	0,71	0,75	0,82	0,78
EL42_solar	0,86	0,92	1,00	0,90	0,73	0,68	0,68	0,63	0,74	0,69	0,72	0,82	0,80
EL43_solar	0,83	0,81	0,90	1,00	0,65	0,62	0,63	0,56	0,70	0,63	0,67	0,80	0,79
EL51_solar	0,74	0,82	0,73	0,65	1,00	0,87	0,77	0,72	0,78	0,70	0,74	0,78	0,73
EL52_solar	0,76	0,73	0,68	0,62	0,87	1,00	0,92	0,81	0,91	0,78	0,80	0,84	0,78
EL53_solar	0,75	0,71	0,68	0,63	0,77	0,92	1,00	0,87	0,94	0,81	0,84	0,86	0,80
EL54_solar	0,66	0,68	0,63	0,56	0,72	0,81	0,87	1,00	0,81	0,91	0,92	0,75	0,75
EL61_solar	0,84	0,75	0,74	0,70	0,78	0,91	0,94	0,81	1,00	0,80	0,85	0,95	0,86
EL62_solar	0,73	0,71	0,69	0,63	0,70	0,78	0,81	0,91	0,80	1,00	0,93	0,78	0,81
EL63_solar	0,78	0,75	0,72	0,67	0,74	0,80	0,84	0,92	0,85	0,93	1,00	0,86	0,90
EL64_solar	0,94	0,82	0,82	0,80	0,78	0,84	0,86	0,75	0,95	0,78	0,86	1,00	0,93
EL65_solar	0,92	0,78	0,80	0,79	0,73	0,78	0,80	0,75	0,86	0,81	0,90	0,93	1,00

Appendix I: Wind & Solar correlation

Appendix J

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54	EL61	EL62	EL63	EL64	EL65
EL30	40,68	28,35	23,15	22,04	28,15	16,61	5,06	20,13	9,42	34,83	18,08	34,83	18,08
EL41	28,35	27,85	23,71	19,81	23,38	13,49	3,60	13,45	5,35	25,43	10,49	25,43	10,49
EL42	23,15	23,71	28,71	25,27	14,95	9,07	3,19	9,34	3,80	20,07	7,72	20,07	7,72
EL43	22,04	19,81	25,27	28,19	12,91	8,57	4,23	9,84	4,77	18,57	9,30	18,57	9,30
EL51	28,15	23,38	14,95	12,91	33,86	20,75	7,64	20,01	9,05	26,27	14,04	26,27	14,04
EL52	16,61	13,49	9,07	8,57	20,75	15,61	10,47	15,88	8,53	16,07	12,01	16,07	12,01
EL53	5,06	3,60	3,19	4,23	7,64	10,47	13,30	11,75	8,00	5,87	9,97	5,87	9,97
EL54	20,13	13,45	9,34	9,84	20,01	15,88	11,75	20,89	12,28	19,02	17,19	19,02	17,19
EL61	9,42	5,35	3,80	4,77	9,05	8,53	8,00	12,28	13,82	8,69	13,52	8,69	13,52
EL62	34,83	25,43	20,07	18,57	26,27	16,07	5,87	19,02	8,69	30,72	16,42	30,72	16,42
EL63	18,08	10,49	7,72	9,30	14,04	12,01	9,97	17,19	13,52	16,42	21,06	16,42	21,06
EL64	34,83	25,43	20,07	18,57	26,27	16,07	5,87	19,02	8,69	30,72	16,42	30,72	16,42
EL65	18,08	10,49	7,72	9,30	14,04	12,01	9,97	17,19	13,52	16,42	21,06	16,42	21,06

Appendix J: Wind covariance

Appendix K

	EL30	EL41	EL42	EL43	EL51	EL52	EL53	EL54	EL61	EL62	EL63	EL64	EL65
EL30	3,01	2,59	2,42	2,41	2,23	2,32	2,35	2,02	2,62	2,21	2,28	2,87	2,62
EL41	2,59	3,23	2,67	2,42	2,56	2,32	2,29	2,17	2,42	2,26	2,27	2,58	2,31
EL42	2,42	2,67	2,63	2,45	2,05	1,95	1,99	1,80	2,15	1,97	1,96	2,35	2,14
EL43	2,41	2,42	2,45	2,81	1,89	1,84	1,92	1,66	2,12	1,87	1,87	2,35	2,17
EL51	2,23	2,56	2,05	1,89	3,00	2,64	2,42	2,22	2,44	2,14	2,17	2,39	2,07
EL52	2,32	2,32	1,95	1,84	2,64	3,11	2,92	2,53	2,90	2,43	2,38	2,62	2,26
EL53	2,35	2,29	1,99	1,92	2,42	2,92	3,27	2,79	3,06	2,58	2,55	2,73	2,38
EL54	2,02	2,17	1,80	1,66	2,22	2,53	2,79	3,15	2,59	2,84	2,73	2,36	2,21
EL61	2,62	2,42	2,15	2,12	2,44	2,90	3,06	2,59	3,25	2,53	2,57	3,00	2,57
EL62	2,21	2,26	1,97	1,87	2,14	2,43	2,58	2,84	2,53	3,09	2,73	2,41	2,34
EL63	2,28	2,27	1,96	1,87	2,17	2,38	2,55	2,73	2,57	2,73	2,82	2,53	2,49
EL64	2,87	2,58	2,35	2,35	2,39	2,62	2,73	2,36	3,00	2,41	2,53	3,10	2,69
EL65	2,62	2,31	2,14	2,17	2,07	2,26	2,38	2,21	2,57	2,34	2,49	2,69	2,72

Appendix K: Solar covariance

Appendix L

	EL30_wind	EL41_wind	EL42_wind	EL43_wind	EL51_wind	EL52_wind	EL53_wind	EL54_wind	EL61_wind	EL62_wind	EL63_wind	EL64_wind	EL65_wind
EL30_wind	40,68	28,35	23,15	22,04	28,15	16,61	5,06	20,13	9,42	34,83	18,08	34,83	18,08
EL41_wind	28,35	27,85	23,71	19,81	23,38	13,49	3,60	13,45	5,35	25,43	10,49	25,43	10,49
EL42_wind	23,15	23,71	28,71	25,27	14,95	9,07	3,19	9,34	3,80	20,07	7,72	20,07	7,72
EL43_wind	22,04	19,81	25,27	28,19	12,91	8,57	4,23	9,84	4,77	18,57	9,30	18,57	9,30
EL51_wind	28,15	23,38	14,95	12,91	33,86	20,75	7,64	20,01	9,05	26,27	14,04	26,27	14,04
EL52_wind	16,61	13,49	9,07	8,57	20,75	15,61	10,47	15,88	8,53	16,07	12,01	16,07	12,01
EL53_wind	5,06	3,60	3,19	4,23	7,64	10,47	13,30	11,75	8,00	5,87	9,97	5,87	9,97
EL54_wind	20,13	13,45	9,34	9,84	20,01	15,88	11,75	20,89	12,28	19,02	17,19	19,02	17,19
EL61_wind	9,42	5,35	3,80	4,77	9,05	8,53	8,00	12,28	13,82	8,69	13,52	8,69	13,52
EL62_wind	34,83	25,43	20,07	18,57	26,27	16,07	5,87	19,02	8,69	30,72	16,42	30,72	16,42
EL63_wind	18,08	10,49	7,72	9,30	14,04	12,01	9,97	17,19	13,52	16,42	21,06	16,42	21,06
EL64_wind	34,83	25,43	20,07	18,57	26,27	16,07	5,87	19,02	8,69	30,72	16,42	30,72	16,42
EL65_wind	18,08	10,49	7,72	9,30	14,04	12,01	9,97	17,19	13,52	16,42	21,06	16,42	21,06
EL30_solar	-3,18	-1,66	-1,13	-1,96	-3,34	-2,36	-1,37	-3,27	-2,64	-2,71	-2,79	-2,71	-2,79
EL41_solar	-2,62	-1,66	-1,13	-1,95	-3,57	-2,82	-2,07	-3,48	-2,24	-2,48	-2,74	-2,48	-2,74
EL42_solar	-3,03	-1,80	-1,31	-2,13	-3,32	-2,46	-1,59	-3,16	-2,10	-2,68	-2,52	-2,68	-2,52
EL43_solar	-3,55	-2,05	-1,74	-2,60	-3,32	-2,29	-1,27	-3,01	-2,01	-3,00	-2,35	-3,00	-2,35
EL51_solar	-1,37	-0,86	-0,34	-0,93	-2,79	-2,32	-1,86	-2,82	-2,11	-1,45	-2,35	-1,45	-2,35
EL52_solar	-1,82	-0,96	-0,08	-0,63	-2,88	-2,13	-1,39	-2,73	-2,54	-1,74	-2,55	-1,74	-2,55
EL53_solar	-2,36	-1,30	-0,26	-0,77	-3,40	-2,42	-1,44	-3,11	-2,89	-2,23	-2,95	-2,23	-2,95
EL54_solar	-0,97	-0,72	0,29	-0,14	-2,45	-2,14	-1,82	-2,62	-2,43	-1,25	-2,58	-1,25	-2,58
EL61_solar	-3,13	-1,73	-0,68	-1,25	-3,85	-2,58	-1,32	-3,37	-2,97	-2,79	-3,03	-2,79	-3,03
EL62_solar	-1,02	-0,44	0,40	-0,16	-2,12	-1,87	-1,62	-2,46	-2,49	-1,10	-2,41	-1,10	-2,41
EL63_solar	-1,59	-1,08	-0,28	-0,70	-2,68	-2,18	-1,68	-2,79	-2,52	-1,66	-2,62	-1,66	-2,62
EL64_solar	-3,60	-2,07	-1,25	-1,93	-4,03	-2,72	-1,41	-3,58	-2,84	-3,16	-3,04	-3,16	-3,04
EL65_solar	-2,73	-1,70	-1,07	-1,50	-3,19	-2,24	-1,28	-2,97	-2,60	-2,43	-2,60	-2,43	-2,60

	EL30_solar	EL41_solar	EL42_solar	EL43_solar	EL51_solar	EL52_solar	EL53_solar	EL54_solar	EL61_solar	EL62_solar	EL63_solar	EL64_solar	EL65_solar
EL30_wind	-3.18	-2.62	-3.03	-3.55	-1.37	-1.82	-2.36	-0.97	-3.13	-1.02	-1.59	-3.60	-2.73
EL41_wind	-1.66	-1.66	-1.80	-2.05	-0.86	-0.96	-1.30	-0.72	-1.73	-0.44	-1.08	-2.07	-1.70
EL42_wind	-1.13	-1.13	-1.31	-1.74	-0.34	-0.08	-0.26	0.29	-0.68	0.40	-0.28	-1.25	-1.07
EL43_wind	-1.96	-1.95	-2.13	-2.60	-0.93	-0.63	-0.77	-0.14	-1.25	-0.16	-0.70	-1.93	-1.50
EL51_wind	-3.34	-3.57	-3.32	-3.32	-2.79	-2.88	-3.40	-2.45	-3.85	-2.12	-2.68	-4.03	-3.19
EL52_wind	-2.36	-2.82	-2.46	-2.29	-2.32	-2.13	-2.42	-2.14	-2.58	-1.87	-2.18	-2.72	-2.24
EL53_wind	-1.37	-2.07	-1.59	-1.27	-1.86	-1.39	-1.44	-1.82	-1.32	-1.62	-1.68	-1.41	-1.28
EL54_wind	-3.27	-3.48	-3.16	-3.01	-2.82	-2.73	-3.11	-2.62	-3.37	-2.46	-2.79	-3.58	-2.97
EL61_wind	-2.64	-2.24	-2.10	-2.01	-2.11	-2.54	-2.89	-2.43	-2.97	-2.49	-2.52	-2.84	-2.60
EL62_wind	-2.71	-2.48	-2.68	-3.00	-1.45	-1.74	-2.23	-1.25	-2.79	-1.10	-1.66	-3.16	-2.43
EL63_wind	-2.79	-2.74	-2.52	-2.35	-2.35	-2.55	-2.95	-2.58	-3.03	-2.41	-2.62	-3.04	-2.60
EL64_wind	-2.71	-2.48	-2.68	-3.00	-1.45	-1.74	-2.23	-1.25	-2.79	-1.10	-1.66	-3.16	-2.43
EL65_wind	-2.79	-2.74	-2.52	-2.35	-2.35	-2.55	-2.95	-2.58	-3.03	-2.41	-2.62	-3.04	-2.60
EL30_solar	3.01	2.59	2.42	2.41	2.23	2.32	2.35	2.02	2.62	2.21	2.28	2.87	2.62
EL41_solar	2.59	3.23	2.67	2.42	2.56	2.32	2.29	2.17	2.42	2.26	2.27	2.58	2.31
EL42_solar	2.42	2.67	2.63	2.45	2.05	1.95	1.99	1.80	2.15	1.97	1.96	2.35	2.14
EL43_solar	2.41	2.42	2.45	2.81	1.89	1.84	1.92	1.66	2.12	1.87	1.87	2.35	2.17
EL51_solar	2.23	2.56	2.05	1.89	3.00	2.64	2.42	2.22	2.44	2.14	2.17	2.39	2.07
EL52_solar	2.32	2.32	1.95	1.84	2.64	3.11	2.92	2.53	2.90	2.43	2.38	2.62	2.26
EL53_solar	2.35	2.29	1.99	1.92	2.42	2.92	3.27	2.79	3.06	2.58	2.55	2.73	2.38
EL54_solar	2.02	2.17	1.80	1.66	2.22	2.53	2.79	3.15	2.59	2.84	2.73	2.36	2.21
EL61_solar	2.62	2.42	2.15	2.12	2.44	2.90	3.06	2.59	3.25	2.53	2.57	3.00	2.57
EL62_solar	2.21	2.26	1.97	1.87	2.14	2.43	2.58	2.84	2.53	3.09	2.73	2.41	2.34
EL63_solar	2.28	2.27	1.96	1.87	2.17	2.38	2.55	2.73	2.57	2.73	2.82	2.53	2.49
EL64_solar	2.87	2.58	2.35	2.35	2.39	2.62	2.73	2.36	3.00	2.41	2.53	3.10	2.69
EL65_solar	2.62	2.31	2.14	2.17	2.07	2.26	2.38	2.21	2.57	2.34	2.49	2.69	2.72

Appendix L: Wind & Solar covariance

References

- Calvo, A., Cerdá, E., & Martín, B. (2017). Energy planning and modern portfolio theory: A review. Renewable and Sustainable Energy Reviews, 77, 636-651 from <https://ideas.repec.org/a/eee/rensus/v77y2017icp636-651.html>
- Caralis, G., Perivolaris, Y., Rados, K., & Zervos, A. (2008). On the effect of spatial dispersion of wind power plants on the wind energy capacity credit in Greece. Environmental Research Letters, 3(015003)
- Cunha, J., & Ferreira, P. (2014). Designing electricity generation portfolios using the mean-variance approach. International Journal of Sustainable Energy Planning and Management
- Ember. (2024). EU wind and solar overtake fossil fuels. Retrieved from <https://ember-energy.org/latest-insights/eu-wind-and-solar-overtake-fossil-fuels>
- Eurostat. (2020). Greece—NUTS level 2. From <https://ec.europa.eu/eurostat/web/nuts/nuts-maps>
- Hellenic Wind Energy Association. (2022). Spatial distribution of wind capacity. <https://eletaen.gr/d-t-statistiki-eletaen-first-semester-2022/>
- Hu, J., Harmsen, R., Crijns-Graus, W., & Worrell, E. (2019). Geographical optimization of variable renewable energy capacity in China using modern portfolio theory.

- IEA (2020). The Cost of Capital in Clean Energy Transitions. International Energy Agency. Retrieved from <https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions>
- Liu, S., Jian, J., Wang, Y., & Liang, J. (2013). A robust optimization approach to wind farm diversification. *Electrical Power and Energy Systems*
- Louraoui, Y. (2021, September 20). Markowitz Modern Portfolio Theory. https://www.simtrade.fr/blog_simtrade/markowitz-modern-portfolio-theory/
- Perez Odeh, R., & Watts, D. (2019). Impacts of wind and solar spatial diversification on its market value: A case study of the Chilean electricity market. *Renewable and Sustainable Energy Reviews*
- Rajput, H., Gupta, A., Sah, H., Gattani, Dr. M., & Satankar, R. (2022). Design and development of the divergent wind turbine
- Santos-Alamillos, F. J., Thomaidis, N. S., Quesada-Ruiz, S., Ruiz-Arias, J. A., & Pozo-Vazquez, D. (2016). Do current wind farms in Spain take maximum advantage of spatiotemporal balancing of the wind resource?
- Statista. (2024). Renewable energy in Greece. Retrieved from <https://www.statista.com/topics/12083/renewable-energy-in-greece/>
- Trade.gov. (2024). Greece renewable energy projects. Retrieved from <https://www.trade.gov/market-intelligence/greece-renewable-energy-projects-2024>
- Thomaidis, N. S. (2012). Designing strategies for optimal spatial distribution of wind power
- Thomaidis, N. S., Christodoulou, T., & Santos-Alamillos, F. J. (2022, February 18). Handling the risk dimensions of wind energy generation
- Thomaidis, N. S., Santos-Alamillos, F. J., Pozo-Vazquez, D., & Usaola-Garcia, J. (2016). Optimal management of wind and solar energy resources. *Computers & Operations Research*
- Thomaidis, Nikolaos S., & Moukas, A.-I. (2022). Designing Efficient Renewable Energy Portfolios for Optimal Coverage of European Power Demand Under Transmission Constraints. *Energies*
- Tsiouma Maria (2023). Can spatial diversification improve the reliability of the aggregate wind energy supply?
- Vorgia Natalia (2023). The effectiveness of spatial and technological aggregation in managing the volumetric risk of renewable energy resources in Greece
- WindEurope. (2024). Wind energy in Europe: 2023 statistics and 2024 outlook. Retrieved from <https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2023-statistics-and-the-outlook-for-2024-2030>