DOCTORAL (PHD) DISSERTATION

MOHAMMAD FAZLE RABBI

Debrecen
2024

UNIVERSITY OF DEBRECEN

FACULTY OF ECONOMICS AND BUSINESS

KÁROLY IHRIG DOCTORAL SCHOOOL OF MANAGAEMENT AND BUSINESS

Head of the Doctoral School: **Prof. Dr. Balogh Péter university professor, DSc**

FOOD, ENERGY, AND ENVIRONMENTAL SECURITY FROM SUSTAINABLE DEVELOPMENT PERSPECTIVES IN SELECTED EU COUNTRIES

Prepared by:

MOHAMMAD FAZLE RABBI

Supervisor:

DR. KOVÁCS SÁNDOR

Associate Professor

DEBRECEN

2024

FOOD, ENERGY, AND ENVIRONMENTAL SECURITY FROM SUSTAINABLE DEVELOPMENT PERSPECTIVES IN SELECTED EU COUNTRIES

The aim of this dissertation is to obtain a doctoral (PhD) degree

PhD in Business and Management

Written by: Mohammad Fazle Rabbi certified MBA (*Human Resource Management*)

Supervisor: Dr. Kovács Sándor

Doctoral final exam committee:

	name	academic degree
Chair:	....	....
Members:	....	....
	....	....
	....	....

Date of the doctoral final exam: 20…. ....

Reviewers of the Dissertation:

name, academic degree	signature
....	....
....	....

Review committee:

	name, academic degree	signature
Chair:	....	....
Secretary:	....	....
Members:	....	....
	....	....
	....	....
	....	....
	....	....

Date of doctoral theses defence: 2024.

DECLARATION

I undersigned (name: **Mohammad Fazle Rabbi**, date of birth: 03/01/1985) declare under penalty of perjury and certify with my signature that the dissertation I submitted in order to obtain doctoral (PhD) degree is entirely my own work.

Furthermore, I declare the following:

- I examined the Code of the Károly Ihrig Doctoral School of Management and Business Administration and I acknowledge the points laid down in the code as mandatory;
- I handled the technical literature sources used in my dissertation fairly and I conformed to the provisions and stipulations related to the dissertation;
- I indicated the original source of other authors' unpublished thoughts and data in the references section in a complete and correct way in consideration of the prevailing copyright protection rules;
- No dissertation which is fully or partly identical to the present dissertation was submitted to any other university or doctoral school for the purpose of obtaining a PhD degree.

Debrecen, 21/02/2024

....

Mohammad Fazle Rabbi

signature

Table of Content

1. INTRODUCTION

The delicate balance for our planet's sustainability is under increasing strain. We face the dual challenge of ensuring everyone has access to food and energy, while simultaneously safeguarding the environment for future generations. This challenge intensifies as the world's population surges. By 2050, an estimated 9.7 billion people will significantly amplify the pressure on vital resources like water and land (Guan et al., 2024). Climate change adds another layer of complexity, potentially disrupting agricultural production and resource availability (Riseh et al., 2024).

Our world is facing the complex challenge of ensuring food security for a growing population while protecting the environment and managing our energy resources responsibly. This challenge, known as the Food, Energy, and Environment (FEE) nexus, requires us to understand the intricate connections between these three seemingly separate aspects.

The current food system, often focused on maximizing production, has come at a significant cost. Practices like intensive agriculture have taken a toll on the environment, leading to issues like pollution and resource depletion. This, in turn, affects public health and creates a precarious balance for the future.

Developing nations face especially acute challenges within the FEE nexus. Limited access to clean water and energy, coupled with dwindling natural resources, threatens their food security (Popp et al., 2014). Striking a balance between economic growth and environmental protection is essential for these countries. A study by Ozturk (2015) suggest that with careful management, economic growth can eventually lead to lower environmental impact, creating a sustainable future.

Developed regions also grapple with FEE security concerns. Solutions like promoting renewable energy, diversifying trade partnerships, and adopting sustainable agricultural practices are crucial. Collaboration between governments, scientists, and the public is vital in building a more resilient future for all.

Our journey towards a sustainable future has only just begun. Each step in the food chain, from production to consumption, impacts the others. This interconnectedness highlights the urgency for action, particularly in developing countries. Embracing eco-friendly agricultural practices and promoting responsible resource use are crucial steps in this journey (Wagh et al., 2024). However, the path is not without obstacles. Climate change throws another layer of complexity into the equation, impacting agricultural yields and requiring some countries to explore options like renewable energy or improved trade policies. Additionally, regional disparities in food security exist, with some countries more vulnerable to food price shocks. Addressing these inequalities requires targeted policies that support rural areas and help generate income.

Researchers have delved into potential solutions within the FEE nexus. The study by Popp et al. (2014a) and Geissler et al. (2024) suggest that biofuels, if sourced sustainably and with lower greenhouse gas emissions than traditional fuels, could play a role. Additionally, minimizing food loss and waste (FLW) is crucial. Shockingly, about one-third of all food produced globally is lost or wasted throughout the supply chain, highlighting the need for improved resource management, and reduced environmental impact (Shen et al., 2024).

Recent events like the COVID-19 pandemic and the ongoing conflict in Ukraine have significantly impacted global food consumption patterns. The pandemic led to disruptions in food shopping, income instability, and rising food prices, while the war disrupted global food and energy supply chains, further threatening food security in many regions. Extreme weather events like heatwaves and droughts add another layer of complexity to this already intricate challenge (Rabbi et al., 2021b).

As a result, food security remains a top global concern, especially considering the diverse landscape within the European Union (EU). It encompasses four key dimensions: availability, accessibility, utilization, and stability. Each dimension is influenced by multiple factors, including agricultural productivity, economic development, policy implementation, and environmental conditions. Geographical differences, such as the contrasting climates across Europe, contribute to variations in food availability, impacting both production and distribution. Furthermore, economic disparities exacerbate inequalities in food accessibility and utilization, affecting people's ability to afford and consume nutritious food. The urban-rural divide adds another layer of complexity, highlighting the need for tailored interventions that address the specific challenges faced by each region within the EU (Rabbi et al., 2023).

The study of FEE security is not just a local or regional challenge; it is intricately linked to global goals. The United Nations' Sustainable Development Goals (SDGs) specifically address the interconnectedness of food, energy, and environment. SDG 2 aims to achieve food security through sustainable practices and efficient energy use, while SDG 13 focuses on climate action (United Nations, 2015). Achieving these specific SDGs, along with others, is crucial for building a sustainable future. This requires global efforts from governments, corporations, and individuals alike, all working together to overcome the challenges within the FEE nexus.

By recognizing the interconnectedness of these challenges and fostering collaboration, we can build a more resilient and sustainable future for all. This is the story of our interconnected world, and it is a story that we can write together.

1.1. Problem statement and research gap

Earlier research collectively suggests that European countries face challenges in FEE security. Mostova & Hutorov (2023) emphasize the challenge of ensuring affordable and accessible food for all in Central and Eastern Europe. They point out that low-income individuals and families are facing a growing challenge as the cost of food continues to rise, jeopardising their access to essential needs. Meanwhile, research by Wahbeh et al. (2022) shed light on a broader picture, identifying 34 key factors impacting food security and suggesting 17 policy solutions to tackle these issues. Boutin et al. (2006) investigated drivers and barriers to an increased use of bioenergy in Ukraine, given the large potential for bio-energy development in the country. A study by Borowski & Patuk (2021) investigated the relationship between various factors and sustainable development in African and European countries. Their findings revealed a strong positive correlation between a country's age share, Carbon dioxide (CO_2) emissions, and natural resource depletion. Additionally, they observed a positive correlation between age share and renewable energy consumption. All the prior research reveals a complex landscape of challenges within the European Union (EU) regarding FEE security. Addressing these challenges requires a multifaceted approach, encompassing both technical interventions and policy solutions. Effective resolution is critical for ensuring sustainable development and safeguarding the well-being of future generations. Collaborative efforts focused on developing innovative and impactful solutions are essential to overcome these hurdles.

Several scholars have explored the Water-Energy-Food-Environment (WEFE) nexus on a global scale. For instance, Yue & Guo (2021) investigated its effectiveness in China. Fetanat et al. (2021) applied the Water-Energy-Food (WEF) nexus concept to assess energy recovery from wastewater treatment, emphasizing sustainability criteria. Additionally, Franz et al. (2018) employed a global production network approach to analyze the complex relationships within the WEF nexus.

However, this research focuses on the European Union (EU) context, specifically addressing the challenges to achieving FEE security in EU countries. Prior research hasn't collectively examined this issue within the selected EU region. Furthermore, this research will identify potential "hotspots" where each sector's activities significantly impact FEE security. Additionally, it will analyze how these impacts contribute to achieving SDG targets, contributing new knowledge to the understanding of FEE security in the EU.

Table 1: Analyzing the complex factors shaping FEE security in the EU

	Dimensions	Food	Energy	Environment
Present Status	**Availability**	Doesn't have adequate supply of staple foods like grains, fruits, and vegetables.	Doesn't have adequate supply of clean, affordable, and secure energy sources.	Doesn't have adequate forest, green and pollution-free environment.
	Access	The increase in food prices results in a decrease in individuals' purchasing power.	The lack of accessibility to clean and renewable energy sources.	Resources in EU are less accessible due to the overexploitation of natural resources.
	Utilization	Insufficient nutritional intake and limited dietary diversification	Insufficient measures taken to facilitate the transition towards secure and sustainable energy sources.	The ecology and its biodiversity are in danger due to a lack of adequate protection and restoration efforts.
Resilience	**Vulnerability**	The increasing prevalence of both malnutrition and obesity.	The reduced proportion of renewable energy in the energy mix has resulted in a higher level of dependence on energy imports.	Climate change leads to an increase in temperature, the occurrence of heat waves, floods, droughts, and a decline in food production.
	Sustainability	The EU's plan for food sustainability is designed to protect the environment while ensuring all people have access to nutritious foods.	The low-carbon transition aims for a clean energy future that boosts the economy, sparks innovation, creates jobs, and improves lives.	The European Green Deal aims to supercharge nature, zero out carbon by 2050, decouple growth from resources, and have a toxin-free future.

Source: Barrett (2010a); Borowski & Patuk (2021); Cockx et al. (2015); Friel et al. (2009); Ladha-Sabur et al. (2019); Leisner (2020); Máté et al. (2020a); Mc Carthy et al. (2018a);

Monforti & Dallemand (2015); Mostova & Hutorov (2023); Popp et al. (2014); Rabbi et al. (2022a, 2023); Rabbi et al. (2021a); Subramaniam et al. (2020a); Sun et al. (2017a).

The table 1 highlights the European Union's (EU's) challenges and goals across three key areas: food, energy, and environment.

Current shortcomings in the EU include limited access to affordable, nutritious food, a dependence on unclean and expensive energy sources, and environmental degradation. These issues are manifested by insufficient supplies of staple foods and clean energy, alongside deforestation, pollution, and a lack of environmental protection efforts.

These challenges have significant consequences. People struggle to afford healthy food and clean energy, while the EU's reliance on imported energy makes it vulnerable to external factors. Additionally, these issues contribute to rising rates of malnutrition, obesity, and environmental damage.

The table 1 also outlines the EU's aspirations for a more sustainable future. The goal is to establish food systems that provide healthy and affordable options for everyone. The EU also plans to transition towards clean, secure, and affordable energy sources. Finally, the European Green Deal represents a comprehensive strategy to achieve a resource-efficient future with zero carbon emissions and a healthy environment.

However, a critical gap exists in the prior research exploring the factors impacting the security and sustainability of Food, Energy, and Environment (FEE) systems across European nations. This study addresses this gap by analyzing eight EU member states: Austria, Belgium, Germany, Netherlands, Czech Republic, Hungary, Poland, and Slovakia. While existing studies provide valuable insights, a comprehensive analysis is necessary to understand the specific challenges associated with each factor and its potential connection to achieving the Sustainable Development Goals (SDGs).

Ensuring food, energy, and environmental (FEE) security for a growing global population demands tackling crucial challenges head-on. These include adapting to climate change, striking a balance between increasing needs for food and energy, and promoting sustainable economic growth. While European research on the FEE nexus is limited, this study aims to investigate the major obstacles to FEE security in eight selected EU countries. It will delve into the intricate connections between FEE security and the pursuit of Sustainable Development Goals (SDGs). In-depth research is essential to support the EU's vision for a sustainable planet and to maintain its leadership in FEE security. This investigation is critical for Europe to navigate societal challenges while fostering a sustainable digital economy and social transformation. The study's findings will significantly contribute to long-term sustainability and security, bolstering European competitiveness and offering solutions to global challenges.

1.1.1. The aim and objectives of the research

This research investigated the complex relationship between food, energy, and environment (FEE) in eight EU countries, focusing on its potential to improve resource use efficiency measured by Domestic Material Consumption (DMC) and its connection to the United Nation's (UN) Sustainable Development Goals (SDGs).

Addressing limitations in existing research, the study employed a novel model to explore the intricate interactions within the FEE system. This approach aimed to unravel the complex dynamics between these factors and their impact on the region's sustainability, identify key challenges and opportunities within the energy sector, particularly regarding their connection to the Sustainable Development Goals (SDGs), and explore the real-world consequences of SDG targets on food-energy-environment security.

This research also addresses knowledge gaps through its key objectives (detailed in Table 2), which aim to contribute to developing effective strategies for promoting sustainable development in eight selected EU countries.

Table 2: Research objectives for achieving FEE security

Objective 1:	To investigate the impact of regional disparities on food security across selected EU countries
Objective 2:	To explore how a combined strategy of efficient resource use, sustainable production, improved infrastructure, dietary variety, and minimal food waste strengthens food security and sustainability.
Objective 3:	To analyse and understand the diverse trends and patterns in the EU energy mix.
Objective 4:	To analyse CO_2 emission trends and identify key factors to develop effective mitigation plans.

Source: Author's compilation

Additionally, by examining these critical aspects, the research aimed to gain a comprehensive understanding of the challenges hindering sustainable development in Europe and provide valuable insights for policymakers.

1.2. Research questions

While acknowledging the complex and interconnected nature of food, energy, and environment (FEE) security and its intricate relationship with the Sustainable Development Goals (SDGs), this research simplifies these multifaceted issues into a set of well-defined research questions presented in Table 3. This approach aims to better understand the interdependencies within the FEE nexus and its implications for achieving the SDGs.

Table 3: Research questions aligned with objectives.

Objectives	Research questions
Objective 1	1. To what extent do regional disparities, specifically in urbanization, GDP, consumption patterns, and import dependency, influence food security across selected EU countries?
Objective 2	2. How does a combined strategy of efficient resource use, sustainable production, better infrastructure, dietary variety, and waste reduction impact food security and sustainability?
Objective 3	3. How do EU energy production and consumption patterns impact energy security?
Objective 4	4. What are the main sources and factors contributing to CO_2 emissions?

Source: Author's compilation

1.3. Research process

The dissertation commenced with a comprehensive research background that aimed to elucidate the existing knowledge gap and substantiate the theoretical framework pertaining to the security and sustainability of FEE within European countries. In addition, the comparative performance in relation to the progress of SDGs (2, 7, and 13) was examined throughout the investigation of sustainable FEE development. Furthermore, Figure 1 depicted the research process employed in the study's progression.

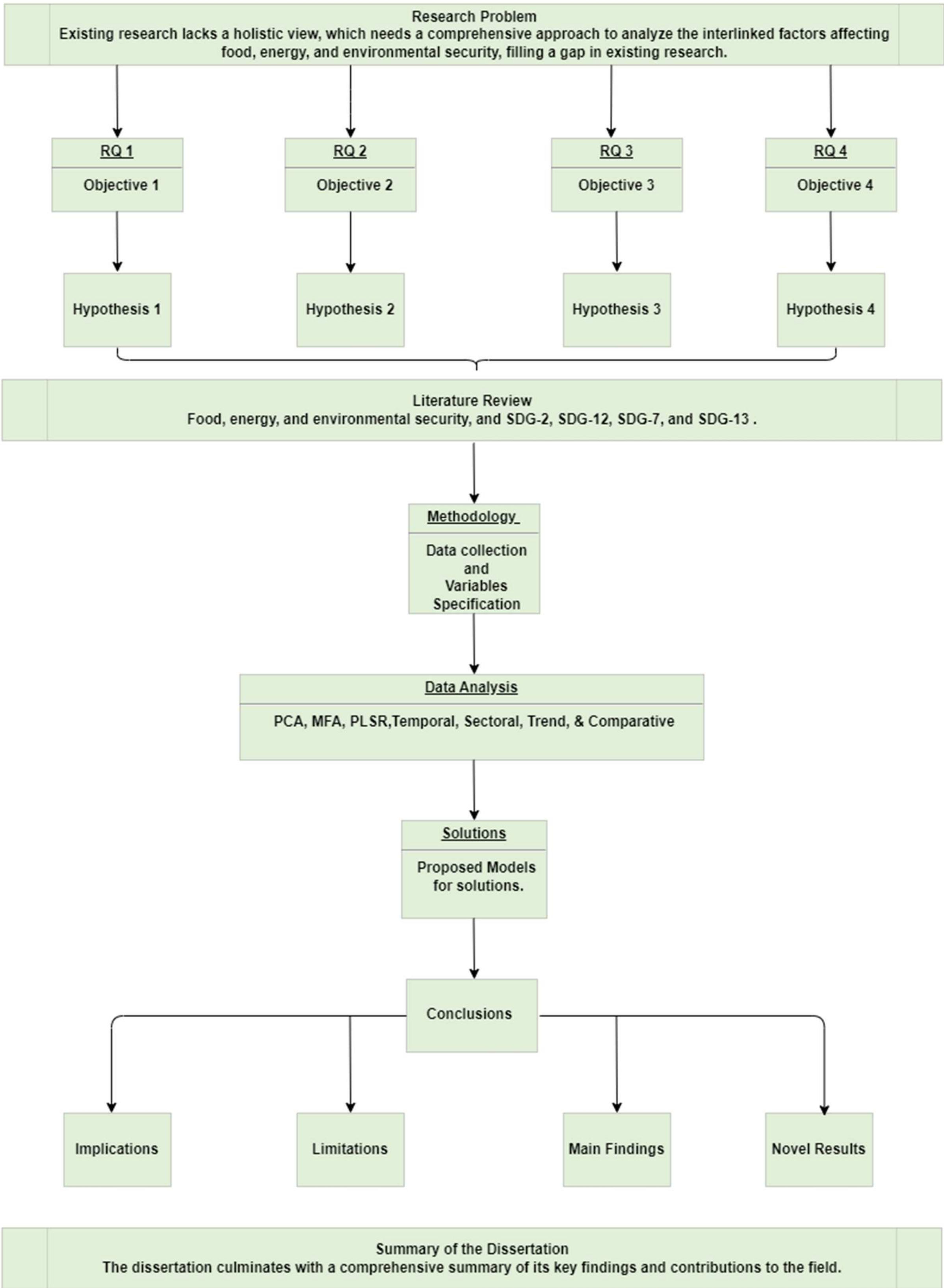

Figure 1: The research processes.

PCA: Principal Component Analysis; MFA: Multiple Factor Analysis; PLSR: Partial Least Squares Regression

Source: Author's compilation

1.4. Structure of the dissertation

This dissertation delved into the intricate interplay between FEE security and sustainability, demanding a well-structured approach to tackle its multifaceted nature. The introduction set the stage, highlighting the importance of exploring the interconnectedness of these domains with SDGs (especially 2, 12, 7 and 13). Definitions of key terms establish a shared understanding, while research objectives guide the investigation.

The literature review delved into existing research on FEE security individually, critically examining theoretical frameworks, methodologies, and empirical studies. It then shifted focus to the literature exploring their interconnections, identifying gaps and justifying further research. A novel conceptual framework was developed, integrating concepts from each security domain. This framework illuminated how factors like climate change, land use, domestic materials, and energy production influence the stability and resilience of these systems. Theoretical models or frameworks were strategically employed to illustrate these complex relationships.

The methodology section unveiled the research design, data collection methods, and analysis techniques utilized. The chosen approach was justified, and any limitations or constraints encountered were transparently discussed. This transparency strengthened the research methodology's rigour, enhancing the credibility of the findings.

The analysis and findings section presented the empirical results, meticulously analysing data to uncover patterns, trends, and relationships between variables relevant to each security domain. Through Multiple Factor Analysis (MFA), Principal Component Analysis (PCA), Partial Least Squares Regression (PLSR), Trend Analysis, Comparative Analysis, Temporal Trend Analysis and Sectoral Analysis, this section shed light on the implications of these findings for comprehending and addressing the challenges inherent in securing FEE.

Three unique models have been incorporated to offer FEE security solutions. These models provided valuable insights into the practical implications of the research, highlighting lessons learned and potential strategies for enhancing security in these crucial areas.

The dissertation culminated with a comprehensive summary of its key findings and contributions to the field. Future research directions were proposed, paving the way for continued exploration and inquiry into these vital issues. Finally, a meticulously curated reference list acknowledged and cited the sources that informed the dissertation's content, ensuring academic integrity and accountability.

2. LITERATURE REVIEW

2.1. Sustainable development

Since the 1970s, concerns about the future of humanity have led to a growing emphasis on the concept of sustainability (Borowy, 2021). This notion is closely aligned with the principles of sustainable development, which have become increasingly prominent in recent decades. Sustainable development has gained widespread attention from various stakeholders, including practitioners, entrepreneurs, policymakers, and researchers, leading to a vast body of contributions to the field. However, despite its prevalence and longstanding presence, the practical and theoretical implications of sustainability remain somewhat complex, calling for further exploration and clarification of different perspectives (Nogueira et al., 2024).

According to Brundtland (1987a), the "Our Common Future" commission's report in 1987 was the first time the word "sustainability" was used. It was defined as "the degree to which present needs can be met without affecting the ability of future generations to live and prosper. Though, the challenge is to raise living standards while not endangering nature and the ecosystem at the same time. This can often lead to disequilibrium with nature and other living creatures in the ecosystem.

Sustainability is conceptualized as trying to deliver the next generation with a vibrant ecosystem that enables them to live in harmony with the environment, the economy, as well as the social sphere. If the ecosystem is balanced, resilient, and interconnected, human beings will be able to immerse themselves in it empathically rather than aggressively. The biological impact of economic activities can be mitigated, and factor endowments restored by restoring ecosystems. This will satisfy existing and future demands (Garren & Brinkmann, 2018).

One key aspect of sustainability involves using renewable natural resources responsibly, ensuring they are not depleted or compromised for future generations. In contrast, it involves using finite resources in a way that prevents future generations from the usage (Moldan et al., 2012). As humanity has continued to expand, there has been a great continuum of unsustainable development, resulting in the socio-ecological collapse of resources in conflict with society's unlimited needs (Snyder, 2020).

A couple of efforts, such as the formation of the SDGs, have been made to curb the feeling of unsustainable in society. As a result of Agenda 21, a sustainable development program was established in 1992 by the United Nations (UN) with the goal of improving human lives and safeguarding the environment. The Millennium Development Goals were established in 2000 with the goal of eradicating poverty by 2015 and tackling socioeconomic issues behind. In 2015, the new agenda was endorsed along with various adjustments and renewals, which includes the 17 SDGs that should be achieved by 2030, replacing the Millennium Development Goals while addressing social, economic, and environmental concerns (Brundtland, 1987b; United Nations, n.d.). These objectives were constituted of 169 targets that must be accomplished by 2030 and will be measured by 247 indicators (Walker, 2021). According to the EC, all 17 goals were created to ensure that no one is left behind (European Commission, 2016; United Nations, 2015). In this way, it is important to explain the conceptual area and its main pillars to make a more solid plan for sustainable development (Mensah & Enu-Kwesi, 2019).

Several additional aspects have been incorporated into the three-pillar idea of sustainability, which is now generally recognised in society; sustainable development practice has been extensively spread and can be found in any document holding crucial information (Moldan et al., 2012; Purvis et al., 2019). The environment, the economy, and society are the focal points; yet these three pillars are not mutually exclusive and are intricately intertwined. Individuals and groups make significant contributions toward this objective by adopting a multi-level strategy that recognises and maps out the linkages, synergies, and trade-offs between various factors.

Furthermore, the implementation of inventive local strategies holds significant potential for addressing the issue of regional inequality within Europe (Faivre et al., 2017). The opportunity to address social and economic difficulties in the region lies in the advancements made in agriculture, education, and environmental technologies (Khorev et al., 2020). The implementation of nature-based solutions, such as the integration of natural elements into urban environments, has the potential to foster a more environmentally friendly and economically viable system (Duane et al., 2022). The concept of conservation refers to the practice of preserving and protecting natural resources, ecosystems, and agriculture, when implemented as an ecosystem-based approach to farming, has the potential to address agri-environmental issues and enhance the well-being of farmers and rural communities (Dwyer, 2016). Furthermore, the adoption of a comprehensive fire control strategy can enhance Europe's capacity to withstand and recover from severe wildfire incidents. Overall, this literature review provided a valuable foundation for understanding the complexities of sustainability and its potential solutions. While it offered a solid foundation, it could benefit from a deeper dive into implementation challenges, exploring alternative perspectives beyond mainstream approaches, and discussing emerging trends that might shape future sustainability efforts. This would enhance its comprehensiveness and offer a more nuanced understanding of this critical topic.

2.2. Sustainable Development Goal pillars

The SDGs are designed to address social issues and reverse the negative consequences of the Anthropocene era, in which humans dominate the environment and actively work to degrade and damage it (Russell-Bennett et al., 2024). The SDGs encompass three fundamental pillars: the FEE. The pillars play a crucial role in attaining sustainable development and effectively tackling the urgent global concerns of our time (Azabdaftari, 2019). The SDGs have the objective of diminishing worldwide disparities and establishing equilibrium among the economic, social, and environmental dimensions of progress (Bhandari, 2022). The UN's characterization of the SDGs is indicative of their multifaceted character, as each target incorporates the three fundamental dimensions of sustainable development (Dalampira & Nastis, 2020). The dissemination and comprehension of the SDGs among the general population have been prioritised, and the utilisation of a straightforward visual representation such as the three-pillar Venn diagram can facilitate comprehension and advocacy of these objectives (Koff & Maganda, 2020). Regional integration has emerged as a pivotal factor in facilitating sustainable development since regions serve as conduits across policy domains and governance levels, hence fostering the advancement of sustainability. Regional integration plays a crucial role in facilitating collaboration and cooperation among countries within a certain geographical area. This process is vital in effectively addressing shared difficulties and facilitating the exchange of best practises aimed at achieving the SDGs.

The attainment of SDGs (2, 7, and 13) in Europe is confronted with a combination of obstacles and prospects. The successful execution and documentation of SDGs predominantly hinge upon national procedures. However, it is crucial to acknowledge the significance of local engagement and community-led efforts in the monitoring of sustainability (González et al., 2023). The phenomenon of climate change has significant implications for forests and the provision of ecosystem services. In line with SDG 13, efforts are being made to mitigate the adverse effects of climate change by reducing greenhouse gas emissions. The alignment between SDG 13 and forests has the potential to make significant contributions to the sustainable management and protection of forest resources. However, it is important to acknowledge that the issues of unsustainable forest extraction and land development can hinder these efforts (Louman et al., 2019). Agenda 2030 promotes the establishment of inclusive and responsible institutions to achieve sustainable development, with a particular emphasis on the significance of stable policies and decision-making processes (Costa et al., 2021). In order to attain the SDGs, including in economically advanced regions such as the EU, it is imperative to establish robust connections and foster innovative collaborations on a transnational scale (MacFeely, 2019).

This review clearly outlines the multifaceted nature of the SDGs and their interconnectedness with the three pillars of FEE. It highlights the role of regional integration in facilitating collaboration and tackling shared challenges towards achieving these goals.

2.3. Theoretical background of food security

Food security is a multifaceted concept deeply intertwined with environmental, economic, and social well-being (United Nations, 1987). As outlined in the UN's Sustainable Development Goals (SDGs), achieving food security requires a comprehensive understanding of the entire food system, encompassing production, processing, distribution, retail, prices, and consumer behavior (Sousa et al., 2024).

The definition of food security has evolved over time. In 1996, the World Food Summit in Rome established the widely accepted definition: "when all individuals have physical and economic access at all times to adequate, safe and nutritious food that satisfies their nutritional requirements and food choices for a healthy and balanced life" (Hertel, 2016; Johan Helland, 2014; Quisumbing et al., 1996; Shaw, 2007).

Furthermore, the High-Level Panel of Experts (HLPE) broadened the concept in 2014 by introducing the "food system" as "all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes" (HLPE, 2014, p. 29).

More recently, food security frameworks typically focused on four dimensions: availability, accessibility, utilization, and stability (Johan Helland, 2014). However, the HLPE's 2020 report on food security and nutrition added two crucial elements: agency and sustainability (HLPE, 2020a). The six key dimensions of sustainable food security are availability (adequate food production, reserves, and net trade), accessibility (physical, economic, and social access to food), nutritional adequacy (sufficient energy, protein, micronutrients, and food safety), stability (reliable access, availability, and quality of food over time), institutional frameworks (governance processes that support food security), and sustainability (practices that maintain ecological, social, and economic systems for future generations).

Individuals play a crucial role in shaping their food systems through their dietary choices, agricultural practices, and consumption habits. Sustainable food security emphasizes actions within the food system that ensure the present generation's needs are met without compromising the well-being of future generations. This includes restoring ecological, social, and economic systems for long-term viability.

Achieving food security necessitates a holistic approach that transcends mere access to food. By comprehending the intricate interplay of the six dimensions and actively promoting sustainable practices, we can pave the way for a future where everyone has access to healthy, nutritious food without sacrificing the well-being of generations to come.

2.4. Food availability

Food security, the ability of a population to access sufficient and nutritious food, relies heavily on food availability (Moyo, 2024). This means producing and supplying enough food to meet everyone's needs. However, simply having enough food isn't enough. Even with sufficient availability, factors like poverty, lack of proper infrastructure, and unequal distribution can hinder access and proper utilization.

Several factors threaten food security. Population growth, poverty, and educational and gender disparities can all limit food production, as noted by Kitole & Sesabo (2024), leading to scarcity and insecurity. Additionally, the production of biofuels can compete with food for resources like land and water, potentially increasing food prices and making it harder for low-income individuals to access it, as highlighted by Screti et al. (2024).

Energy usage is another crucial aspect intertwined with food security. The entire process from food production and processing to packaging and transportation requires significant energy, heavily reliant on fossil fuels, as emphasized by Monforti & Dallemand (2015) and Marshall (2001). This dependence contributes to greenhouse gas emissions and environmental challenges.

Accessibility is further impacted by factors like food policies, supply chains, and consumers' purchasing power, as Ladha-Sabur et al. (2019) point out. Certain processed foods, with their high energy requirements for processing (Greco et al., 2020), stringent hygiene standards, and consumer preferences for convenience, especially in meat and dairy production (Rokicki et al., 2021), contribute to a larger energy footprint. Transportation, particularly the reliance on road networks in many countries like the UK, further adds to the energy consumption associated with the food system. Striking a balance between accessibility and reduced energy consumption is crucial for a sustainable food system.

Climate change poses another significant threat. Rising greenhouse gas emissions and CO_2 levels can negatively impact agricultural land suitability, crop yields, and overall food production, as highlighted by Schmidhuber & Tubiello (2007). Additionally, rapid urbanization, as described by Chen (2007), can decrease available agricultural land and contribute to soil contamination, ultimately impacting food production capacity.

Addressing these challenges through sustainable practices, responsible resource management, and innovative solutions is essential to ensure long-term food security for all. By tackling these issues, we can create a food system that is not only efficient and accessible but also environmentally responsible and capable of meeting the needs of a growing population.

2.5. Food accessibility

Food security is not merely a matter of having enough food available. As Koralesky et al. (2024) argues, individuals must have access to the existing food supply. This access encompasses both the physical ability to obtain food and the financial means to afford it.

The Food and Agriculture Organization (FAO) defines food security as a situation where everyone, always has physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and preferences for an active and healthy life. However, numerous factors can hinder this access (Ahmad et al., 2024).

One significant factor is food price fluctuations, as highlighted by Köse & Ünal (2022). These fluctuations, particularly in the global market, can disproportionately impact vulnerable populations who are already struggling to afford food. Additionally, poosr infrastructure, such as inadequate transportation and market systems, can further exacerbate this issue. As Guo et al. (2024) point out, these inefficiencies increase the cost of food by raising the price of agricultural inputs and transportation costs for consumers.

Income also plays a critical role in access to food, as highlighted by Guo et al. (2024). Low-income households often face greater vulnerability to food insecurity due to limited resources to purchase food. Furthermore, Fadare et al. (2024) emphasize the detrimental impact of violent conflicts on food security. These conflicts can disrupt food production and distribution networks, hindering access to food and exacerbating existing vulnerabilities faced by low-income populations and others already struggling with food security.

In essence, achieving and maintaining food security requires addressing the complex interplay of factors influencing access, including food price fluctuations, inadequate infrastructure, limited income, and the disruptions caused by violent conflicts. By understanding these challenges and implementing appropriate solutions, we can work towards a world where everyone has access to the food they need to live a healthy and active life.

While effective in addressing short-term food shortages and disasters, food aid has limitations, as Abouelenin & Hu (2024) acknowledge. Concerns exist regarding its long-term impact, cost-effectiveness, and targeting of specific populations. These programs often face challenges such as high administrative costs, delays in delivery, and difficulties in reaching the most vulnerable populations.

Neves Freiria et al. (2024) emphasize the importance of considering individual needs within households when addressing food security. They argue that relying solely on household food security can mask inequalities in access within the family unit, as gender and age can significantly influence individuals' access to food.

Overall, achieving food security is a complex challenge requiring a multifaceted approach. This approach must address not only food availability but also individual access, affordability, and intra-household distribution. Recognizing the diverse factors influencing food security, such as economics, infrastructure, conflict, and individual needs within households, is crucial for developing effective solutions to ensure everyone has access to the food they need for a healthy and active life.

2.6. Food utilization

Food security goes beyond mere access to food. As Kandel et al. (2024) emphasizes, the quality of the available food and its utilization by individuals and households are crucial aspects. This utilization refers to the ability to properly utilize the nutrients present in the food for optimal health. Furthermore, the nutritional value of food, including both macronutrients and micronutrients, plays a significant role. This is because our bodies need to be able to absorb and metabolize these nutrients effectively.

Studies have established a concerning link between the quality of food and the prevalence of both malnutrition and obesity in Europe (Elmadfa & Meyer, 2009; Tamargo, 2022). Unhealthy dietary patterns, characterized by excessive consumption of unhealthy fats and sugars, coupled with inadequate intake of complex carbohydrates, fruits, and vegetables, are major contributors to the rise in overweight, obesity, and associated health problems (Kobylińska et al., 2022). Imbalanced diets lacking in essential micronutrients can lead to malnutrition (Royo-Bordonada, 2016).

Poverty and food insecurity further complicate this issue, creating a paradoxical situation where both malnutrition and obesity can coexist within vulnerable communities (Appiah-Twumasi & Asale, 2022). The influence of the food industry on policy is concerning, as self-regulation often prioritizes the promotion and sale of unhealthy foods, especially to children. Addressing these concerns requires advocating for and promoting nutritious dietary choices, particularly among vulnerable populations like pregnant women and the elderly. Additionally, targeted nutrition initiatives tailored to individuals at risk are crucial.

Research by Fernandes & Höfelmann (2024) revealed a surprising link between food insecurity and obesity. Their study found that women experiencing mild food insecurity were 30% more likely to be overweight compared to those who were food secure. This highlights the complex and often counterintuitive nature of the relationship between food security and weight status.

While Farre et al. (2011) discuss the potential of genetic engineering to create more nutritious staple crops to address malnutrition globally, it is important to acknowledge that this is just one piece of the puzzle. Addressing food security and nutrition requires a multifaceted approach that considers various factors beyond solely increasing the nutritional content of food.

Fontanet & Cauchemez (2020) highlight the importance of herd immunity in disease prevention, even though only a small proportion of the population needs to be immune. Notably, COVID-19 infection can negatively impact nutrient absorption and utilization due to weakened immunity. This emphasizes the importance of ensuring a reliable supply of micronutrients with good bioavailability, as food components can influence absorption, particularly of minerals (Hall et al., 2007). Further research using metabolomics might offer insights into potential treatments based on food processing methods and biofortification strategies.

Research by Kandel et al. (2024b) suggests a strong link between dietary diversity and food insecurity. Households that struggle to include a variety of food groups in their diets are more likely to face inadequate food intake per person and a lack of overall calories. This finding underscores the importance of promoting diverse diets as a critical strategy in tackling food security challenges. By encouraging a wider range of foods in people's diets, we can work towards ensuring everyone has access to the nutrients they need.

2.7. Stability

Food stability, the ability of populations to consistently access safe, nutritious, and affordable food, is essential for a healthy and functioning society. In Europe, numerous factors influence this delicate balance, ranging from agricultural practices and economic policies to environmental conditions.

Challenges threaten food stability in Europe. Climate change, with its increasing frequency of extreme weather events like droughts and floods, disrupts agricultural production and supply chains (Godde et al., 2021). Food waste also presents a significant challenge, with the European

Union discarding an estimated 88 million tonnes annually (European Commission, 2021). Addressing this issue is crucial for enhancing resource efficiency and fostering food stability.

Furthermore, socioeconomic disparities contribute to uneven access to food across Europe. Studies by Berning et al. (2024) highlight the link between poverty and food insecurity, with marginalized communities facing a greater risk of hunger and inadequate nutrition. Additionally, Europe's reliance on global trade exposes it to vulnerabilities like volatile commodity prices, supply disruptions, and geopolitical tensions. Research by (Pradhan et al., 2020) emphasizes the importance of diversifying food sources and strengthening regional food systems to mitigate these risks.

However, trends and solutions offer hope for improving food stability. Transitioning to sustainable agricultural practices like crop diversification and conservation agriculture is crucial for building resilience to environmental challenges and improving food stability (Franzluebbers & Gastal, 2019). Additionally, technological advancements in precision farming, genetic engineering, and digital agriculture offer promising solutions to increase food production efficiency and minimize environmental impacts (Clapp & Ruder, 2020).

Effective policy interventions are also essential. Research by (Thow et al., 2018) highlights the importance of policy coherence across sectors like agriculture, health, and the environment to achieve food security and nutrition goals. Finally, encouraging consumer behaviour change towards more sustainable and healthy dietary patterns plays a crucial role in improving food stability and reducing environmental footprints. Research by Pandey et al. (2023) explores strategies like education, labelling, and nudging interventions to promote sustainable food choices.

Ultimately, achieving food stability in Europe necessitates a comprehensive approach that addresses environmental, socioeconomic, and governance challenges. Integrating insights from diverse research fields is crucial for policymakers, practitioners, and stakeholders to build resilient food systems. This collaborative effort is vital to ensure equitable access to safe and nutritious food for all European citizens, requiring the fostering of sustainable agricultural practices, harnessing technological innovations, implementing effective policies, and driving sustainable consumer behaviour.

It is crucial to consider the regional disparities within the selected EU countries when examining their food security. These disparities, encompassing factors like agricultural productivity, resource access, economic development, and policy implementation, can significantly affect the achievement of food security goals across different regions.

Therefore, when analyzing food security in the context of these regional variations, the research hypothesis should be formulated with an understanding of the diverse contexts within each chosen EU country. This ensures the hypothesis effectively addresses the overarching research question while acknowledging the multifaceted nature of food security, encompassing availability, accessibility, utilization, and stability within each region. As a result, the present investigation proposed the following hypothesis:

Hypothesis 1 (H1). *Food access, affordability, quality, and overall security are directly linked to regional disparities, higher urbanization, and economic growth.*

2.8. Food security and Sustainable Development Goal 2 and 12

One of the most critical aspects of the SDGs was that their goals and objectives for growth were fundamentally interconnected while also being interlinked (Tosun & Leininger, 2017). Various aspects of the SDGs were argued to be congruent or synergistic and involve trade-offs or contradictions with the national and global implications. Its interdependencies mean that it might help alleviate several issues simultaneously by achieving one target. For instance, there will be synergies between addressing climate change and improving energy security, human health, ecosystems, and biodiversity (Le Blanc, 2015), and almost every objective of the SDGs has something to do with food problems, either directly or indirectly. Finding solutions to these problems is key to reaching the goals.

Initially, food security was considered as a production problem, which is in line with SDG 2. An important benefit is that it has the potential to radically alter food systems, giving local, small-scale farmers a much more substantial position in the economy.

Table 4: Targets for achieving SDG 2

Targets No.	Sub-goals	Goal 2: Zero hunger & sustainable food
2.1	Achieve food security for all	Strive for universal access to safe, nutritious food by 2030, prioritizing vulnerable groups like children, pregnant mothers, the elderly, and those experiencing poverty or food insecurity.

2.2	End all forms of malnutrition	Ending all malnutrition by 2030 demands urgent action, particularly for young children. While hitting 2025 stunting and wasting targets is crucial, we can't neglect adolescents, pregnant women, and the elderly. A comprehensive strategy focusing on vulnerable populations is key to a malnutrition-free world.
2.3	Empower small-scale producers	Promote equitable access to resources and opportunities for small-scale food producers, aiming to double their agricultural output and incomes by 2030, with a particular focus on empowering women, indigenous peoples, family farmers, pastoralists, and fishermen.
2.4	Build sustainable food systems	Implement sustainable agricultural practices by 2030 to increase productivity, protect ecosystems, and build resilience to climate change, prioritizing improvements in land and soil quality.
2.5	Promote fair and equitable benefits	Ensure fair and equitable sharing of benefits from genetic resources and traditional knowledge on a global scale, while preserving genetic diversity through effectively managed seed and plant banks by 2030.
2.a	Invest in rural development	Increase investments in rural infrastructure, agricultural research, technology, and gene banks, particularly in least developed countries, to enhance agricultural productivity in developing nations.
2.b	Ensure fair trade	Advocate for an international agricultural trade system aligned with fair trade principles, eliminating protectionism, and supporting the objectives of the Doha Development Round.
2.c	Stabilize food prices	Address food price volatility by promoting efficient food markets, timely market information sharing, and ensuring access to food reserves.

Source: (United Nations, 2024a)

Target 2.1 of SDG 2 aims to ensure that all people have access to food, and target 3.1 aims to improve nutrition and end all types of malnutrition simultaneously (target 2.2). They intend to achieve this by increasing the livelihoods and sustainability of local food producers (target 2.3) (UN, 2020a; United Nations, 2015).

Furthermore, SDG 12, a cornerstone of sustainable development, is instrumental in securing food supplies throughout the EU, encompassing vital aspects of food security (Vann Yaroson et al., 2024). This encompasses the availability, accessibility, and utilization of food, essential for ensuring a healthy and active life for all individuals.

Table 5: Targets for achieving SDG 12

Targets No.	Sub-goals	Goal 12: Sustainable consumption & production for all	12 RESPONSIBLE CONSUMPTION AND PRODUCTION
12.1	Embrace collaborative action	All nations must work together to follow the 10-Year Framework and embrace sustainable consumption and production practices. This includes remembering the development needs of less developed countries and ensuring that everyone has the opportunity to participate in a sustainable future.	
12.2	Achieve resource efficiency	By 2030, we must use natural resources sustainably and efficiently.	
12.3	Combat food waste	Halving global food waste per person by 2030, while minimizing losses throughout production chains, is crucial for a sustainable and equitable food system. This ambitious goal requires collaboration from individuals, businesses, and governments.	
12.4	Reduce pollution	Though the 2020 goal for reducing chemical and waste has passed, responsible lifecycle management remains crucial. It's vital for protecting health and the environment, and paving the way for a sustainable future.	

12.5	Minimize waste generation	By 2030, significantly reduce waste generation by preventing, reducing, recycling, and reusing.
12.6	Drive corporate sustainability	Encourage companies, especially large ones, to adopt sustainable practices and report on their efforts.
12.7	Promote sustainable procurement	Promote sustainable public purchasing practices aligned with national goals.
12.8	Empower informed choices	By 2030, ensure everyone has the knowledge and awareness to live sustainably in harmony with nature.
12.A	Support developing countries	Empower developing nations to build robust scientific and technological capabilities to achieve sustainable consumption and production practices.
12.B	Monitor tourism's impact	Develop tools to monitor tourism's impact on sustainable development, promoting job creation and local culture.
12.C	Phase out harmful subsidies	Reforming fossil fuel subsidies that encourage waste is crucial. It should consider each country's context, with tax revamps and phase-outs for environmentally harmful subsidies. Prioritizing developing nations while minimizing negative impacts is essential.

Source: (United Nations, 2024c)

SDG 12 addresses each dimension comprehensively. Firstly, it promotes resource efficiency in agriculture and food production, intelligently managing land, water, and energy to maximize yields while minimizing environmental harm, thereby bolstering food security and ecological sustainability. Secondly, SDG 12 aims to significantly reduce food waste along the supply chain, leading to increased food distribution to those in need, reduced strain on natural resources, and lowered greenhouse gas emissions, ultimately empowering vulnerable populations within the EU. Thirdly, the goal advocates for sustainable agricultural practices such as organic farming, agro-ecology, and precision agriculture, which enhance climate resilience, conserve biodiversity, and improve soil health, ensuring long-term food security.

Furthermore, it emphasizes making safe and nutritious food accessible to all, particularly addressing food insecurity and malnutrition among vulnerable groups, thereby promoting well-being across EU communities.

Moreover, SDG 12 fosters a transition to a circular economy within the food system, promoting resource reuse, recycling, and repurposing to minimize waste and environmental impact, optimizing resource utilization, reducing reliance on finite resources, and creating new economic opportunities. Additionally, it encourages policy coherence across sectors like agriculture, trade, environment, and health, fostering coordinated strategies to address interconnected challenges in food security, sustainability, and consumption patterns, leading to more effective and holistic solutions. SDG 12 serves as a roadmap for the EU to achieve food security through sustainable production and consumption practices, addressing resource efficiency, food waste, sustainable agriculture, access to nutritious food, circular economy principles, and policy integration, thus building a resilient and sustainable food system for present and future generations.

Leveraging the well-established connection between SDGs and food security, the following hypothesis was formed:

Hypothesis 2 (H2). *Implementing strategies for efficient production, better infrastructure, diverse diets, and reduced waste contributes to a sustainable food future.*

2.9. Theoretical background of energy security

Ensuring a reliable and steady supply of energy is a critical concern for nations worldwide, including the European Union. It stands as one of the core principles guiding their energy policy, alongside efficiency and environmental sustainability (Hassan et al., 2024).

Traditionally, energy security was assessed based on four key aspects: availability, accessibility, affordability, and acceptability. Availability and affordability were considered the most crucial factors, impacting other dimensions. However, the definition has evolved to incorporate contemporary concerns like human rights, individual security, and environmental sustainability.

Several organizations have defined energy security. The International Energy Agency (IEA) emphasizes the "four A's": availability, affordability, accessibility, and acceptability (IEA, 2019). The Asia Pacific Energy Research Centre (2007) (APERC) further expanded upon these aspects, including the longer-term goal of sustainability.

From a supply security perspective, Burlinson et al. (2024) highlights the importance of both short-term physical availability and long-term affordability. Jewell et al. (2014) defines it as the "low vulnerability of vital energy systems," encompassing both risk and resilience.

Several critical elements contribute to energy security, including resource nationalism, secure and affordable provision, diversification of energy sources, safe transportation of energy and fuel, and preparedness for future changes. While historically focused on securing reliable fossil fuels through centralized systems, energy security has evolved into a broader concept encompassing three key pillars: ensuring sufficient and readily available energy sources (availability and accessibility, often termed energy independence), providing access to low-cost resources for all (affordability and equitable distribution), and ensuring long-term sustainability and environmental responsibility (sustainability and environmental viability) (Rabbi et al., 2022b). These three pillars form the foundation for various contemporary energy security concepts.

The growing dependence on natural gas, particularly in the EU, and the recent conflict in Ukraine have highlighted the critical role of energy security in shaping European energy strategies (Rodríguez-Fernández et al., 2020). It is projected that global energy demand will continue to rise, primarily driven by non-OECD countries. The primary energy mix currently has an 82% share in fossil fuels, and its position will change significantly in the future, with a projected drop to 75% by 2040 (IEA, 2014). While fossil fuels currently dominate the primary energy mix, their share is expected to decline, paving the way for renewables and increased energy efficiency.

Energy efficiency is often seen as a cornerstone of energy security. Reducing demand can lessen reliance on imported sources, contributing to a more secure supply (Zhang et al., 2013). Technological advancements and improved energy management practices across various sectors are facilitating a decrease in energy intensity. However, government policies like fuel economy standards and building energy codes can further accelerate these advancements (Ang et al., 2015; IEA, 2017; Nuttall & Manz, 2008).

Overall, navigating the complexities of energy security requires a comprehensive understanding of its multifaceted nature. Adaptability to evolving challenges and a commitment to a sustainable future are crucial for ensuring long-term energy security in our interconnected world.

2.10. Energy security and Sustainable Development Goal 7

Affordable and clean energy for all is a crucial aspect of the 2030 agenda for sustainable development goal 7. This goal necessitates a two-pronged approach: ensuring access and promoting efficiency (Rebelatto et al., 2019).

On the access side, the objective is to provide everyone with reliable, sustainable, and modern forms of energy at an affordable price. This can be achieved through various means, including reducing energy demand, and implementing stricter regulations and monitoring of energy use.

Energy efficiency plays a key role in this strategy. By consuming less energy, individuals and societies benefit from lower costs and a more productive use of resources. This is particularly important as global resource prices rise, making efficient energy use a critical factor for economic prosperity (Maistry & Annegarn, 2016).

Our energy needs have a significant environmental impact, often causing the release of harmful gases like carbon dioxide. These emissions threaten both human well-being and the natural world. Moving towards sustainable energy solutions that are both clean and efficient is crucial for safeguarding the future of our planet.

Table 6: Targets for achieving SDG 7

Targets No.	**Sub-goals**	**Goal 7: Affordable, reliable, clean, and modern energy for all**
7.1	Power the world sustainably	Secure affordable, sustainable, and advanced energy services for all by 2030, empowering communities and closing the energy gap.
7.2	Unlock energy efficiency potential	Achieving a dramatic rise in renewable energy's contribution to the global energy mix by 2030 is crucial. This ambitious goal will propel a clean energy transition, ultimately fostering a healthier planet for all.
7.3	Accelerate clean energy innovation	Accelerate global energy efficiency efforts twofold by 2030, maximizing existing resources and unlocking sustainable growth.
7.a	Bridge the energy gap	Boost investment in clean energy infrastructure and technology across renewables, efficiency, and cleaner fossil fuels by 2030, fostering international collaboration and research breakthroughs.
7.b	Investment in clean energy	Prioritize clean energy access for developing nations by 2030, with targeted investments in new infrastructure, advanced technologies, and tailored assistance programs

	for least developed countries, island states, and landlocked regions.

Source: (United Nations, 2024b)

Understanding the impact of a diverse energy mix, as well as variations in production and consumption, is crucial for assessing energy security. Consequently, the following hypothesis was proposed:

Hypothesis 3 (H3). *A more diverse energy mix with significant variations in production and consumption patterns will have a positive impact on energy security.*

2.11. Theoretical background of environmental security

Global environmental change is the main threat, based on ecosystem-to-human relations, the impact of global environmental changes on environmental destruction, the consequences of increasing social demand for energy, ecosystem services, and environmentally friendly products. Environmental security refers to the overall public safety from environmental hazards created by natural or human processes within or across national boundaries attributable to ignorance, disaster, mismanagement, or design (Suhardono et al., 2024; Zurlini & Müller, 2008).

Another theory that explained environmental security was the status of human dynamics, including restoring the environment degraded in war activities, resource scarcity, environmental destruction, and biological risks that may contribute to social disruption and conflict. Proactive minimization of anthropogenic risks to the biosphere's functional stability and hence its human interdependence constituted environmental security (Zurlini & Müller, 2008).

Climate change is another important aspect that puts more pressure on the expected disparity in the dynamics of natural resources. Climate change affects and directly impacts the nexus of the FEE through several bidirectional interactions, which are interconnecting in the food-energy-environment nexus. Over the last 50 years, particularly in the industrial era, climate change has mainly been caused by anthropogenic greenhouse gas (GHG) emissions to the environment. Energy from the sun drives the climate system. Some of this energy was reflected in the environment, but the vast majority was absorbed by the ground and the water and then radiated back into space. The term "greenhouse effect" refers to a phenomenon that occurs when some of the radiant heat emitted by the lower atmosphere is absorbed and then re-emitted (Shrestha et al., 2014).

The burning of fossil fuels for transport and electricity generation and industrial activity represented many of those emissions. Several of the GHGs came from food crop fields and biofuel production, combined with expanding the agricultural areas, which contributed to accelerating global warming by cutting off both temperate forests and tropical forests (Bhatti et al., 2024).

Moreover, climate change is driven by a series of phenomenon that will intensify nexus problems and have detrimental consequences for future water, energy, and food security. The rise in extreme weather conditions, such as prolonged droughts, flooding, heatwaves, and cyclones, posed significant food and energy security threats. The water supply for food production, energy generation, and possible crop failures were the most critical issues. Growing plant variability and decreased average rainfall limited hydropower generation, affected rain-fed agriculture in many areas, and increased industry water competitiveness (WWAP, 2014).

While efforts to combat climate change are crucial, some solutions like biofuels, shale gas, and carbon capture, despite being touted as sustainable, might just create new problems. They could have unintended consequences related to food and energy security. Even beyond these specific technologies, climate change itself throws a wrench into the energy equation, forcing us to constantly re-evaluate our choices.

2.12. Environmental security and Sustainable Development Goal 13

Our planet faces a growing challenge of climate change. This disruption throws weather patterns into chaos, causes sea levels to rise, and unleashes powerful storms and other extreme events. These consequences impact economies, communities, and individual lives around the world.

The main driver of climate change is the rise in greenhouse gases released by human actions. These emissions are at record levels, and unless we act, global temperatures could surge past 3 degrees Celsius this century, with some areas experiencing even more dramatic increases.

The harshest effects of climate change are often felt by the poorest and most vulnerable populations. Since climate change is a global issue, emissions from one location can have consequences everywhere. International cooperation is crucial for a successful transition to a low-carbon economy.

The Paris Agreement, a landmark international treaty adopted in December 2015 at COP21, marked a crucial step in the fight against climate change. The agreement's central aim is to curb global warming to well below 2 degrees Celsius from pre-industrial levels, with a more ambitious target of 1.5 degrees Celsius to prevent the most devastating impacts.

The fight against climate change is a core issue for achieving a sustainable future. This is reflected in the UN's Sustainable Development Goals (SDGs), with SDG 13 dedicated to taking swift action to tackle climate change and its consequences. This goal is broken down into five targets and eight indicators set by the UN. Targets define the goals, while indicators serve as benchmarks to measure progress towards achieving those goals. These five key objectives outlined in SDG 13 represent the essential actions each country needs to acknowledge as part of their individual commitments.

Table 7: Targets for achieving SDG 13

Targets No.	**Sub-goals**	**Goal 13: Combat climate change and protect the future**
13.1	Preparing for climate-related risks and disasters	Build robust national defences against climate risks and disasters.
13.2	Integrate climate action into national planning	Make tackling climate change a priority in every nation's roadmap.
13.3	Education, awareness, and capacity building	Bolster education, awareness, and capacity to combat climate change, adapt to its impacts, and issue timely warnings.
13.a	Full capitalization of the Green Climate Fund	Secure full funding to empower developing countries with effective mitigation tools and ensure transparent implementation, as promised by developed nations.
13.b	Support vulnerable groups	Advocate for measures that empower women, youth, and marginalized groups in vulnerable nations to manage and plan for climate impacts.

Source: (United Nations, 2024d)

Balancing economic development with environmental protection remains a complex challenge. Specifically, SDG 13 focuses on combating climate change and presents a crucial yet intricate task. This objective aligns with the Paris Agreement, a legally binding pact recently reaffirmed by over half the world's nations responsible for most global emissions. While both efforts share common ground, it's important to remember their distinct origins. The SDGs function as voluntary commitments, whereas the Paris Agreement constitutes a legally binding framework (Morton et al., 2017).

This hypothesis concerning environmental security is premised on the established connection between food production and energy utilization:

Hypothesis 4 (H4). *Food production practices and energy consumption patterns significantly contribute to carbon dioxide (CO2) emissions.*

3. METHODS AND METHODOLOGY

3.1. Methods and data collection

This investigation dived into FEE security in specific European countries. It explored both challenges and opportunities related to these critical issues. The research painted a comprehensive picture, leveraging quantitative and qualitative data, aligned with relevant SDGs. This SDG lens allowed for deeper insights and evaluation of findings. Ultimately, the research aimed to guide effective and targeted actions towards achieving sustainability goals.

Secondary data from well-respected sources like FAO, Global Food Security Index (GFSI), European Statistics (EUROSTAT), OECD, and World Bank (WB) data underpinned the research. Additionally, diverse grey literature, including reports, policies, news articles, and technical papers provided a real-time perspective and enriched the understanding of the European FEE complexities. This diverse range of sources ensured a holistic understanding of Europe's complex challenges and progress in achieving FEE security.

Investigating the link between food security and Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 12 (Responsible Consumption and Production) in **Study 1 (food security)** required a robust methodology capable of handling complex relationships between numerous interconnected variables. Unlike simpler regression methods that might struggle with such intricate data, Partial Least Squares Regression (PLSR) proved ideally suited for this task. PLSR facilitated the simultaneous analysis of two sets of variables: those directly related to food security and those associated with the SDGs. This comprehensive approach enabled us to not only identify key factors influencing food security but also critically assess their connection to achieving the relevant SDGs.

The PLSR model captures the relationships between the X and Y variables through a combination of outer and inner components. The outer components represent the variation within each block (X and Y) individually, while the inner components capture the latent variables that explain the shared variance between them. This complex interplay can be mathematically expressed as:

Consider a scenario for analyzing a dataset that consist of I observations and J variables, denoted by the X block. Here, x_{ij} represents the i-th observation for the j-th variable, and the matrix X_{IxJ} has dimensions IxJ. Furthermore, $X^{(j)}$ indicates the j-th column of matrix X. Similarly, suppose there is another dataset with the same number of observations as Y and K variables, where Y_{IxK} denotes the i-th observation for the k-th variable, and Y_{IxK} forms a IxKmatrix.

The outer relation for X block is:

$$X_{IxJ} = \sum_{l=1}^{L} t_{Ix1}^{(l)} \cdot p'^{(l)}_{1xJ} + E_{IxJ} = TP' + E \qquad (1)$$

The outer relation for Y block is:

$$Y_{IxK} = \sum_{l=1}^{L} u_{Ix1}^{(l)} \cdot q'^{(l)}_{1xK} + F_{IxK} = UQ' + F \qquad (2)$$

Consider two error matrices, E (of dimension IxJ) and F (of dimension IxK). Additionally, we have two "score" matrices, $t^{(l)}$ and $u^{(l)}$ (both IxL), representing scores for X and Y, respectively. These matrices can be further decomposed into column vectors: $t^{(l)}$ (of dimension $Ix1$) for T and $u^{(l)}$ for U, where l represents the l-th column (and there are L columns in total, indicating the number of latent components).

Similarly, we have two matrices, P' (of dimension LxJ) and Q' (of dimension LxK), containing "loadings." These can also be expressed as row vectors: $p'^{(l)}$ (of dimension $1xJ$) for P' and $q'^{(l)}$ (of dimension $1xK$) for Q'. Here, l again refers to the l-th row (out of L total rows). The prime symbol ($'$) denotes matrix transposition.

This explains the relationship between error matrices, score matrices, loading matrices, and their corresponding vector representations. It emphasizes that these elements play a role in representing scores for X and Y.

$$T_{IxL} = \sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot W'^{(j)}_{1xL} = XW' \qquad (3)$$

and

$$t_{Ix1}^{(l)} = \sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot w_{j,l} \qquad (4)$$

The weight matrix for the variables in the X block is denoted by $W'^{(j)}$, where each entry $w_{j,l}$ represents the weight of the l-th latent component on the j-th variable.

The X-scores are also used to predict the variables in the Y block. In this case, the formula (4) replaces $u_{Ix1}^{(l)}$ from formula (2) with $t_{Ix1}^{(l)}$. This indicates that the X-scores are used as predictors for the Y block variables.

$$Y_{IxK} = \sum_{l=1}^{L} \left(\left(\sum_{j=1}^{J} X_{Ix1}^{(j)} \cdot w_{j,l} \right) \cdot q'^{(j)}_{1xK} \right) + G = XW'Q' + G \quad (5)$$

The Partial Least Squares Regression (PLSR) technique analyzes data by first reducing the predictor variables (X) to a set of principal components (PCs). These PCs, represented by factor scores ($t^{(l)}$), are then used to predict component scores ($u^{(l)}$) derived from the dependent variable (Y). Finally, the predicted Y component scores are used to estimate the original Y values.

PLSR's key strength lies in its ability to maximize the relationship between the factor scores of the predictor and dependent variables ($t^{(l)}$ and $u^{(l)}$, respectively). It achieves this by strategically selecting X -scores that best correspond to the Y-scores, ensuring a strong pairing between the latent independent and dependent variables (Garson, 2016). Herman Wold's pioneering Nonlinear Iterative Partial Least Squares (NIPALS) method (Wold, 1975) is used to calculate the components of PLS. Geometrically, the NIPALS approach involves projecting the original X matrix onto a plane defined by the scores of the X components. This projected data is then correlated with the Y values (Wold et al., 2001). A common visualization technique involves plotting the corresponding columns (representing dimensions) of the W' weight matrix and the Q' loading matrix on the same coordinate system. This visualization helps to illustrate the associations between the two sets of variables.

A two-part analysis explored the connections between food security and the Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 12 (Responsible Consumption and Production). In each analysis, Principal Component Analysis (PCA) was used to unveil underlying patterns and visualize these relationships in a two-dimensional biplot.

To identify the key factors influencing food security and its relation to these SDGs, a three-step food security analysis was conducted. First, relevant indicators were chosen based on prior research and categorized under established food security pillars and the targeted SDGs.

Next, PCA identified the most influential components within the data and assessed the importance of individual variable-factor relationships. Finally, Partial Least Squares Regression (PLSR) tested the impact of these variables on two key factors derived from PCA, representing food security and the targeted SDGs, respectively. This approach allowed for a comprehensive analysis of both the factors influencing food security and their connection to achieving the relevant SDGs. PAST software (Hammer & Harper, 2001) was used for all PCA calculations.

Several studies (Chatterjee et al., 2021; Ibukun & Adebayo, 2021; Lamichhane et al., 2021; Odhiambo et al., 2021; Suantika et al., 2020; Vysochyna et al., 2020; Yao et al., 2020) utilized principal component analysis (PCA) and partial least squares regression (PLSR) to assess the influence of food security and sustainable development goals (SDGs) under various conditions. The analysis employed Tanagra 1.4.50 software (Rakotomalala, 2005). To guarantee the generalizability of the models, a cross-validation technique was implemented, splitting the data into 75% for training and 25% for testing. The models' performance was assessed using R-squared change and Root Mean Squared Error (RMSE).

In order to assess how sustainable development influences food security, a specific set of indicators was selected. The table (Table 8) summarizes these relevant indicators for various aspects (accessibility, availability, quality, stability, and Sustainable Development Goals) of food security in the listed European Union countries. The table also provides details like the timeframe (2012-2019), data sources, abbreviations used, and explanations for how each indicator is measured.

Table 8: Measurement of variables for assessing food security in the context of sustainable development

Pillar		Period	Indicator	Source*	PCA component	Abbreviation	Measurement	Previous Literature
Food security block (Y) /dependent variables/	Food accessibility	2012-2018	Gross Domestic Product (GDP) per capita	EIU	PC1	gdppercapita	US$ at PPP** per capita	(Campi et al., 2021; Marino & Pariso, 2020)
		2012-2018	Road infrastructure	EIU	PC4	roadinfra	Score (0-4) 4 = best	(STEWART, 2003; Wenban-Smith et al., 2016)

		2012-2018	Port infrastructure	EIU	PC1	portinfra	Score (0-4) 4 = best	(STEWART, 2003; UN, 2020b)
		2012-2018	Rail infrastructure	EIU	PC1	railinfra	Score (0-4) 4 = best	(STEWART, 2003)
	Food availability	2012-2018	Urban absorption capacity	EIU	PC2	urbabsorb	GDP (% of real change) - period of urban growth	(Wenban-Smith et al., 2016)
		2012-2018	Volatility of agricultural production	EIU	PC3	volagrprod	Standard Deviation (0-1)	(Campi et al., 2021)
		2012-2018	Political stability	EIU	PC2	polstab	Score (0-100) 100=best	(Campi et al., 2021)
		2012-2018	Food loss	FAO	PC4	foodloss	Waste/supply (ton)	(Bodirsky et al., 2020; UN, 2020b)
	Food quality	2012-2019	Diet diversification	FAO, EIU	PC4	dietdiv	% (Percent)	(Bodirsky et al., 2020; Johnston et al., 2014)
		2012-2019	Protein quality	EIU	PC1	proteinqual	Score (0-100) 100=best	(Campi et al., 2021)
		2012-2019	Average food supply	FAO	PC1	avefoodsupply	Kcal/person/day	(Campi et al., 2021)
	Food stability	2014**-2019	Severe Food Instability	FAO	PC3	foodinst	% of the total population	(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018a)
		2012-2017**	Safe Drinking Water	FAO	PC3	safedrink	% of the total population	(Young et al., 2021)
		2012-2016**	Prevalence of Obesity	FAO	PC3	prevobesity	% in population (above 17 years)	(Bodirsky et al., 2020)
Sustainable Development Goals block (X)/ independent variables/	SDG 2 and SDG 12	2012-2018	Public expenditure on agricultural R&D	EUROSTAT	PC3	Agric R & D	Score (1-9) 9 = highest	(Campi et al., 2021)
		2012-2019	Agricultural Factor Income	EUROSTAT	PC1	AFI	% (2010=100 %)	(European Commission, 2019)
		2012-2019	Poverty proportion	EIU	PC2	povprop	% under global poverty line ($3.2/day)	(Intergovernmental Science-Policy Platform on Biodiversity and

								Ecosystem Services, 2018a)
		2012-2019	the area under organic farming	EUROSTAT	PC2	orgfarm	% of the total utilized agricultural area	(de Backer et al., 2009; Rounsevell, M.; Fischer, M.; Rando, A. T. M.; Mader, 2018)
		2012-2017**	Ammonia emission from agriculture	EUROSTAT	PC1	ammemis	tonne	(de Backer et al., 2009)
		2012-2018**	Harmonised risk indicator for pesticides	EUROSTAT	PC2	HRI1	% (2011-2013 average =100%)	(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018a)
		2014-2017**	Rate of obesity	EUROSTAT	PC4	obesity	%	(Bodirsky et al., 2020)

[1] *Notes: * EIU: Economist Intelligence Units* (European Intelligence Units, 2021)*; EUROSTAT: Statistical Office of the European Union* (Eurostat, 2020b)*; FAO: Food and Agricultural Organization* (FAO, 2020)*; **: missing data were estimated from OLS regression.*

This study examines how sustainable development practices influence a nation's food security. It focuses on Sustainable Development Goals (SDGs) 2 and 12, creating a framework to analyze food security and sustainable development together.

Three key aspects were used to evaluate food security: affordability (FAF), accessibility (FAC), and quality (FQ). Affordability considers a country's economic ability to buy food during both stable and volatile times, including factors like income and food spending. It also analyzes how import tariffs and reliance on external sources affect vulnerability to price changes.

Accessibility assesses the physical availability and ease of access to food. It considers the adequacy of food supply, potential disruptions, infrastructure for agricultural productivity, local solutions for distribution and loss reduction, and political stability.

Finally, food quality examines the nutritional value and variety of typical diets, focusing on factors like energy intake, nutrient consumption, and food diversity. This dimension is referred to as "food utilization" due to its emphasis on individual dietary needs.

These food security pillars demonstrably support the broader environmental objectives outlined in the UN's 2030 Agenda for Sustainable Development. They directly contribute to goals like monitoring sustainable food production, ensuring access to clean and affordable energy, and minimizing the environmental impact of urbanization. Additionally, they promote the conservation of marine areas and biodiversity protection.

To ensure a robust evaluation of their model, they employed a cross-validation technique to divide the data into training and testing sets. In this approach, two years of data (25%) from each country were randomly selected for the testing set, while the remaining data (75%) comprised the training set.

Building on this foundation, the second study (**energy security**) focused on energy production and consumption data from 2010 to 2021. Here, the researchers utilized a Trend and Comparative Analysis approach to gain a comprehensive understanding of energy security dynamics over the past decade. This rigorous approach involved a Trend Analysis of energy in eight EU countries. Specifically, they delved into the electricity landscape using World Bank (WB) data on both electricity demand and generation. To effectively represent and analyze this data, the researchers employed various mathematical tools and visualizations.

First, key variable (D_{ij}) was electricity demand for country i in year j defined. Here G_{ij} was electricity generation for country i in year j. The number of countries was represented by n (here, n = 8). Afterwards, summary statistics were utilized to gain insight into each country's electric energy profile.

The following formula was used for the summary statistics:

$$\overline{D}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} D_{ij}$$

Mean electricity demand was denoted by $\overline{D}_i$. Average demand for each country was calculated by summing demand across all years (N_i) and this was divided by the number of years. Hence, the standard deviation of electricity demand can be calculated as follows:

$$\sigma_{Di} = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}\left(D_{ij} - \overline{D}_i\right)^2},$$

where σ_{Di} indicates deviation of demand around the mean. Minimum ($D_{min,i}$) and maximum electricity demand ($D_{max,i}$) defined the range of demand for each country. Similar calculations were applied to statistics for electricity generation (G_{ij}), where minimum and maximum electricity generation was denoted by $G_{min,i}$ and $G_{max,i}$.

Finally, to understand the data clearly $Bar\ Plot(i) = \overline{D}_i\ and\ \overline{G}_i$ were created for each country, displaying both the mean electricity demand $\overline{D}_i$ and generation $\overline{G}_i$. This allowed for quick comparisons and identification of potential trends across all countries.

By combining mathematical expressions with clear visualizations, this analysis provided a comprehensive understanding of the electricity demand and generation landscape within the selected EU countries. In addition, to create the trend lines for the examination of the energy consumption trend in eight EU nations using data from various sources the following mathematical formulas and equations were used:

For each energy source j in the dataset, a linear trend line was fitted using the ordinary least squares regression method. This resulted in the following linear equation:

$$y = mx + b$$

The normalized energy consumption is denoted by y, x denotes the year, m denotes the slope, indicating the rate of change (positive for an increase and negative for a decrease) in consumption over time, and b represents the baseline level of consumption. Trend lines can provide insight into the direction and magnitude of energy consumption shifts.

A Comparative Analysis of renewable energy consumption across countries provided an insightful view of the EU energy landscape. This approach involves calculating the percentage of consumption for different renewable sources (e.g., solar, wind) in each nation. Comparing these percentages across regions reveals the relative contributions of each source, highlighting areas with potential for further development. This comparison allows policymakers to identify opportunities to diversify their energy mix and prioritize investments in sectors with the greatest growth potential.

The calculations of the total consumption for each type of renewable energy across all countries were as follows:

- Total Renewables Consumption = ∑ (Renewables Consumption for each country)
- Total Solar Consumption = ∑ (Solar Consumption for each country)
- Total Wind Consumption = ∑ (Wind Consumption for each country)

The Comparative Analysis can be represented by the following equations:

Percentage of Renewables Consumption =

$$\frac{\text{Total Renewables Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}} X\ 100\%$$

Percentage of Solar Consumption =

$$\frac{\text{Total Solar Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}} X\ 100\%$$

Percentage of Wind Consumption =

$$\frac{\text{Total Wind Consumption}}{\text{Total Renewables Consumption} + \text{Total Solar Consumption} + \text{Total Wind Consumption}} X\ 100\%$$

This robust mathematical framework, underpinned by a tailored set of equations, enabled a comprehensive assessment of fossil and renewable energy consumption throughout selected European countries. Applying this model to real-world data highlighted the substantial contributions of renewable energy to the energy mix of eight EU nations. Matlab R2023b provided the computational power to perform these insightful calculations.

To understand how food and energy production and consumption affect the environment, **Study 3 (environmental security)** focused on the combined environmental and climate change effects of major carbon dioxide (CO_2) emitters from different sectors. Data for this study was sourced from the official database of the Food and Agriculture Organization of the United Nations (FAO) between 2010 and 2021(FAOSTAT, 2021).

In the Temporal Trend Analysis, the dataset was grouped by year to facilitate the analysis. The mean values for each variable were calculated for each year, providing a snapshot of the average emissions levels over the entire dataset. Temporal trends were visualized through line plots, allowing for a clear depiction of how emissions from different variables evolved over a specified timeframe. The formula used in the analysis was as follows:

$$Average_{V_i}(t) = \frac{1}{N_j}\sum_{j=1}^{N_j} D_{ijt}$$

Here V_i represents the emissions from eight different variables, for example, On-firm energy use, Agrifood systems waste disposal. The emission value is represented by D_{ijt} for variable V_i. The number of countries is denoted by N_j and t indicates the year. The X-axis represents the year from 2010 to 2021. The Y-axis represents the average emission value ($Average_{V_i}(t)$) for variable V_i in the *t-th* year. If the trend was upward then $Average_{V_i}(t)$ increased over the years, this indicated a positive temporal trend. The downward trend was indicated by a decreasing $Average_{V_i}(t)$ value and it indicated a negative temporal trend.

To understand the sources of greenhouse gas emissions in the European Union, a sectoral analysis was conducted. Emissions were categorized (e.g., energy, industry, agriculture), and their contributions were quantified by summing emissions across EU countries. Percentages were calculated to show each sector's proportional share of the total emissions. A pie chart visually depicted the distribution, aiding in identifying dominant contributors. This analysis helps identify key sectors for targeted emission reduction strategies, ultimately contributing to a cleaner EU.

$$Total\ EmissionsV_i = \sum_{j=1}^{N} D_{ij}$$

Here, V_i represents emission from food production, process, and consumption stages. N represents the total number of countries and D_{ij} represents the CO_2 emission value for each country. The emission value was transformed into a percentage using the following formula:

$$PercentageV_i = \frac{Total\ EmissionsV_i}{Total\ Emissions} X\ 100$$

While the total emissions data provided a comprehensive picture, converting it into percentages offered a clearer understanding of emission rates across different countries. This analysis was facilitated by the Matlab (version R2023b) software package.

Moving on to **Study 4 (FEE security)**, which focused on Food, Energy, and Environment (FEE) security, the chosen variables underwent thorough empirical testing to confirm their impact on selected EU countries' FEE security levels. This approach was informed by the insights gleaned from previous empirical studies. This study delves into the intricate connections between food security, energy use, and climate change. To achieve this, Multifactor Analysis (MFA) was employed to examine a broad spectrum of variables. MFA, a technique pioneered by Thurstone (1931) and further developed by Escofier & Pages (1994), is particularly adept at analyzing sets of correlated variables that can be naturally grouped. Its strength lies in its ability to handle complex relationships within and between these categories of variables.

As the next section details, selecting the appropriate variables for analyzing food, energy, and environmental security necessitates a meticulous approach, considering the intricate interconnectedness and potential trade-offs among these crucial domains, as shown in Table 9. This comprehensive understanding empowers policymakers, researchers, and practitioners to develop holistic solutions for effectively tackling the interwoven challenges of food, energy, and environmental security (Tötösy, 2002). While geographically a single continent, Europe is often divided into Western and Eastern regions based on historical and political factors (Kłoczowski, 2004).

The Visegrád Group (V4), comprising the Czech Republic, Hungary, Poland, and Slovakia, stands as a pivotal alliance within Central Europe. These four nations, along with Austria, Belgium, Germany, the Netherlands, and Switzerland, often find themselves grouped together due to their intertwined economic ties and shared concerns. This shared analysis was founded on the close economic connections and similar interests these countries share.

Table 9: Explanations of indicators for food security, energy utilization, and climate change

Pillar	Period	Indicator	Source*	Abbreviation	Measurement
Climate change	2012-2017	Air pollution	W.B.	air_pollution	Micrograms per cubic meter
	2012-2018	CO_2 emission (Cropland)	W.B., FAO	co2_crop	Gigagrams
	2012-2018	CO_2 emission (Grassland)	W.B., FAO	co2_grass	Gigagrams
	2017-2018	Soil erosion	HWSD	soil_erosion	Score (1-4) 1 = best
	2017-2018	Forest area	W.B.	forest_change	% of the total land
	2012-2018	Temperature rise	EIU	temperature_rise	Score 0 = least vulnerable
Energy usage	2012-2015	Energy intensity level	W.B.	energy_int_level	Megajoule at PPP** GDP
	2012-2018	Renewable electricity output	EUROSTAT	ren_electric_output	% of total output

	2012-2018	Renewable energy consumption	EUROSTAT	ren_energy_cons	% of the final energy
	2012-2018	Final energy consumption from biomass and renewable waste	EUROSTAT	final_energy_cons	Thousand tons of oil equivalent
Food affordability (FAF)	2012-2018	Food consumption as a share of household expenditure	W.B.	food_consump	% of total household expenditure
	2012-2018	Gross Domestic Product (GDP) per capita	EIU	gdp_per_capita	US$ at PPP** per capita
	2012-2018	Agricultural import tariffs	WTO	agr_imp_tarif	% (Percent)
	2012-2018	Food import dependency	FAO	food_imp_depend	% (Percent)
Food accessibility (FAC)	2012-2018	Average food supply	FAO	food_supply	Kcal/person/day
	2012-2018	Volatility of agricultural production	EIU	agr_prod_vol	Standard Deviation (0-1)
	2012-2018	Urban absorption capacity	EIU	urban_absorb	GDP (% of real change) - period of urban growth
	2012-2018	Population growth	W.B., EIU	population_growth	% (Percent)
	2012-2018	Road infrastructure	EIU	road_infra	Score (0-4) 4 = best
	2012-2018	Port infrastructure	EIU	port_infra	Score (0-4) 4 = best

	2012-2018	Political stability	EIU	pol_stab	Score (0-100) 100=best
	2012-2018	Public expenditure on agricultural R&D	EIU	pub_exp_agrrd	Score (1-9) 9 = highest
	2012-2018	Food loss	FAO	food_loss	Waste/supply (ton)
Food quality (FQ)	2012-2018	Diet diversification	FAO, EIU	diet_divers	% (Percent)
	2012-2018	Dietary availability of vegetal iron	FAO	diet_veg_iron	Mg/person/day
	2012-2018	Dietary availability of animal iron	FAO	diet_anim_iron	Mg/person/day
	2012-2018	Protein quality	EIU	protein_qual	Score (0-100) 100=best

[1] *Notes: * EIU: Economist Intelligence Units* (European Intelligence Units, 2021)*; EUROSTAT: Statistical Office of the European Union* (Eurostat 2020)*; FAO: Food and Agricultural Organization; HWSD: Harmonized World Soil Database; WB.: World Bank* (The World Bank, 2020)*; WTO: World Trade Organization* (WTO, 2020). ***: Purchasing Power Parity.*

Multifactor analysis (MFA) utilizes a two-step approach for data exploration and visualization. In the first stage, each data block, represented as a rectangular matrix with dimensions (I x J), where I denote the number of observations and J denotes the number of variables, undergoes Principal Component Analysis (PCA). This analysis aimed to identify underlying patterns within each block. Subsequently, the information extracted from each PCA is normalized using the square root of its first eigenvalue, ensuring data comparability across different blocks (Abdi et al., 2013).

The second stage involved performing a global PCA on the normalized data. This final step allowed visualization of observations in a lower-dimensional space, typically two-dimensional (2D), with factor scores representing the coordinates of each observation.

In this specific investigation, five (T)datasets, referred to as "blocks," were analyzed. Each block comprised a rectangular data matrix denoted by $(I \times J[t])$, where I represents the number of observations and $J[t]$ represents the number of variables in the t-th block. All data matrices were preprocessed by centering and normalizing, denoted by $X[t]$. Additionally, each observation was assigned a "mass," reflecting its importance and directly proportional to its weight. This information was stored in a diagonal matrix M with dimensions $(I\ x\ I)$. Merging the normalized blocks resulted in a new, combined data matrix, denoted by Z $(I \times T)$, referred to as the global data matrix (Escofier & Pages, 1994).

The singular value decomposition of the global data matrix Z is then estimated using a standard PCA.

$$Z = U\Delta VT\ with\ UTU = VTV = I,$$

In singular value decomposition (SVD) of matrix Z, the diagonal matrix containing the singular values is denoted by Δ, while U and V represent the left and right singular vectors, respectively. The formula for calculating global (F) factor scores can then be expressed as:

$$F = M - 1/2U\Delta,$$

Where each horizontal row represents a single observation, and each vertical column represents a specific characteristic or measurement of that observation. This is a common way to organize data, allowing for easy comparison and analysis of different observations across various aspects.

While the Multiple Factor Analysis (MFA) method balances variable distribution across groups, its true strength lies in its ability to reveal unique insights and hidden structures within the data. Unlike individual studies, MFA meticulously organizes variables, leading to powerful visualization and the identification of novel factors. This method not only uncovers these factors but also excels at graphically depicting observations and their connections, allowing researchers to identify distinct clusters within the data (Pagés & Husson, 2005). MFA excels when tackling large and complex datasets with numerous variables and observations, creating a unified model that reveals relationships between observations and different data groups (Pagès, 2014). For this analysis, FactoMiner, an R package dedicated to Multivariate Analysis (Husson et al., 2008), was utilized.

3.2. Analytical procedures

Effective data analysis acted as a strategic cornerstone for research, uncovering the data's nature and outlining methods for its collection, evaluation, and interpretation. This ensured the study's significance and impact.

Analyzing historical data was crucial for understanding long-term trends and predicting their future implications on critical issues like food security, allowing us to proactively address challenges and achieve the Sustainable Development Goals (SDGs).

A range of software tools was employed to analyze the data presented in Table 10 below.

Table 10: Methodological approaches for data analysis

SL No.	Research objectives	Data analysis strategy	Software Used for Analysis
1.	To explore food production, consumption, and DMC efficiency for sustainable food security.	▪ Multiple Factor Analysis (MFA) ▪ Principal Component Analysis (PCA)	PAST and R
2.	To evaluate SDG indicator impact on sustainable food security.	▪ Global space and partial analysis ▪ Partial Least Squares regression (PLSR)	R and Tanagra
3.	To analyse and understand the diverse trends and patterns in the EU energy mix.	▪ Trend Analysis ▪ Comparative Analysis	Matlab
4.	To analyse CO_2 emission trends and identify key factors to develop effective mitigation plans.	▪ Temporal trend analysis ▪ Sectoral Analysis	Matlab

Source: Author's compilation

4. ANALYSIS AND RESULTS

4.1. Food security (Study 1)

The traditional focus on food security in the EU's food system is facing a paradigm shift, driven by concerns about environmental sustainability. EU Commissioner Virginijus Sinkevičius highlighted this shift and emphasized the need to prioritize climate change, resource conservation, and biodiversity alongside ensuring food availability.

The current system faces complex challenges: food waste, overconsumption, obesity, and a significant environmental footprint, as outlined by Fortuna, (2020). While the agriculture, manufacturing, and food & beverage sectors contribute roughly €7 trillion annually, they are heavily reliant on natural resources. Additionally, unhealthy diets were responsible for nearly 1 million deaths in the EU in 2017 (EC, 2020; EU, 2021).

Study 1 (food security) aimed to identify efficient Domestic Material Consumption (DMC) patterns and use in select EU countries, contributing to sustainable food security in line with SDGs. It utilized a model comprising key SDG indicators impacting food security, analyzing their relationships with PLSR.

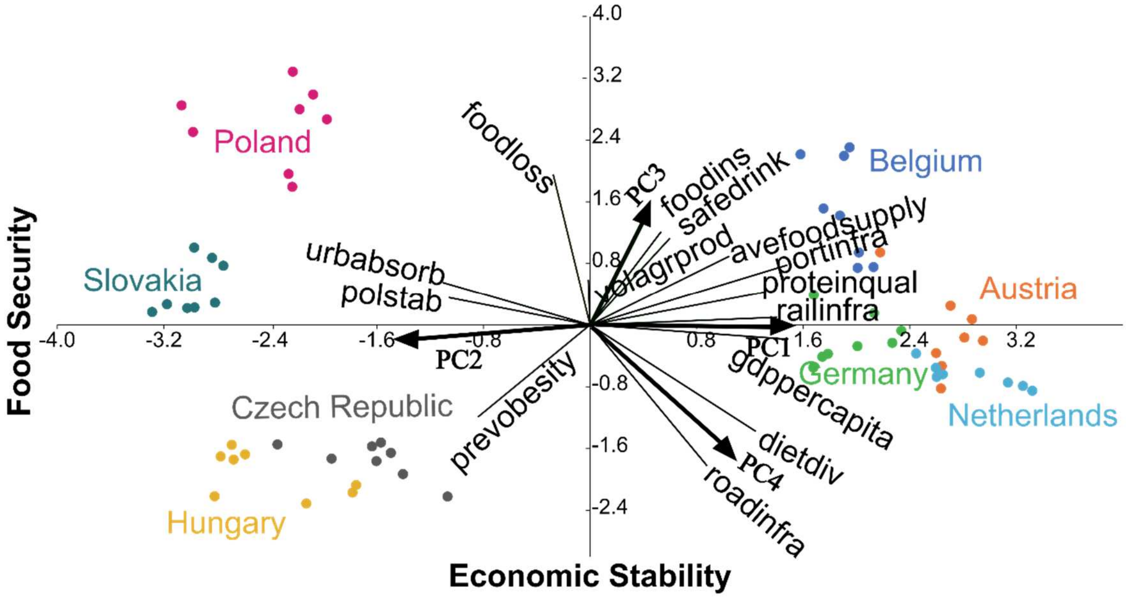

Figure 2: Exploring food security: insights from PCA analysis of block (Y).

Note: arrows represent the four PCs. Source: Authors' calculation

The model comprised two blocks: "SDGs" (*X* matrix) and "food security" (*Y* matrix). Prior to analyzing their interaction, PCA was applied to each block independently, revealing their internal structures. A two-dimensional biplot visualized both the PCs and individual country scores.

The study analysed the food security landscape of eight EU countries using PCA. The first four components explained 60% of the variance. Component 1 (PC1), accounting for 36%, linked port and rail infrastructure, GDP, and protein quality. PC2 (9%) was associated with urbanization, political stability, and obesity prevalence. PC3 (5%) was tied to agricultural volatility, food instability, and obesity. Lastly, PC4 (10%) was connected to dietary diversity, road infrastructure, and food loss.

Higher GDP nations like Germany, Austria, and the Netherlands exhibited strong PC1 influence. However, global factors like rising meat consumption, urbanization, and unhealthy FAF pose challenges. Urbanization, linked to PC2, disrupts healthy dietary patterns, and increases obesity (Kearney, 2010). Hungary and the Czech Republic exemplify this, displaying higher obesity rates associated with lower FAC and FQ.

Austria, Belgium, and Germany showcase strong PC1 influence, indicating dependence on food supply, protein quality, water safety, and port infrastructure. These countries boast lower agricultural volatility and food instability. Notably, urban areas concentrate environmental consequences of food production, impacting food safety. The EU prioritizes sustainable systems to minimize health costs from unhealthy diets. Diet diversity, tied to PC4, significantly impacts EU citizens' health, but only 10% of the variance suggests limited access to diverse foods for some, leading to potential nutrient deficiencies.

Poland and Slovakia face unique issues reflected in their low PC2 scores. Limited urban absorption capacity and political instability hinder their ability to ensure food security under urban stress. Further analysis (Figure 3) would provide deeper insights into these specific challenges.

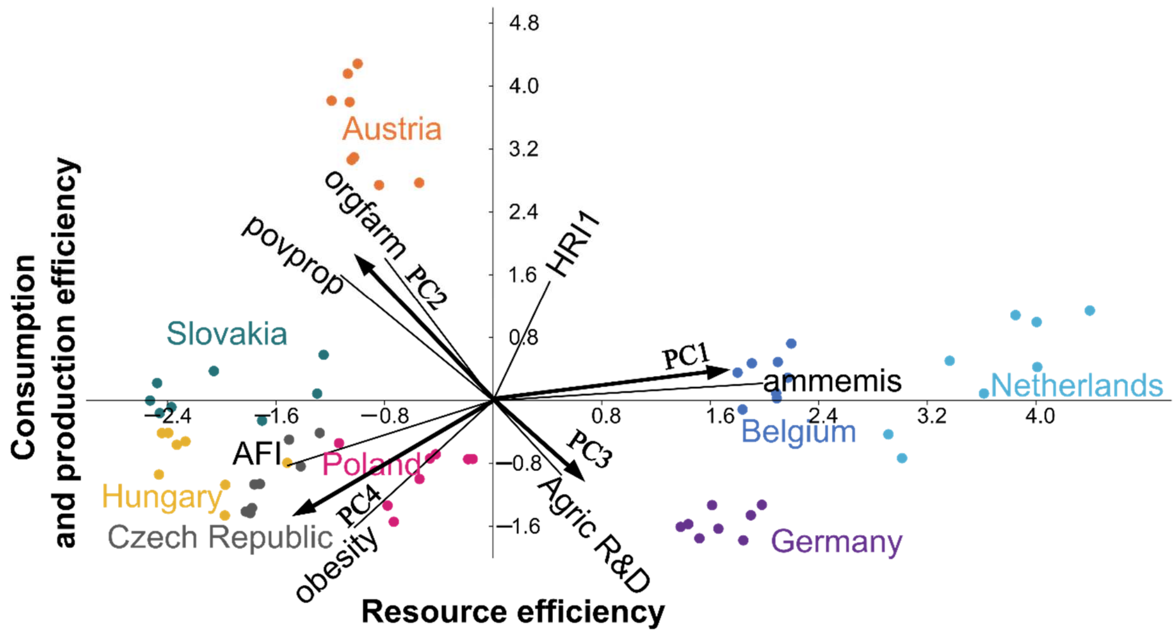

Figure 3: Exploring SDG 2 and 12: insights from PCA analysis of block (X).

Note: arrows represent the four PCs. Source: Authors' calculation

Resource Consumption and Emissions accounted for 37% of the variance in Figure 3's PCA. Agricultural Factor Income (AFI) negatively impacted sustainability by elevating DMC. Ammonia emissions (NH3) were notably high in developed EU countries, indicative of suboptimal manure management and excessive fertilizer application. Conversely, circular material uses rate (circularmat) positively affected sustainability by diminishing reliance on virgin resources (HLPE, 2020b).

The second PC revealed that factors like renewable energy use and poverty levels significantly influence each other, explaining 22% of the observed variations organic farming, prevalent in Austria and Slovakia, potentially contributes to diminished environmental impact. Austria and Slovakia exhibit higher adoption rates of renewable energy consumption, possibly mitigating climate change and resource depletion. Conversely, a higher poverty proportion in Slovakia underscores the necessity for equitable resource access (Reisch et al., 2013).

The third PC revealed that Research & Development and Waste Management explained an 18% variance. Higher agricultural research & development (R&D) spending in Germany, Netherlands, and Belgium suggested potential for innovation and efficiency enhancements. Meanwhile, increasing recycling rates in these countries contribute to circularity.

Obesity and health factors jointly contributed to 6% of the variation captured by the fourth PC. Obesity rates are lower in V4 countries (Hungary, Poland, Czech Republic, Slovakia) compared to other EU countries, potentially attributable to diverse dietary patterns. Nonetheless, malnutrition remains a concern in V4 countries, emphasizing the necessity for improved nutrition education and access to wholesome food (Reisch et al., 2013).

The escalating DMC across most EU countries raises apprehensions regarding sustainable food security. Heightened ammonia emissions, particularly in developed nations, necessitate enhanced manure management and fertilizer practices. Global surges in obesity rates pose a threat to SDG 2 (Zero Hunger) due to shifts in dietary habits.

Encourage sustainable agricultural practices aimed at diminishing resource consumption and emissions. Augment investment in renewable energy sources and organic farming. Enhance waste management strategies and resource recuperation efforts. Tackle malnutrition and advocate for healthy dietary choices to combat obesity.

This analysis discerned critical factors influencing the environmental impact of European agriculture. Addressing these challenges through targeted policies and practices is imperative for fostering sustainable food systems and advancing SDG objectives.

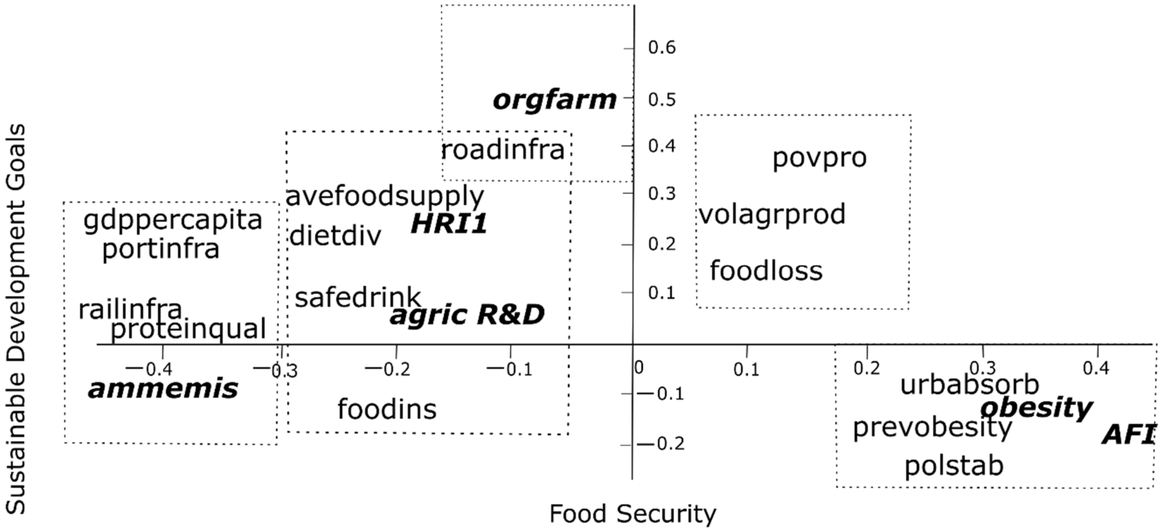

Figure 4: PLS component analysis: examination of weights (W') and loadings (Q') for the initial two components.

Source: Authors' calculation

Examining the individual components of food security and the SDGs block revealed key factors at play (Figures 2 & 3). In the next step, PLSR was used to explore the relationships between these elements (Figure 4). This analysis shed light on how different aspects of food security interact with broader SDG objectives, providing valuable insights for achieving sustainable food systems.

In the analysis of variable importance within the PLSR model, the most influential factors affecting food security in EU countries were identified. These factors, ranked in descending order of significance, were as follows: Domestic Material Consumption (1.34), where higher consumption patterns were associated with reduced food security; AFI (1.26), highlighting the pivotal role of farm profitability in ensuring food availability; Circular Material Use Rate (1.21), indicating that employing recycled materials can mitigate environmental impact and enhance sustainability efforts; Ammonia Emission (1.13), revealing the adverse effects of intensive farming practices on emissions and subsequent impacts on food security; and Obesity (1.07), which despite its apparent paradox, served as a potential indicator of underlying nutritional imbalances. Additionally, less impactful factors encompassed pesticide risk and poverty levels.

Figure 4 illustrated the complex interplay between various indicators contributing to food security and Sustainable Development Goals (SDGs) within EU countries. While agricultural production volatility exhibited weaker direct correlations with food security and SDGs, it can still contribute to food loss and heightened poverty.

Urbanization (urbabsorb) and political stability were associated with obesity rates, with more developed economies experiencing higher levels due to stable political environments and greater capacity to provide for increasing urban populations. A shift towards organic farming (orgfarm) practices seems to bolster energy efficiency by balancing renewable inputs against productivity gains, thus enhancing food security.

Furthermore, indicators such as agricultural research and development, waste management practices, and measured pesticide risk (HRI1) were all connected to food quality as defined by dietary diversity and overall food supply. Though factors like severe food instability and access to safe drinking water influenced food stability, their overall impact was less pronounced.

Crucially, food production and consumption processes demonstrated strong ties to agricultural R&D (agri R&D), waste management (waste), dietary diversity, average food supply, and safe drinking water. This strong correlation ($r=0.612$; $p<0.001$) suggested that sustainable practices in both production and consumption have a net positive effect on both SDGs and food security, lending support to the first hypothesis.

Finally, circular material uses (circularmat) rate and domestic material consumption (DMC) influenced food availability and consumption, while additionally being linked to ammonia emissions. Higher domestic material consumption can lead to increased emissions, whereas promoting circular material use offers the potential to mitigate them. Figure 4 specifically identified domestic material consumption (with the highest VIP score of 1.34) as the most impactful factor in determining both food security and the attainment of SDGs across EU countries. This strong correlation ($r=0.935$; $p<0.001$) supported the second hypothesis.

Table 11: Relative Root Mean Square Error (RMSE) as a percentage of the mean for dependent variables

Variables	Test	Train	Orig
volagrprod	26.84%	38.51%	36.30%
urbabsorb	51.46%	55.53%	54.48%
foodloss	31.32%	22.70%	21.87%
polstab	16.52%	25.71%	24.16%
roadinfra	23.55%	15.22%	15.51%
portinfra	8.04%	10.03%	9.76%
railinfra	8.74%	11.81%	11.23%
gdppercapita	9.39%	7.26%	6.89%

avefoodsupply	5.47%	6.40%	6.13%
proteinqual	6.92%	8.04%	7.87%
dietdiv	5.24%	3.79%	3.73%
severefoodins	40.94%	38.98%	37.92%
safedrinkwater	2.24%	4.94%	4.61%
prevobesity	6.41%	7.38%	7.33%

Source: authors' calculation

The performance of the model was evaluated using cross-validation. Table 11 showed the relative error (RMSE) for each dependent variable, expressed as a percentage of the average value. While some variables such as severe food instability, urban expansion, and agricultural production volatility had higher error rates, the predictions for other variables, particularly accessibility and quality, were considered acceptable. Furthermore, a paired sample t-test revealed no significant difference between the training and testing data. The average difference between predicted and actual values was 0.944, and the statistical test results ($t=-0.635$, $p=0.537$) supported this finding.

4.2. Energy security (Study 2)

4.2.1. EU's Electricity Demand and Production

Across eight EU member states, electricity demand and generation patterns revealed both convergence and divergence over the past decade (2010–2022).

The electricity landscape across several European countries reveals diverse trends. In figure 5. Austria and Belgium witnessed a rise in electricity demand, reaching 74.62 TWh and 87.62 TWh, respectively, compared to previous values. However, domestic generation struggled to keep pace, leading to a significant increase in reliance on imports, jumping from 3 TWh to 10+ TWh for Austria and 5 TWh to 10+ TWh for Belgium.

In contrast, Czechia stands out for its remarkable stability. Both electricity demand (around 70.29 TWh) and domestic generation (around 85 TWh) remained relatively steady, achieving near self-sufficiency in electricity production.

Germany, on the other hand, experienced robust demand growth, exceeding 600 TWh, but faced a decline in domestic generation, dropping to 580 TWh. This resulted in a substantial rise in import dependence, surging from 80 TWh to 130+ TWh.

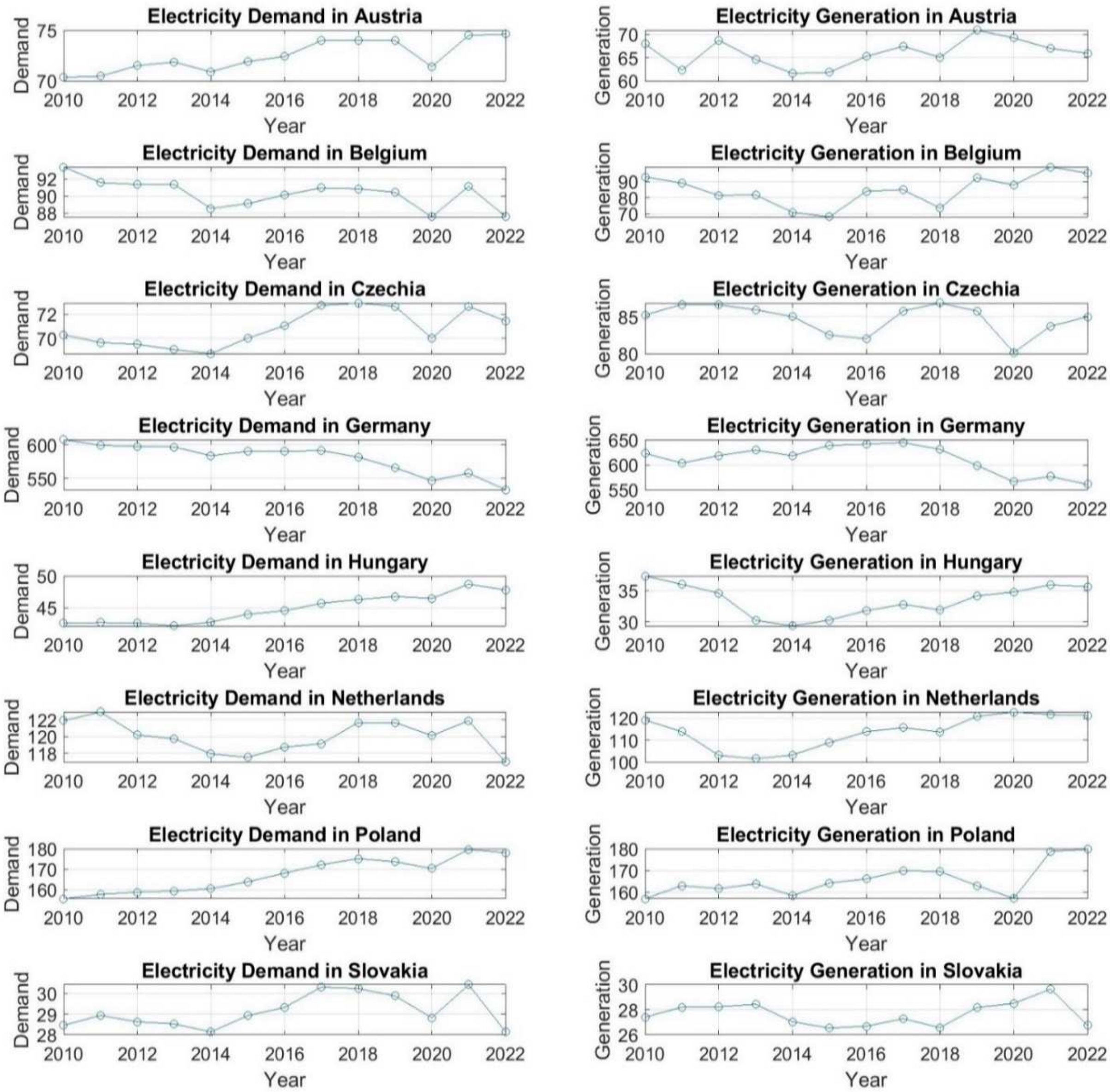

Figure 5: Analysing trends in electricity demand and generation across the selected EU countries. *Note:Terawatt hour (TWh) measures vast amounts of electricity, often used for expressing national or global production/consumption.*

Source: Authors' own compilation.

Hungary presented a unique case, bucking the trend with decreases in both demand (reaching 35 TWh) and domestic generation (dropping to 33 TWh). Consequently, its reliance on imports lessened, decreasing from 5 TWh to 2 TWh.

The Netherlands exhibited a similar pattern to Austria and Belgium. Demand climbed to 120+ TWh, outpacing generation growth (reaching 105 TWh). This led to an increase in import dependence, rising from 10 TWh to 20+ TWh.

Poland's situation mirrored some aspects of Germany's. Demand rose to 180+ TWh, but domestic generation declined to 175 TWh. This fueled a growing dependence on imports, although the exact increase was not specified.

Overall, the electricity sector across these European countries presents a diverse picture, with some experiencing rising demand and increasing reliance on imports, while others maintain relative stability or even see a decrease in import dependence.

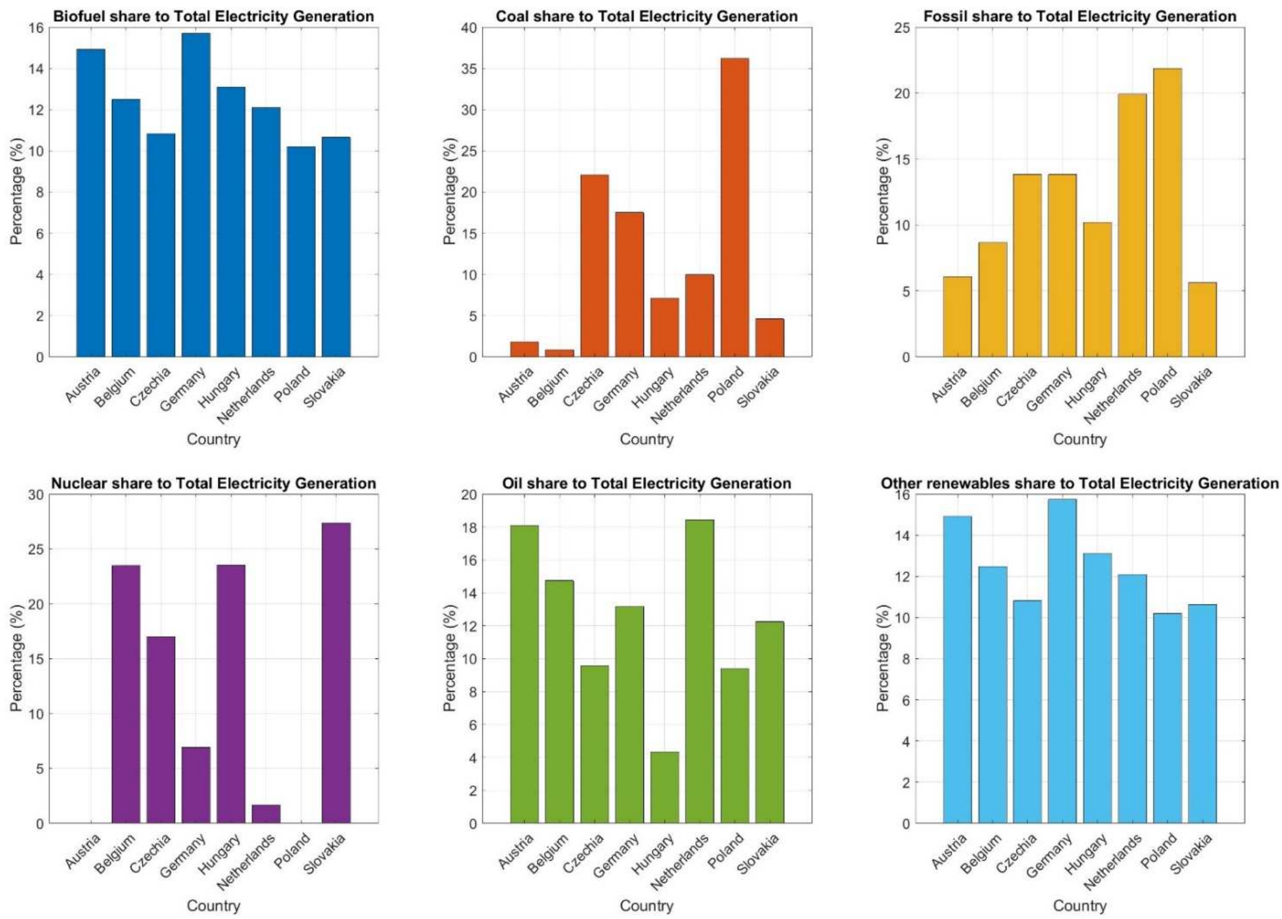

Figure 6: Electricity generation shares across the selected EU countries from various sources.

Source: Authors' own compilation.

These diverse trends highlighted the varying factors influencing electricity markets across the EU. Examining specific drivers behind these changes, such as energy policy shifts, infrastructure development, and fuel mix variations, would offer valuable insights into regional energy security and sustainability.

The bar chart (Figure 6) showed the electricity generation shares of eight EU countries Austria, Belgium, Czechia, Germany, Hungary, Netherlands, Poland, and Slovakia from 2010 to 2022. The share of electricity generation was from various sources (biofuel, coal, electricity, fossil, low-carbon, nuclear, oil, and renewable), and the colour of the bars represented the type of source. The countries were listed on the x-axis, and the years were listed on the y-axis. While most the selected EU countries are transitioning towards renewables and away from fossil fuels, a closer look revealed diverse trajectories. Austria, Belgium, and the Netherlands were leading the charge with significant renewable growth and fossil fuel decline. Germany stood out for achieving the highest renewable rise while reducing both fossil fuels and nuclear. Czechia and Slovakia showed modest progress, while Hungary bucked the trend with rising fossil fuels and stagnant renewables. Poland stood alone with the smallest renewable increase alongside rising fossil fuels.

These diverse trends highlighted a growing preference for renewables across the EU, with varying degrees of progress. Hungary's exceptionality underscored the need for targeted efforts and knowledge sharing to achieve a unified vision of a sustainable European energy future.

The past decade has witnessed a significant shift in the energy landscape of eight analyzed countries. The share of electricity generation from fossil fuels has steadily declined, dropping from an average of 64.4% in 2010 to 40.3% in 2022. This decrease can be attributed to several factors, including rising fossil fuel costs, the growing accessibility of renewable sources, and government policies promoting renewable energy use.

Nuclear power also saw a decrease in its share of electricity generation in most of these countries. The average share fell from 28.2% in 2010 to 19.2% in 2022. This decline can be partly attributed to the Fukushima nuclear disaster in 2011, which led to the closure of numerous nuclear power plants in Europe.

In contrast, the share of electricity generated from renewable sources has seen a remarkable rise across all eight countries. The average share in 2010 was just 7.4%, while in 2022, it had climbed to 39.5%. This surge can be explained by several factors, including the decreasing cost of renewable energy technologies, government policies supporting their adoption, and a growing public awareness of the environmental benefits of renewable energy.

However, across the selected EU countries, the energy landscape displayed diverse sources of electricity generation. Austria and Slovakia relied heavily on hydro and nuclear power, respectively, exceeding 50% of their mix. While Germany boasted the highest share of renewables at over 47%, Poland remained heavily reliant on coal at nearly 70%. Nuclear power played a significant role in Hungary (44%) and Belgium (46%), while natural gas held the top spot in the Netherlands (56%). Czechia stood out with coal as its leading source (43%), but renewables were increasing. Despite differences, a common trend emerged: a gradual shift away from coal and towards renewables, except for Poland, where coal dominance persisted.

The EU sets common targets and directives like 55% emissions reduction goals, aiming for a secure, sustainable, and affordable energy future. However, individual nations possess unique strategies and priorities shaped by specific circumstances, resources, and preferences. For instance, Germany's ambitious "Energiewende" plan contrasts with Poland's reluctance to shift from coal and its opposition to certain EU goals. Limited integration and interconnection across EU energy markets and networks constrained the potential for cross-border collaboration and energy security, leaving countries like Poland and Hungary dependent on single suppliers. Others, like Germany and the Netherlands, benefitted from greater interconnection and diversification.

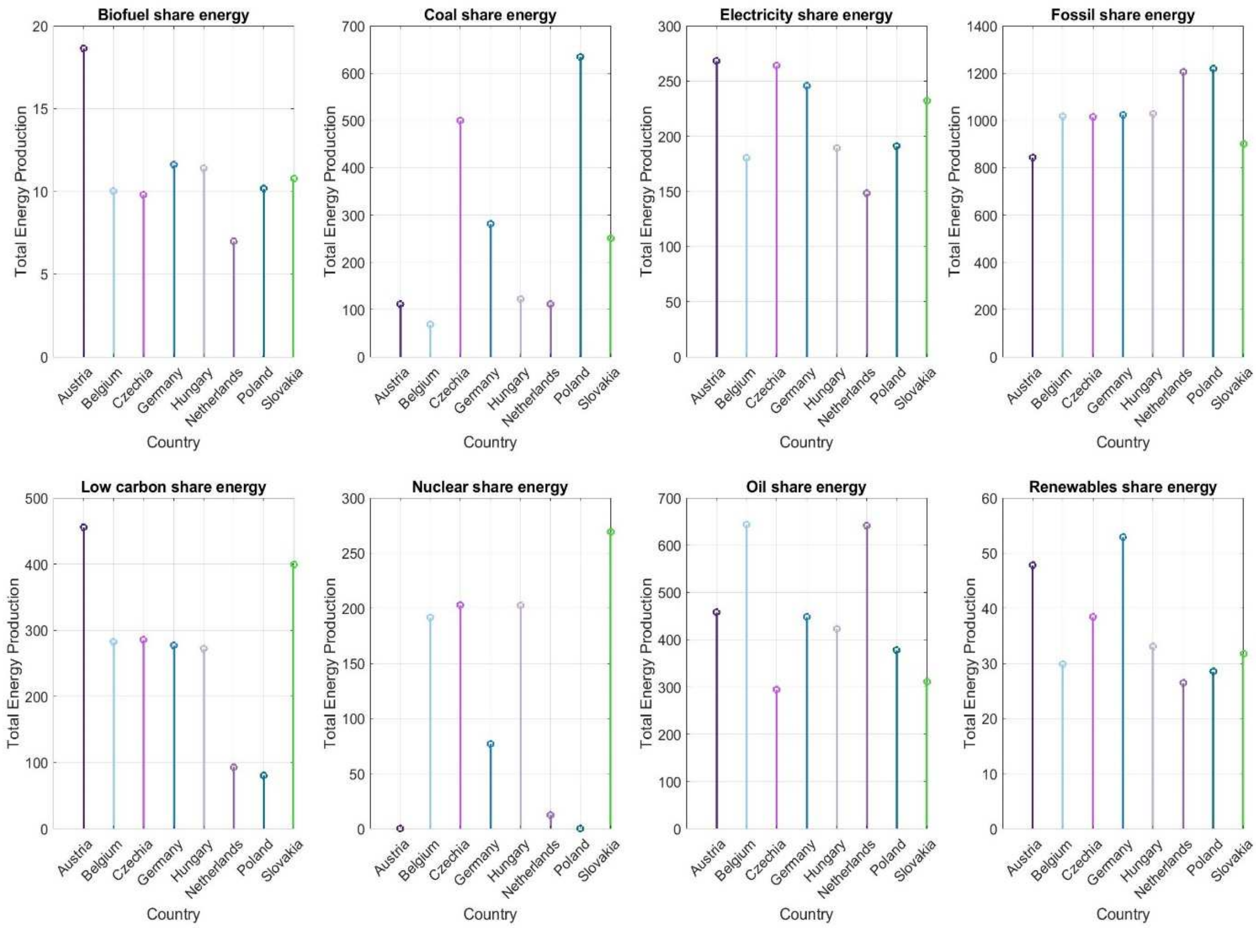

Figure 7: Share of energy generation sources across the selected EU countries

Source: Authors' own compilation.

Lollipop charts (Figure 7) depicted the total energy production across diverse sources (biofuel, coal, gas, hydro, low carbon, nuclear, and oil consumptions) for the selected EU countries between 2010 and 2022. The nations include Austria, Belgium, Czechia, Germany, Hungary, Netherlands, Poland, and Slovakia. Each nation was represented by a distinct colour, with dots depicting production values and lines (lollipops) extending to the horizontal axis. These visualisations revealed compelling trends and patterns in the evolving energy mix of the selected EU countries.

Poland and Germany were leading in coal share, yet Germany boasted the highest renewables, showcasing its transition towards a low-carbon future. In contrast, Poland's low renewables and high fossil fuel dependence suggested vulnerability and a lack of diversification. Czechia and Hungary were relying heavily on nuclear energy, a stable and low-carbon source, but were facing challenges like safety, waste management, and public acceptance. Their limited renewable share restricted further decarbonisation and innovation. Belgium and the Netherlands were the lowest in biofuel, despite their potential for emissions reduction and fossil fuel independence. Their low nuclear share might reflect future phase-out plans. Austria and Slovakia had the highest share of electricity, indicating electrification and system integration, as well as the potential for smart grids and demand-side management. Their high low-carbon share underlined their commitment to climate action and energy security.

The trend analysis (Figure 8) illustrated the energy consumption patterns of the selected EU countries across various sources (biofuel, coal, gas, hydro, low-carbon, nuclear, and oil) from 2010 to 2022. The visualizations revealed intriguing insight into the evolving energy landscape and its implications for demand, supply, and sustainability.

Coal consumption was on the decline. A notable trend was the decreasing coal consumption in most countries, except Poland. The decline in coal use is likely driven by a confluence of factors, including stricter environmental regulations, carbon pricing schemes, government subsidies for renewable energy, and growing public pressure for cleaner energy solutions. While positive, addressing the challenges associated with transitioning coal-dependent communities remains crucial. Biofuel consumption has been on the rise. Austria exhibited a notable increase in biofuel consumption, while other countries saw moderate growth or stability. This suggested a growing appreciation for this renewable and low-carbon fuel, but raised concerns about land use, food security, and biodiversity impacts necessitated responsible expansion strategies.

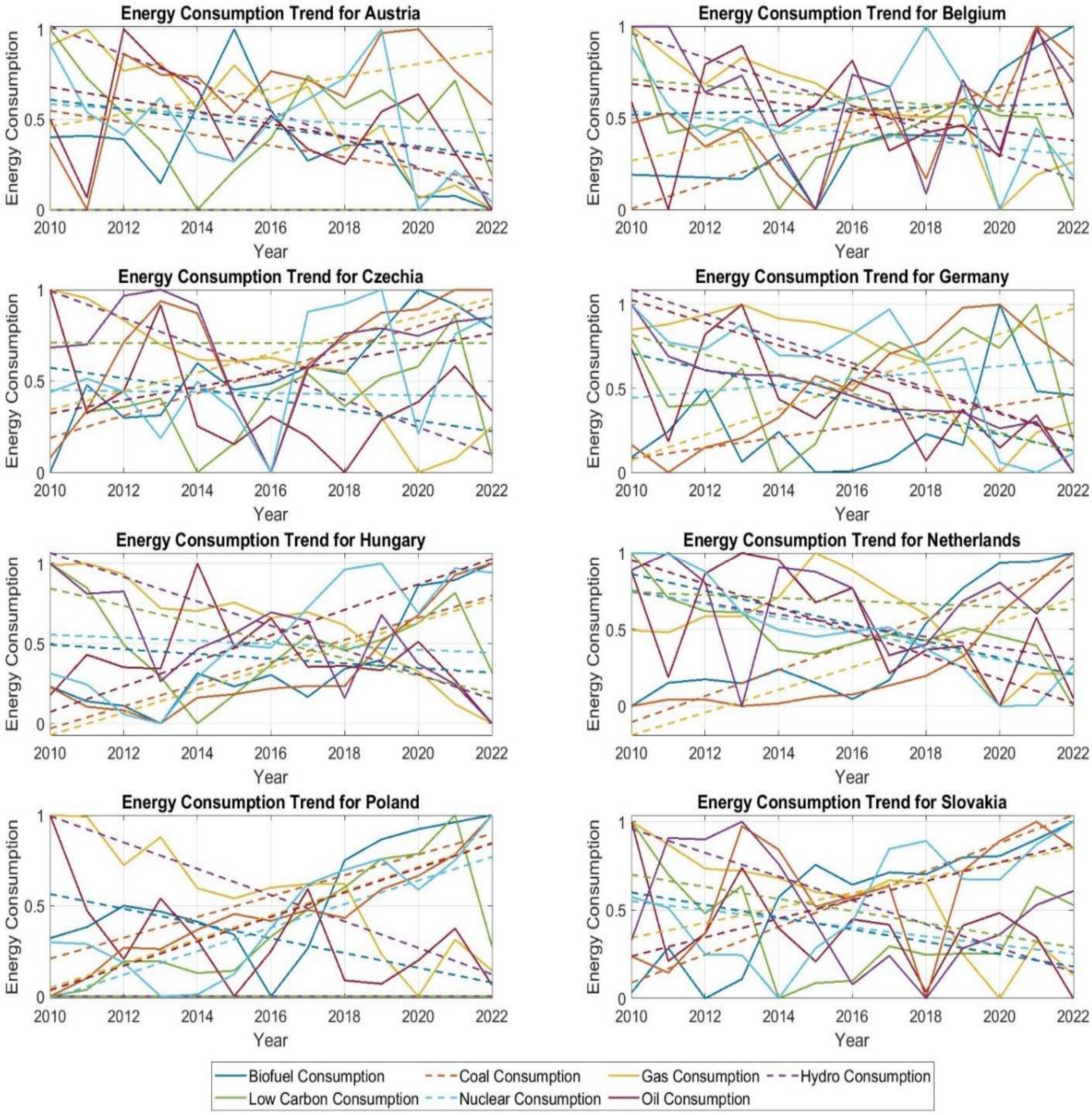

Figure 8: Analysis of energy consumption trends across the selected EU countries

Source: Authors' own compilation.

Gas consumption was a controversial bridge fuel. While often viewed as a transition fuel, gas consumption showed an increasing trend in most countries, except for Germany and the Netherlands. This raised concerns about methane leakage, price volatility, and geopolitical dependencies. Balancing the need for energy security with the urgency of decarbonisation requires careful navigation. Hydropower is stable but has limited potential. Hydrocarbon consumption remained relatively stable across all countries, reflecting the limited potential for expansion. While this renewable source offered reliability and flexibility, environmental and social impacts, water scarcity, and climate vulnerability necessitated thoughtful management.

Low-carbon energy consumption gained momentum. The Netherlands championed significant growth in low-carbon consumption, while others showed stability or slight increases. This demonstrated a commitment to decarbonisation and aligned with EU climate goals. However, recognising the distinct advantages and disadvantages of nuclear and renewable energy sources within this category was crucial for informed policy decisions.

Nuclear power energy consumption was diverging. A noticeable decline in nuclear energy occurred in Germany, while other countries-maintained stability or slight declines, except for Belgium's increasing reliance. This highlighted the ongoing debate around its role in the energy transition, with concerns about safety, waste management, and public acceptance needing careful consideration. Oil consumption had a mixed picture. The oil consumption painted a mixed picture across the selected countries. While economic factors, efficiency improvements, and policies influence demand, its continued use in transport, heating, and other sectors necessitates strategies for responsible reduction and transition.

The visualizations provided a valuable starting point, but further exploration is necessary. Delving deeper into the specific policies, economic factors, and public attitudes influencing these trends offer a more comprehensive understanding of the evolving energy landscape in the EU and illuminate pathways towards a sustainable future.

4.2.2. Renewable energy consumption

Since the Industrial Revolution, population growth and rising living standards have fueled a surge in energy demand (Pham et al., 2020). As economies boom, the need for renewable sources is skyrocketing (Shahbaz et al., 2020). However, traditional fossil fuels like coal, oil, and gas can no longer satisfy this thirst (Hasan et al., 2023). Unsustainable energy consumption across various sectors threatens resource depletion. To address this, the EU has pledged to achieve climate neutrality by 2050, requiring a significant reduction in greenhouse gas emissions. The transformation of the transportation sector's energy sources is seen as a crucial factor in achieving this goal.

The Comparative Analysis explored the global landscape of renewable energy consumption, examining the contributions of various sources like ssolar and wind across different countries. The analysis began by establishing a baseline by assessing the total consumption of each renewable energy source, providing a global and regional perspective on their usage.

Figure 9 revealed that Slovakia led the pack, obtaining the highest percentage of its renewable energy from renewable sources (93.1%), followed by Austria (89.6%) and Czechia (81.3%). On the other end of the spectrum, Poland received the lowest percentage (69.4%), followed by the Netherlands (63.3%) and Germany (63.2%). This data suggests these countries are making significant strides towards adopting renewable energy sources.

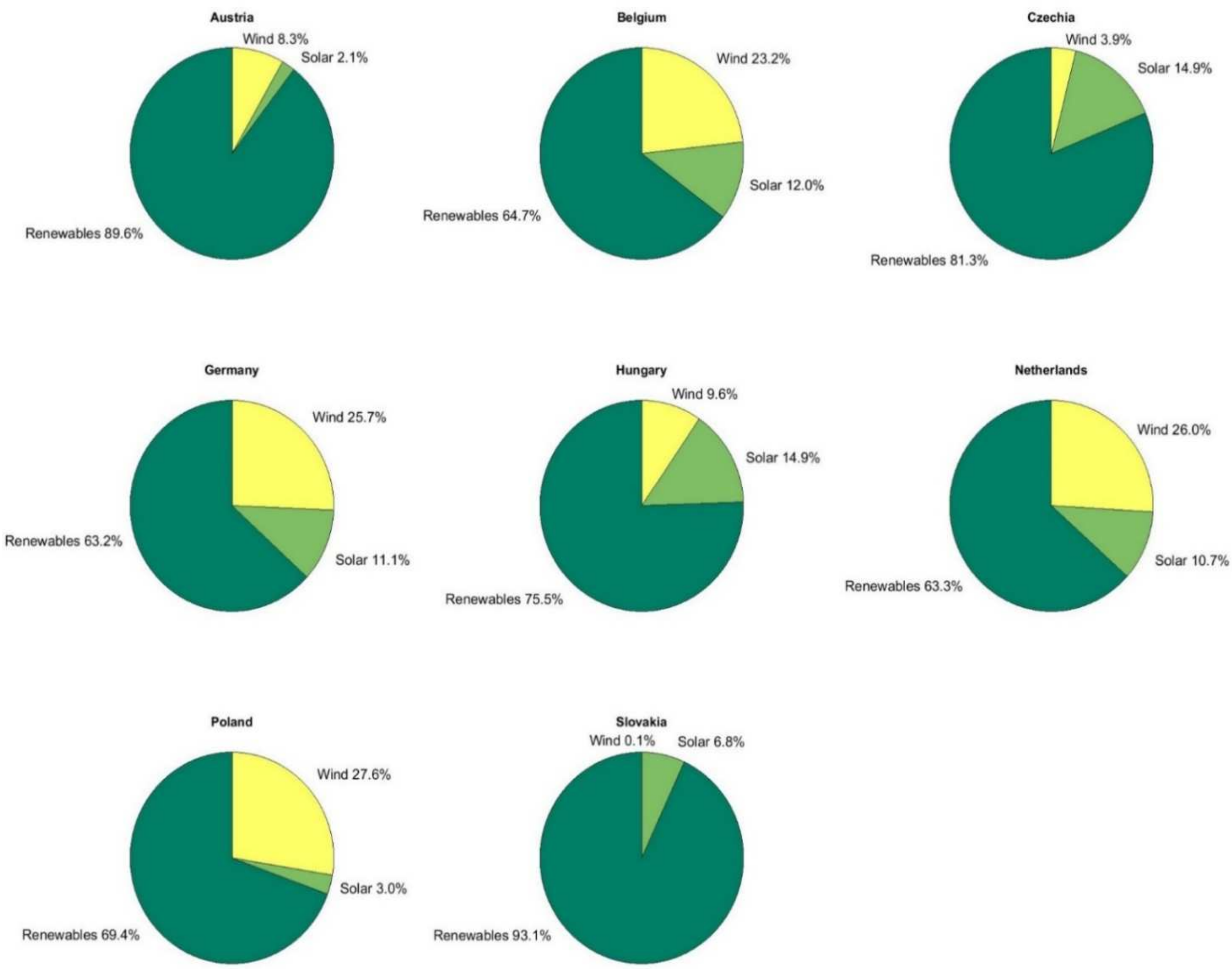

Figure 9: Comparative Analysis of renewable energy consumption across the selected EU countries

Source: Authors' own compilation.

Focusing on wind energy specifically, Hungary emerged as the top user, obtaining the highest percentage of its renewable energy from wind (25.7%). Poland (27.6%) and the Netherlands (26.0%) followed closely behind. Interestingly, Slovakia obtained the lowest percentage (0.1%), followed by Czechia (3.9%) and Austria (8.3%).

Moving on to solar power, Germany held the top spot, with the highest percentage of its renewable energy coming from solar (14.9%). Hungary (11.1%) and Belgium (14.9%) came in second and third, respectively. Slovakia had the lowest percentage (6.8%), followed by Poland (3.0%) and Austria (2.1%).

Based on their renewable energy consumption, the selected countries could be categorized into three groups: high (Slovakia, Austria, Poland), medium (Germany, Hungary, Netherlands), and low (Belgium, Czechia).

This Comparative Analysis provided valuable insights into the current state of renewable energy adoption globally, highlighting the variations across regions and the immense potential for further development. Moreover, it firmly emphasized the critical role of renewable energy as a sustainable solution for addressing energy security, environmental concerns, and mitigating climate change.

4.3. Environmental security (Study 3)

Figure 10 presented the Temporal Analysis of carbon dioxide emissions trends across the selected 8 EU countries from 2010 to 2021.

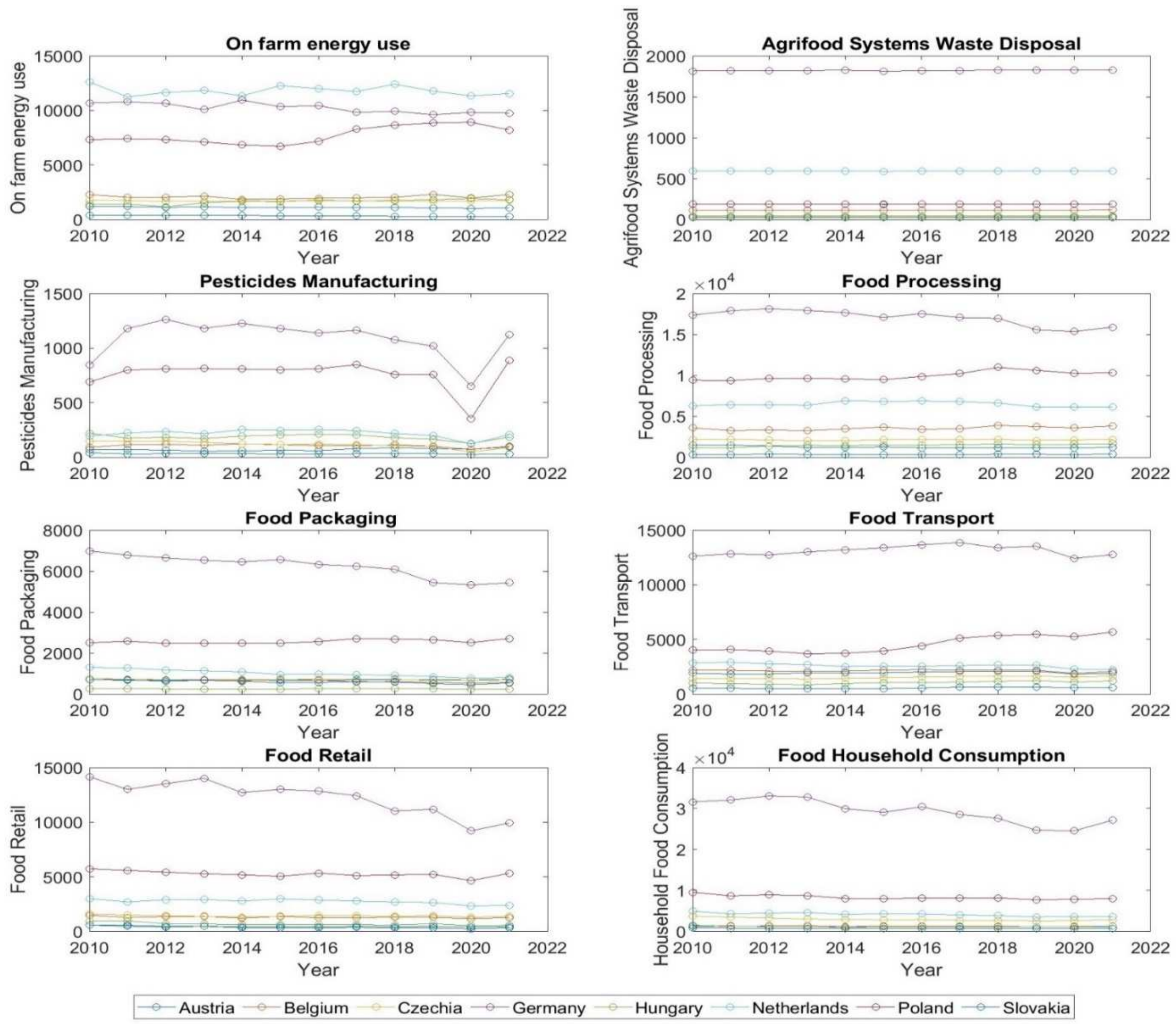

Figure 10: Temporal analysis of carbon dioxide emission trends across the selected EU countries

Source: Authors' own compilation.

The x-axis represented the year, and the y-axis represented the carbon dioxide emissions in kilotons.

While all selected EU countries (Austria, Belgium, Czechia, Germany, Hungary, Netherlands, Poland, and Slovakia) demonstrated reductions in overall emissions, the study identified Germany as the leader, achieving significant declines across several sectors, including on-farm energy use, food processing, packaging, and retail.

However, the findings also highlighted disparities between countries. Hungary saw the most significant decrease in waste disposal emissions, while food transport emissions rose in all nations except Hungary, with the Netherlands experiencing the sharpest rise. Similarly, food consumption witnessed reductions in most countries, with Germany again leading the way with a 20% drop, while Hungary and Poland are behind.

The study attributed the overall decline in emissions to advancements in energy efficiency, the adoption of renewable energy sources, and adjustments in agricultural practices.

Nevertheless, it emphasized the need for further efforts in specific areas and countries. While Germany emerged as a frontrunner, other nations like Hungary and Poland require focused strategies to address lagging sectors like food consumption. Additionally, tackling the rising food transport emissions across most countries is crucial for achieving comprehensive sustainability within the agri-food sector.

Overall, the study offers a nuanced perspective on the progress and challenges in reducing carbon dioxide emissions within European agri-food systems. While it acknowledges the positive strides made by several nations, it also underlines the need for targeted efforts in specific countries and sectors to ensure comprehensive and sustainable development across the entire region.

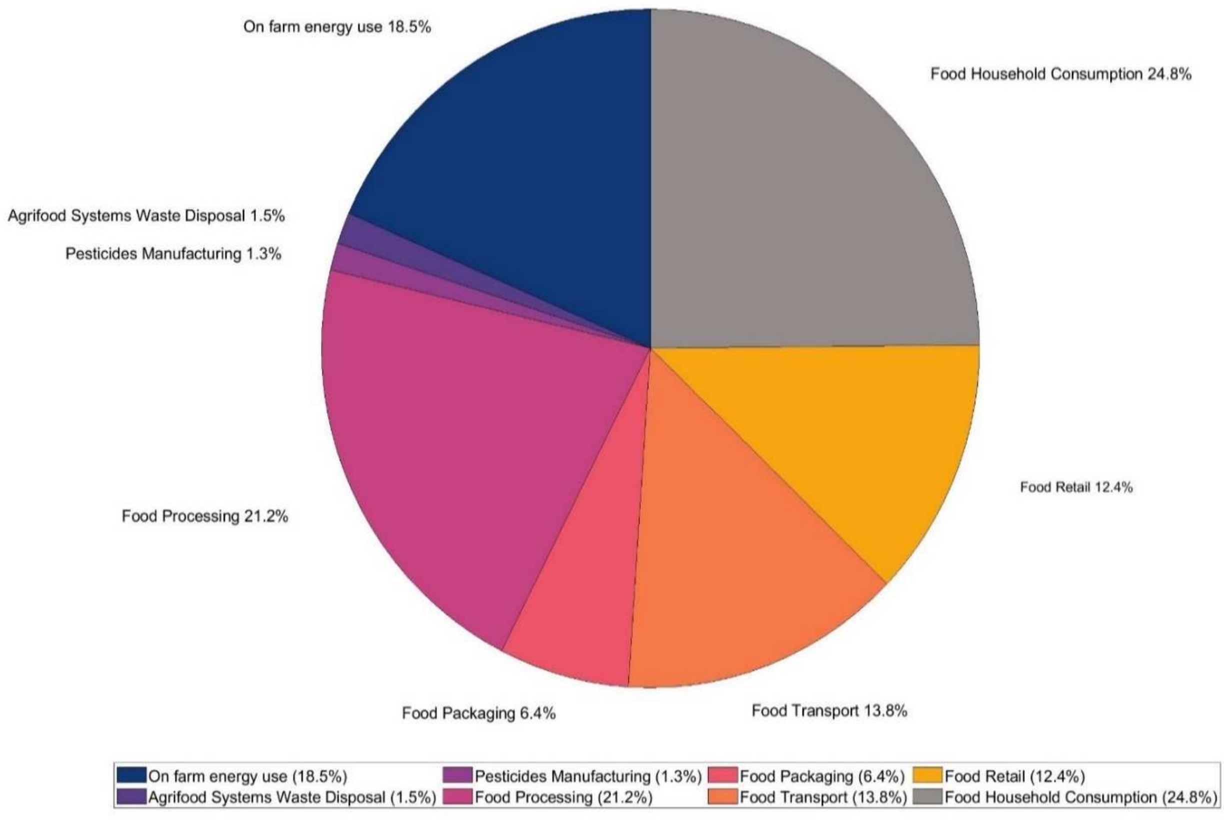

Figure 11: Comprehensive examination of sector-specific carbon dioxide emissions
Source: Authors' own compilation.

The agri-food sector plays a significant role in contributing to CO_2 emissions, with household consumption being the most prominent source, accounting for nearly a quarter (24.8%) of the total. Food processing (21.2%) and on-farm energy use (18.5%) follow closely behind. Other contributing factors include food transport, retail, waste disposal, pesticide manufacturing, and packaging, collectively representing the remaining 34.1% of emissions.

Breaking down the categories further, household consumption emissions stem from activities like cooking, storing, and preparing food at home. Food processing emissions originate from industrial processes involved in manufacturing food products. On-farm energy use emissions come from activities like operating tractors, irrigating fields, and heating greenhouses.

Emissions throughout the supply chain contribute to the overall impact. Food transport includes emissions from transporting food by various means, such as trucks, ships, and airplanes. Food retail emissions arise from the operation of grocery stores and other food retailers. Agri-food systems waste disposal contributes emissions from the disposal of food waste in landfills and incinerators. Pesticide manufacturing and food packaging emissions come from the production of these materials.

The pie chart presented in Figure 11 visually depicts the relative contribution of each sector to the total emissions within the agri-food sector, highlighting the areas demanding the most attention for emission reduction efforts.

It is crucial to acknowledge that the agri-food sector is a major contributor to CO_2 emissions in the EU. While household consumption, food processing, and on-farm energy use are the most significant sources, there are opportunities to mitigate this impact. Implementing strategies like reducing food waste, improving energy efficiency throughout the supply chain, and adopting more sustainable packaging materials can collectively contribute to a significant decrease in CO_2 emissions from the agri-food sector.

4.4. Food, Energy, and Environment security (Study 4)

4.4.1. Multifactor analysis

MFA's unique power lies in its ability to represent observations through "partial factor scores." This allows the analysis to simultaneously consider diverse variable sets and position each observation within the data landscape. This comprehensive approach unveils richer and more nuanced relationships within the data.

Motivated by the need to explore novel pathways for addressing crucial challenges and Sustainable Development Goals (SDGs), this research delves into the interconnectedness of climate change, energy consumption, and food security (defined as accessibility and satisfaction with adequate nutrition). Multiple Factor Analysis (MFA) was employed to analyze correlations between these factors, specifically accounting for the regional variations within the selected EU countries. MFA's strength lies in its ability to handle complex and large datasets by dissecting distinct classes of observations defined by different variable groups.

MFA commenced with PCA analyses on food security, energy resources, and climate change. Loadings between pillar components and the global analysis elucidated interrelationships. The MFA plotted countries on a 2-dimensional map, visualizing the examined variables. This analysis defined disparities between countries in FEE factors and identified the primary drivers of these differences.

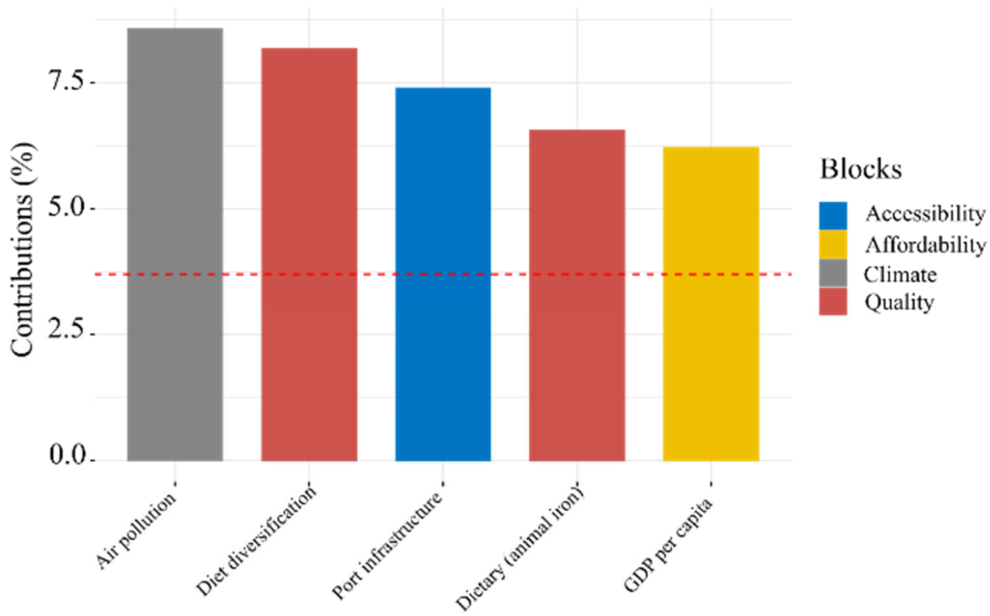

Figure 12.a: Analysis of contribution of indicators and blocks to dimension 1 (37.8% inertia) in MFA

Authors' own compilation.

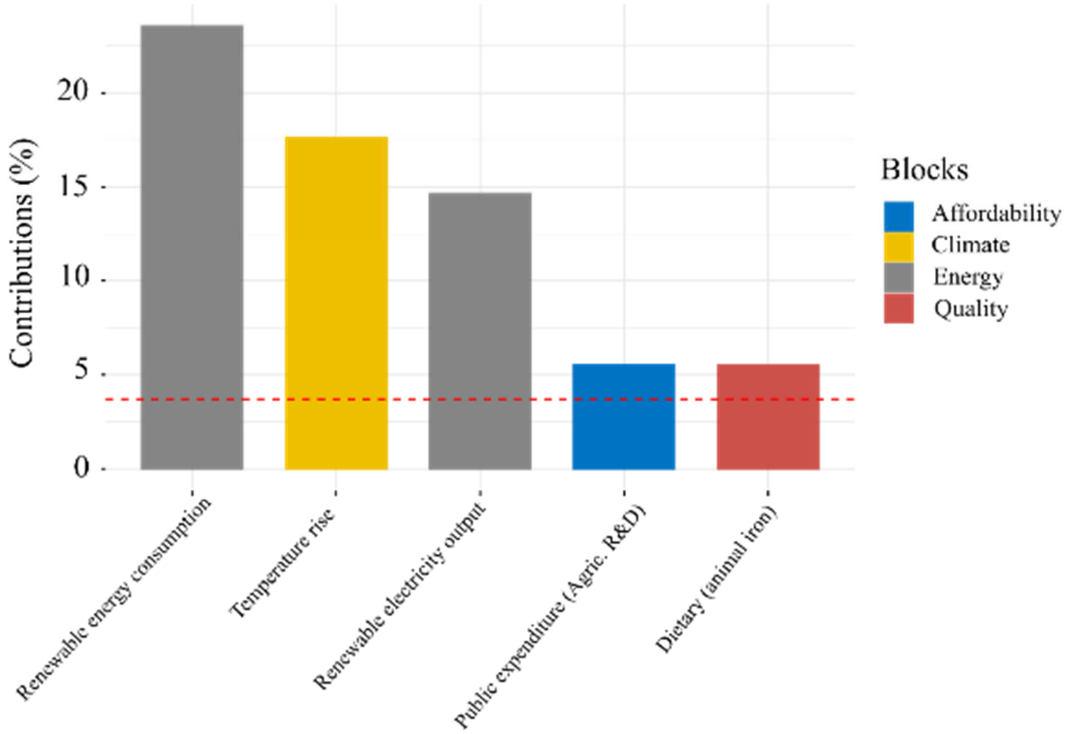

Figure 12.b: Analysis of contribution of indicators and blocks to dimension 2 (14.0% inertia) in MFA

Authors' own compilation.

A total of 37.8 percent of the inertia was represented by the first-dimensional (DIM1) eigenvalue (Figure 12.a). DIM1 was linked to air pollution, diet diversity, port infrastructure development, and GDP per capita (productivity). 13.9 percent of the inertia was proportional to the second dimension (DIM2). Renewable energy, rising temperatures, nutritional diversity, and investments in agricultural R&D were all correlated with DIM2 to a greater or lesser extent (Figure 11.b).

FAF quantifies a country's population's ability to pay for food in both regular times and in times of food-related shocks. For example, the GDP per capita and the food expenditures of consumers. That's why FAF protects against external price shocks from food import tariffs and food dependency. FAC affects both food availability and the ease with which people can obtain food. FAC refers to the degree to which a country has a secure food supply, how vulnerable its food supply is to disruptions, how well its agricultural infrastructure can increase agricultural output, how well its local and innovative capacity can mitigate food loss, and how stable its government is. Finally, dietary diversity, quality, and accessibility are all included in FQ. Individuals' calorie and nutrient consumption, as well as the variety of foods they consume, fall under this heading, also known as "utilisation" (FAO, 2020).

Additionally, the selected pillars shed light on the status of the environmental goals outlined in the 2030 Agenda for Sustainable Development (UNDG, 2017). In order to achieve the SDGs, it is important to renew our commitment to finding innovative solutions to the most pressing global challanges. For example, the goal of SDG 2 is to "End hunger, achieve food security and better nutrition, and promote sustainable agriculture" (Love, 2016). The zero-hunger challenge promotes several goals, including the reduction of malnutrition among young children, year-round access to sufficient food, environmentally friendly agricultural practices, a rise in smallholder productivity and income, and the minimization of FLW. Goal 7.1 of the sustainable development agenda emphasizes this need for universal access to clean, cheap energy. Goal 11.6 helps lessen urbanization's negative environmental impact; goal 14.5 promotes the preservation of coastal and maritime areas; and goal 15.5 seeks to safeguard endangered species from extinction.

4.4.2. Validation of results

Multiple techniques, including a random sample with replacement (bootstrapping), a permutation test inside each block to maintain exchangeability, an exhaustive (leave one out) (Stone, 1977), and a non-exhaustive (split-half) estimation, were used to validate the MFA components (Kohavi, 2001). Techniques such as cross-validation and rotation estimation are essential for determining the degree to which a predictive model works in the real world (Allen, 1974).

Initially, a bootstrap simulation (N=1000) was conducted, with resampling applied to all indicators within each iteration (Table 12). To perform permutation tests, a randomized dataset was created by permuting objects within each block. The dispersion of explained variances from the MFA components determined critical values. Based on these distributions, two-sided p-values were calculated, testing the null hypothesis that the initial explained variances were not significant compared to the simulated variances. Results indicated that the first and second components (DIM1 and DIM2) consistently explained the greatest proportion of variance (Table 12).

Table 12: Assessment of the explanatory efficacy of MFA components: validation findings

Component (dimension)	Explained variance (%)	Bootstrap simulation* (p-value)	Permutation test within each block* (p-value)	Split half test* (p-value)	LOO** validation (% of variation)

1.	37.8%	0.794	<0.001	0.320	6.9
2.	14.0%	0.132	0.056	0.802	14.7
3.	13.5%	0.502	<0.001	0.173	8.3

*Notes: * N=1000 iterations. **Leave-one-out (LOO).*

To conduct a split-half test, the dataset was first divided into two equal halves. MFA analysis was then performed separately on each section. To assess the explained variance of MFA components across several iterations, a Wilcoxon signed-rank sample test was used with N-fold cross-validation (Wilcoxon, 1945). The two splits showed no statistically significant difference, with the second component demonstrating the greatest stability.

Leave-one-out cross-validation was used to estimate the variation coefficients (i.e., the standard deviation divided by the mean). The MFA was run eight times, with one country omitted from the analysis each time. Regardless of whether the coefficient value was below the 20% threshold, these validation tests confirmed the stability of the first two selected components, indicating their suitability for describing the data.

4.4.3. Global space and partial analysis

The global analysis revealed a complex web of interconnected factors influencing the investigated area. This analysis, presented in Figure 13, helped visualize the contributions of different variable groups (pillars) to the overall structure. The resulting two-dimensional global space map, created using Multidimensional Scaling (MFA), divided the countries into four distinct clusters, each with unique characteristics related to climate, energy situation, and food supply.

The first quadrant grouped countries with high renewable energy production and consumption, coupled with strong economic indicators (GDP per capita) and diverse and plentiful food supplies. This cluster included Austria, Germany, and Switzerland. Notably, Germany, positioned closer to the center, displayed a high percentage of forest area and final energy consumption.

In contrast, the V4 countries (Hungary, Poland, Slovakia, and the Czech Republic) clustered together in the second and third quadrants, deviating significantly from the first dimension's origin. Hungary, situated in the second quadrant, exhibited a stronger association with soil erosion and temperature rise compared to other EU countries. This association can be attributed to Hungary's extensive agricultural plains, particularly maize production, which is vulnerable to high temperatures and low precipitation.

Furthermore, Slovakia, located on the border of the second and third quadrants, displayed a higher urban absorption rate compared to its neighbors, Poland, and the Czech Republic. However, Slovakia's mountainous interior and widespread forest cover limit its agricultural output due to the scarcity of arable land.

Moving to the third quadrant, Poland and the Czech Republic were characterized by high levels of political stability, improved energy efficiency (measured by energy intensity), and significant food consumption.

Finally, the fourth quadrant, comprising the Netherlands and Belgium, demonstrated higher food quality (protein) and increased government spending on agricultural research and development (R&D). This focus on research and development suggests potential for future advancements in the agricultural sector of these countries.

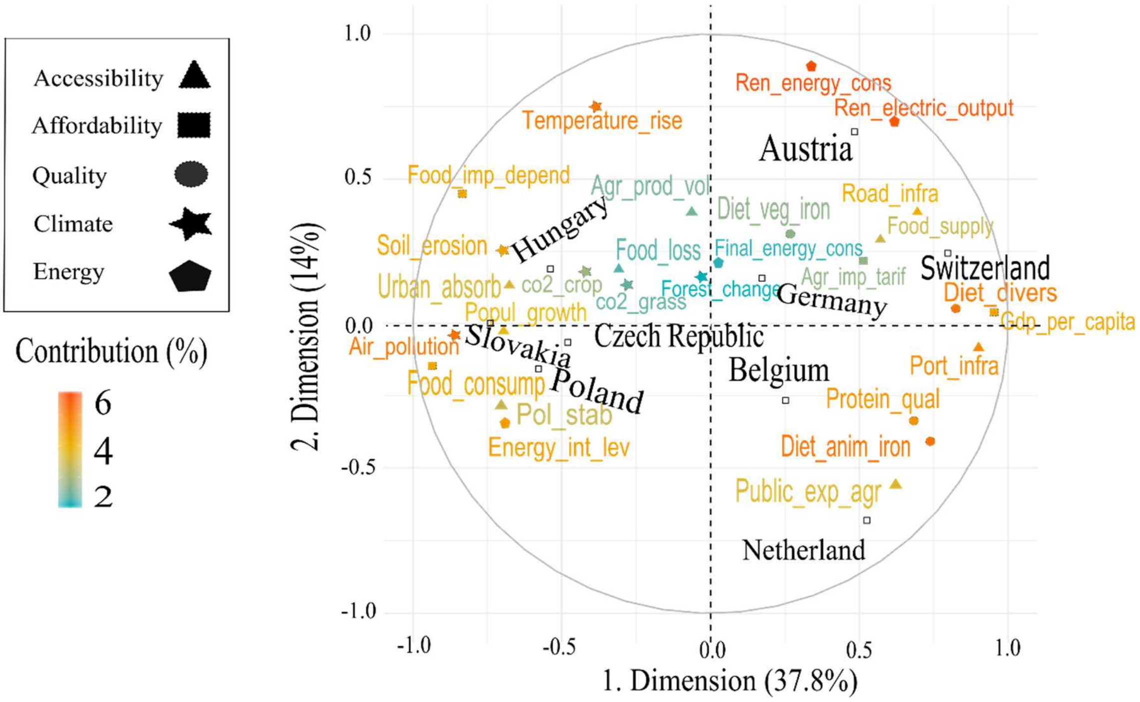

Figure 13: Identifying regional impacts: percentage of contributions of EU blocks to components (DIM1 & DIM2) in MFA

Authors' own compilation.

The results presented in Figure 13 suggest a complex interplay between energy consumption, global climate change, and food security. High food consumption and import dependency (FAF) and high food production and export independence (FAC) were associated with countries that have a higher energy intensity level, measured by energy supply per GDP. This energy intensity was further linked to higher levels of air pollution, soil erosion, and temperature rise, which are all indicators of climate change. Additionally, population growth, political stability, and urban expansion were found to be influential factors in this relationship.

Higher GDP per capita, found on one extreme of the first dimension (DIM1), was associated with both increased food availability (FAC) and improved food quality (FQ). This link was established through greater investment in agricultural research and development, food supply chains, and port infrastructure. Additionally, higher income levels led to improved dietary diversity and protein intake, further enhancing food quality.

In contrast, the second dimension (DIM2) revealed a negative association between rising temperatures and the use of renewable energy sources and electricity generation. This suggests that factors like greenhouse gas emissions and the conversion of forests to other land uses negatively impact the overall contribution of biomass and renewable resources to the energy mix, potentially hindering the transition towards sustainable energy sources.

Figure 14 visualizes the individual positions of each EU country (partial analysis) based on the first two principal components identified in the global analysis. Each country is represented by a single point, indicating its relative standing across the five different pillars (FAF, FAC, FQ, energy intensity, and climate change). This allows for an assessment of both the overall status of the EU and the individual and regional variations among its member states.

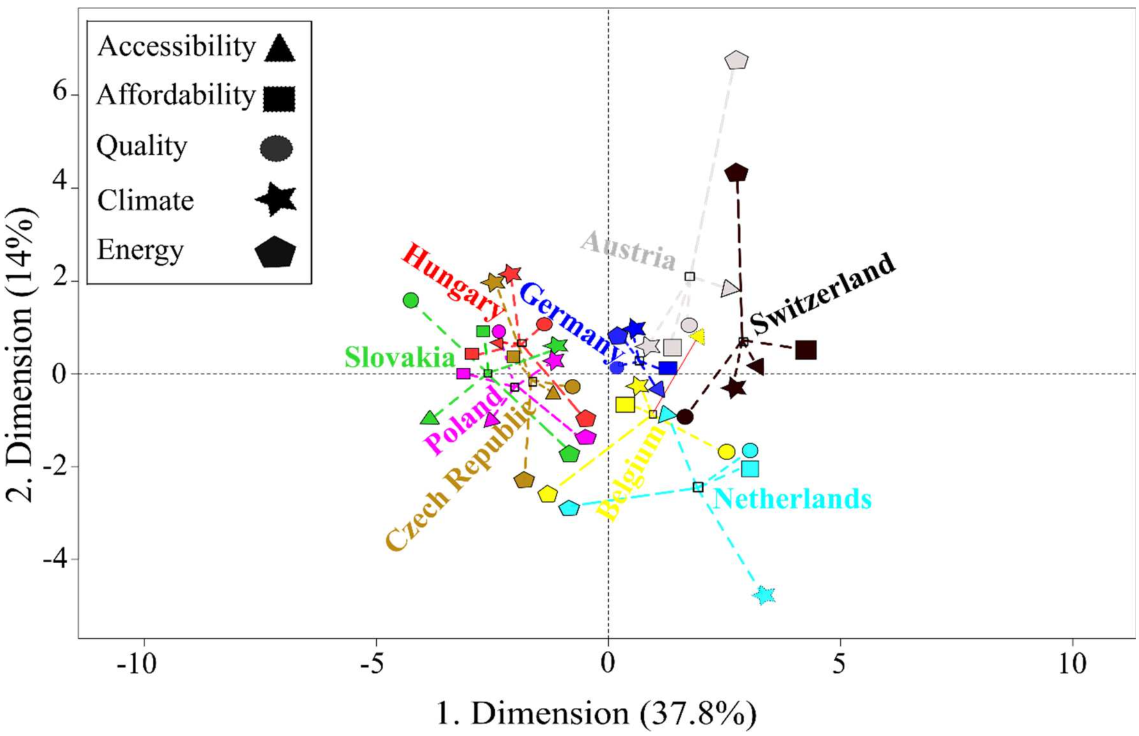

Figure 14: Relative contributions of DIMs to inertia advancement in EU countries (DIM1: 37.8%, DIM2: 14% in MFA)

Authors' own compilation.

The V4 group (Hungary, Poland, Czech Republic, and Slovakia) appears to be more significantly impacted by energy usage and climate change challenges than by food insecurity concerns. This disparity is compounded by a general lack of both renewable energy consumption and electricity generation across all V4 countries. Preliminary findings also suggest that Hungary faces heightened vulnerability due to significant temperature increases related to climate change. Additionally, Slovakia and Poland exhibit notable levels of "urban absorption" (FAC), while Hungary struggles with the most severe "fragmentation of agricultural land" (FAF) situation, and the Czech Republic faces significant problems with "food quality" (FQ), impacting dietary diversity and protein quality.

In stark contrast, countries like Austria, Germany, and Switzerland display a distinct characteristic: high levels of both consumption and generation of renewable energy. Additionally, the Netherlands stands out as a leader in environmental protection and sustainable food policy within the EU due to its low vulnerability to climate change, improved food protein quality, and greater dietary diversity (Solorio, 2011).

5. DISCUSSION

5.1. Food security (Study 1)

The food security state in the selected European region, encompassing Austria, Belgium, Netherlands, Germany, Hungary, Poland, Czech Republic, and Slovakia, is multifaceted, characterized by both commonalities and disparities. Western European nations in this region, namely Austria, Belgium, Netherlands, and Germany, generally enjoy greater food security. This can be attributed to factors such as well-established agricultural infrastructure, diverse and robust food supply chains, and higher average income levels that facilitate broader access to food.

However, the situation in Eastern European countries like Hungary, Poland, Czech Republic, and Slovakia presents a different picture. These nations face distinct challenges rooted in their historical socio-economic transitions, which sometimes included periods of food insecurity due to factors such as poverty, income inequality, and less developed agricultural sectors compared to their Western counterparts.

Despite these differences, several shared challenges impact food security across all these nations. Urbanization, a significant trend in the region, strains agricultural resources and disrupts traditional farming practices. Additionally, evolving dietary preferences, with an increasing demand for imported foods, further complicate the food security landscape. Climate change adds another layer of complexity, posing a common threat to agricultural productivity through extreme weather events such as droughts, floods, and heat waves.

To ensure sustainable food security across the region, effective governance, adaptable agricultural policies, and investments in resilient food systems are crucial. These investments should focus on building systems capable of withstanding the various challenges mentioned above. Moreover, addressing food waste through improved storage, distribution, and consumer behavior modification plays a vital role in maximizing available resources. Finally, fostering international cooperation in trade and supply chain management can strengthen regional food security by ensuring access to diverse food sources and mitigating potential disruptions in individual countries' food supplies.

Food security in selected European countries is a complex and dynamic issue, presenting both strengths and challenges. The region can ensure sustainable food security for its population by implementing comprehensive strategies that encompass effective governance, adaptable agricultural practices, and international cooperation, in the face of evolving challenges.

A key finding of this study highlights the intricate relationship between domestic material consumption (DMC) and food security. While highly competitive EU countries didn't face immediate food security concerns, the research revealed a multifaceted role for DMC in this arena.

The study further delves into the potential tension between the Sustainable Development Goals (SDGs), which prioritize economic development, and the need to monitor absolute resource use patterns. This potential conflict, the research suggests, could jeopardize environmental integrity. It found a concerning correlation: rising DMC from 2000 to 2010 (48.7 to 71.0 billion tonnes) directly corresponded with increased resource use in food production and other goods. This finding underscores the significant challenge of achieving sustainable food security in the face of rising material consumption.

Furthermore, the study pointed out the global issue of food waste. According to the Food and Agriculture Organization (FAO), a third of all food produced is wasted annually, causing significant economic and environmental losses. Despite this, global food distribution remains unequal, with over 820 million people suffering from hunger or malnutrition, while over 2 billion are overweight or obese (FAO, IFAD, UNICEF, WFP, 2019a).

However, the UN's sustainable development agenda aims for a 50% reduction in FLW by 2030. Optimizing resource use and minimizing waste generation through a circular economy approach can contribute to both economic growth and environmental sustainability. While changing consumption patterns is crucial, research by Read et al. (2020b) emphasizes the complex interplay between resource use at various stages of the food supply chain and the potential environmental benefits of FLW reduction.

Interestingly, the study conducted a Partial Least Squares Regression (PLSR) analysis, revealing a decoupling of economic growth from capital utilization in the EU between 2012 and 2019 (Figure 3). This decoupling is attributed to improved port and rail infrastructure, facilitating smoother food distribution, and triggering increased production processes. Additionally, the study found that the average economic value generated per kilogram of DMC in the EU has risen significantly since 2012, indicating increased resource productivity efficiency. However, achieving food security necessitates efficient utilization and effective management of scarce natural resources.

The research observed a 1.21% CMU rate between 2012 and 2017. This approach promotes resource efficiency, environmental sustainability, and lower carbon emissions. Increased CMU leads to reduced demand for raw materials in agriculture (DMC), consequently lowering ammonia emissions associated with livestock production.

However, the study emphasizes that previous research has primarily focused on greenhouse gas (GHG) emissions, which are more significant in high-income countries (Vermeulen et al., 2012). While agricultural activity contributes significantly to overall food system pollution, including land-use changes, the research did not find a significant correlation between harmonized risk indicators for pesticides and food production/safety.

It is crucial to note that the average ammonia emissions from agriculture in the selected EU countries between 2012 and 2017 were 1.13 tonnes per year, primarily originating from livestock manure. Managing livestock manure effectively is essential for environmental policies related to air and water quality. Reducing ammonia emissions is vital for sustainable development.

Balancing food security goals under the Sustainable Development Goals (SDGs) and transitioning towards sustainability can be challenging due to their interdependencies. This research investigates key characteristics impacting sustainable food security, with a focus on Agricultural Factor Income (AFI) which increased by 1.26% per labour unit from 2012 to 2019.

Developed countries' market interference, through subsidies and surplus goods exports, negatively impacts global food production by displacing local farmers in developing countries (Ackrill, 2005). Conversely, public investment in agricultural research and development can promote diversified farming systems and introduce new crops, ultimately improving food security.

The study observed that AFI significantly varied across the selected European countries. Interestingly, it correlated with urban absorption capacity, obesity prevalence, and political stability. This suggests that even with increased urbanization and associated pressures, maintaining food security is possible through increased AFI.

Furthermore, the research highlights a potential concern in the correlation between economic affluence and obesity prevalence in the urban population. This raises concerns about potential negative consequences associated with economic growth. The study also found a worrying trend: a 1.07% increase in obesity rates in selected EU countries from 2014 to 2017.

In addition, the research emphasizes that political instability significantly exacerbates food insecurity. Political turmoil, wars, and refugee crises have been major contributors to declining food security in the selected EU countries since 2012.

Despite advancements, numerous challenges persist in securing food access and fostering healthy diets globally. This includes the plight of marginalized rural farmers facing limited market access due to inadequate transport infrastructure (Godfray et al., 2010). Conversely, a well-developed road network promotes food distribution efficiency and reduces food insecurity across the European Union (EU).

However, the issue extends beyond Europe. An alarming reality persists that over 820 million people globally battle hunger, malnutrition, and insufficient food intake, further compounded by limited access to clean drinking water (Coff et al., 2008). This scarcity hinders not only human health but also food production, processing, and manufacturing, highlighting the crucial role of water quality and quantity. Additionally, access to water facilitates industrial development, job creation, and income generation, ultimately impacting economic access to food for billions.

Disparities in waste management across the EU mirror variations in consumption patterns and economic wealth, directly linked to dietary diversity. EU countries manage waste through diverse strategies, including landfilling, incineration, recycling, composting, and waste-to-energy generation.

Furthermore, energy sources, both renewable and non-renewable, depend on agricultural practices and food systems. Studies reveal a significant correlation between the share of renewable energy and the extent of organic farming land and road infrastructure in the EU. Organic systems, with their lower energy inputs and carbon sequestration capabilities, contribute less to greenhouse gas emissions compared to conventional practices. While renewable fuels offer an opportunity to decrease reliance on fossil fuels and mitigate environmental damage, their separate supply and transport chains are still impacted by road infrastructure.

Beyond food security, Europe faces a multitude of pressing socio-economic challenges demanding immediate attention. These include persistent unemployment, inadequate infrastructure hindering economic growth, the need for improved transportation links, the multifaceted impacts of mass migration, insufficient purchasing power, inconsistent policy implementation, and inadequate environmental safeguards (Alińska et al., 2018; Sotarauta, 2012). Concerted efforts are crucial to address these challenges and ensure the well-being of EU citizens.

The study emphasizes that while poverty may not directly correlate with food security, the inherent volatility of agricultural production raises concerns. This instability poses significant challenges for both producers and consumers, facing financial hardship due to fluctuating food prices. Price drops can negatively impact farmers and producers, while higher prices create difficulties for consumers to meet their nutritional needs. Despite the availability of resources, a substantial portion of the world's population still grapples with chronic malnutrition, underscoring the complex nature of food security and emphasizing the urgent need for holistic solutions (FAO, IFAD, UNICEF, WFP, 2019b).

The increasing interconnectedness of global trade has a significant impact on biodiversity. International trade often generates significant amounts of food loss and waste (FLW), threatening the survival of 30% of global species. This occurs because food produced in one region may be exported, leaving the local environment depleted of resources. Additionally, these manufacturing processes often increase the cost of waste generation, further straining resources (Lenzen et al., 2012).

Beyond immediate environmental impacts, FLW also has a significant connection to food security and ties directly to multiple Sustainable Development Goals (SDGs), specifically targets 12.3, 12.4, and 12.5. This highlights the need for a shift towards sustainable consumption and production patterns, as outlined by the EU's commitment to implementing effective SDG strategies.

Research by Springmann (2018) explicitly explores the link between FLW reduction and improved global nutrition. Similarly, Kummu et al. (2017) identified three distinct groups of countries based on how their food production relates to dietary changes, FLW reduction, and yield increases.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018b)(IPBES) identified the Transition Movements pathways, categorized into resource-sparing lifestyle pathways focusing on shifting consumption patterns to reduce Domestic Material Consumption (DMC) and transformation capability mechanisms emphasizing local equality, deliberation, and social stability for achieving sub-regional diversification, sustainable land use, and alternative livelihoods, as the most comprehensive framework aligning with the UN SDGs (Rounsevell, M.; Fischer, M.; Rando, A. T. M.; Mader, 2018).

These elements, including innovative land management practices, reduced energy consumption, and local empowerment, align with key SDGs, particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), due to their focus on the cross-sectoral aspects of food security challenges (Videira et al., 2014).

The link between efficient resource management and sustainable food security is being actively explored through research on food security and domestic material consumption (DMC). However, the concept of DMC itself is still developing, necessitating further interdisciplinary research to establish reliable indicators and explore solutions to address food security challenges. As the current study on food security in the EU highlights, broader awareness campaigns are crucial to educate both rural and urban populations about the impact of DMC on food security and the achievement of Sustainable Development Goals (SDGs) 2 and 12. This understanding and collaboration across various disciplines and communities are vital in ensuring long-term food security and achieving broader sustainability goals.

SDG 2 aims to end hunger, achieve food security, and promote sustainable agriculture. The study emphasizes the urgent need to address the multifaceted nature of food security across all three dimensions. Urbanization and economic factors are identified as key determinants, particularly affecting urban populations who face distinct challenges compared to rural areas. As cities continue to grow, ensuring equitable access to nutritious food becomes increasingly vital but also more complex.

The study further highlights the impact of consumption habits and reliance on imports on food affordability. Food systems heavily reliant on imports are vulnerable to external shocks, worsening affordability issues, especially for vulnerable populations. Sustainable intensification and efficient domestic material consumption (DMC) emerge as crucial strategies to enhance affordability while minimizing environmental impact, aligning with SDG 12's focus on sustainable consumption and production.

Disparities in food security between Western and Eastern European countries are also revealed, with Western nations generally experiencing better outcomes. Addressing these disparities requires targeted interventions considering regional differences in economic development, infrastructure, and dietary patterns. Upgrading infrastructure, including roads, railways, and ports, can improve food distribution networks, contributing to improved food security.

Concerns about diet quality, particularly protein intake, are also raised in the study, as it impacts both individual health and broader environmental sustainability. Promoting dietary diversity and reducing food waste are identified as crucial strategies to improve diet quality and minimize the environmental footprint of food production and consumption.

Overall, the study emphasizes the interconnectedness of food security, sustainability, and broader development goals. Achieving SDGs 2 and 12 requires a comprehensive strategy that addresses the complex challenges of access, affordability, and quality within diverse socioeconomic and environmental contexts. Sustainable intensification, efficient resource management, infrastructure upgrades, dietary diversity, and waste reduction are all essential components for enhancing food security and promoting sustainable development across the EU and beyond.

5.2. Energy security (Study 2)

Enhancing energy security demands a global, cooperative, and long-term approach. Two critical challenges necessitate immediate attention: mitigating climate change caused by fossil fuel use and providing access to clean, affordable energy, including renewables, for the world's poorest populations. Overcoming these challenges requires prioritizing the energy transition.

The analysis (Figure 5) of electricity trends in eight European Union member states (Austria, Belgium, Czechia, Germany, Hungary, Netherlands, Poland, Slovakia) from 2010 to 2022 reveals both a shift towards renewable energy and continued divergence in their energy landscapes.

The transition toward a climate-neutral future is fueled by a confluence of factors. On the one hand, the European Union's ambitious legislation, like the European Green Deal, sets binding targets and regulations to push member states towards sustainability. These policies are further bolstered by state-level support for research and development in clean technologies, accelerating innovation and paving the way for wider adoption. Additionally, a growing global consensus recognizes the urgency of mitigating climate change, leading to a collective desire to minimize reliance on fossil fuels and their associated environmental consequences. This multi-pronged approach, encompassing legislative mandates, financial incentives, and a shifting public consciousness, is propelling the world towards a more sustainable future (Bioeast, 2021). Across the EU, a diverse picture emerges regarding electricity demand, generation, and consumption over the past decade. While some countries, like Austria and Belgium, saw rising demand, others experienced a decline, like Hungary. This disparity was mirrored in domestic generation capacity, with Czechia achieving near self-sufficiency, while Germany increasingly relied on imports.

Renewable energy sources are gaining prominence across most EU member states, fueled by EU targets, cost reductions, and climate concerns. This trend was countered by a decline in fossil fuels, except for Poland, and a mixed picture for nuclear power. Notably, Hungary remained an exception, showing a minimal shift towards renewables. Biofuels, particularly in Austria, were on the rise, while gas consumption exhibited an increasing trend in most countries, raising concerns about methane leakage and geopolitical dependencies. Nuclear energy consumption varied, with Germany experiencing a decline while Belgium showed increasing reliance.

While there is a growing preference for renewable energy sources across the EU, the pace of adoption varies considerably. Austria, Belgium, Germany, and the Netherlands are leading the way with significant growth in renewables and a decline in fossil fuel use. Germany stands out for achieving the highest increase in renewable energy while simultaneously reducing both fossil fuels and nuclear power.

Despite a shared focus on renewables, member states exhibit distinct electricity generation profiles. Austria and Slovakia rely heavily on hydro and nuclear power, respectively. Germany boasts the highest share of renewables, while Poland remains heavily reliant on coal. Nuclear power plays a significant role in Hungary and Belgium, while natural gas holds the top spot in the Netherlands. Czechia relies on coal as its leading source, but renewables are increasing.

In this study, a major point of divergence is the continued dependence on coal. While consumption is declining in most countries, Poland remains an outlier with high fossil fuel dependence and the slowest renewable energy adoption rate.

Limited interconnection and collaboration within EU energy markets pose challenges to security and hinder progress towards a unified energy future. Countries like Poland and Hungary are particularly vulnerable due to their dependence on single suppliers.

However, the increasing use of natural gas as a "bridge fuel" necessitates careful consideration. While it offers a transition from coal, concerns about methane leakage, price volatility, and geopolitical dependence remain. Striking a balance between energy security and decarbonization goals is crucial.

Focusing solely on total renewable energy consumption masks variations within the category. Recognizing the distinct advantages and disadvantages of nuclear and specific renewable sources (solar, wind) is essential for informed policy decisions.

The expansion of biofuels requires responsible strategies to address potential land-use, food security, and biodiversity impacts. Similarly, thoughtful management of hydropower is necessary to minimize environmental and social impacts, water scarcity, and climate vulnerability.

The selected 8 EU member states analyzed are undergoing a significant transformation in their energy landscapes. While a shift towards renewable energy sources is evident, the pace and composition of the energy mix vary considerably. Further research is needed to delve deeper into the driving forces behind these trends and inform strategies for a secure, sustainable, and affordable energy future across the EU.

The diverse energy trends across the European Union (EU) highlight the need for tailored policy interventions, technological advancements, and collaborative efforts to achieve a sustainable energy future. Each member state faces unique challenges and opportunities, requiring comprehensive strategies that balance energy security, environmental sustainability, and economic development goals. Addressing these disparities is crucial for building a more resilient, affordable, and environmentally sound energy future for all EU members.

Scientists overwhelmingly agree that human activity is causing global warming, which presents a serious risk. The Energy Policy Review of Indonesia (2008) emphasizes that two-thirds of greenhouse gas emissions stem from energy production and consumption. This necessitates an urgent energy revolution towards a low-carbon economy.

However, the findings of energy security analysis (Figure 9) highlight the need for targeted efforts and knowledge sharing to achieve a unified vision for a sustainable European energy future. Hungary's case exemplifies the importance of such collaboration. Understanding the specific policies, economic factors, and public attitudes influencing these trends can inform policy decisions at national and regional levels.

This investigation reveals a substantial rise in renewable energy consumption of a remarkable 204.34% increase from 2010 to 2022, emphasising the crucial role of sustainability efforts in shaping a more environmentally friendly energy landscape. This aligns perfectly with Sustainable Development Goal 7 (SDG7), which aims to ensure access to affordable, reliable, and sustainable energy for everyone by 2030.

This significant growth signifies progress towards achieving SDG7 targets. Replacing traditional fossil fuels with cleaner alternatives like solar, wind, hydroelectric, and biomass power reduces greenhouse gas emissions and mitigates climate change. Embracing these technologies enhances energy security, promotes economic growth, and fosters sustainable development, all of which align with SDG7 objectives.

Furthermore, this increase highlights the effectiveness of sustainability policies implemented at various levels. Governments, businesses, and other stakeholders recognize the urgency of transitioning to renewable energy to address climate change. Policy tools like feed-in tariffs, renewable energy mandates, tax incentives, and carbon pricing mechanisms have incentivized investments in renewable energy infrastructure and driven clean energy adoption.

The study also emphasizes the importance of sustained investments in renewable energy projects and innovation. Investments in research and development, technological advancements, and infrastructure upgrades are essential to overcome barriers and scale up clean energy solutions. By channeling resources towards renewable energy initiatives, governments and investors can accelerate the energy transition, contribute to achieving SDG7 targets, and unlock new economic opportunities and jobs in the renewable energy sector.

Overall, the significant increase in renewable energy consumption offers a positive trajectory towards achieving SDG7 and advancing sustainable energy access and environmental stewardship. By leveraging sustainability policies and investments, all stakeholders can drive further progress towards a cleaner, more resilient, and inclusive energy future. However, continued collaboration and concerted action are crucial to overcome remaining challenges and ensure equitable access to clean energy for all, in line with the principles of sustainable development outlined in SDG7.

Therefore, a unified EU effort towards a sustainable energy future based on renewable energy is crucial to address climate change, enhance energy security, and ensure a prosperous future for all member states.

Box 1: EU powers up: significant strides in renewable energy bring clean progress

- **Green power surge:** In 2021, Approximately 22% of the EU's energy came from renewable sources like wind and solar, contributing to cleaner skies.

- **Climate champions:** By switching to renewables, the EU slashed its greenhouse gas emissions by a third (32%) in 2020, showing the power of green energy.
- **Transport transformation:** From a tiny 2% in 2005, renewable energy use in EU transportation soared to over 10% by 2020, fueled by biofuels and electric vehicles.
- **Raising the bar:** The EU's Renewable Energy Directive sets an ambitious goal of 32% of its energy must come from renewables by 2030.
- **Going even greener:** With an even bolder vision, the REPowerEU Plan aims to achieve a staggering 45% renewable energy share by 2030, paving the way for a carbon-neutral EU by 2050.

*Source: European Environment Agency 2023 (*Renewable Energy*, 2023).*

The EU is indeed making strides towards renewable energy but faces hurdles in sectors like transportation and heating. While electricity generation has seen more progress, integrating sources like wind and solar that fluctuate will test the power grid's limits. To achieve their ambitious climate goals for 2030 and 2050, the EU needs to ramp up renewable energy use across all sectors, not just electricity.

5.2.1. The REPowerEU plan: securing, affordable and sustainable energy.

Western nations are actively reducing their reliance on Russian energy, presenting a challenge for Europe, which has historically depended heavily on Russia for fuel. This situation has propelled decarbonization to the forefront as a solution, allowing Europe to achieve energy independence and climate goals simultaneously.

Renewable energy is rapidly replacing fossil fuels in national and regional electricity grids. The ambitious RepowerEU plan, launched by the European Union in 2022, aims to drastically cut energy imports from Russia and ultimately eliminate fossil fuels for member states (European Commission, 2022).

A united European front is crucial to accelerate the shift towards clean energy. This collective effort is not just about energy security, but also about fulfilling Europe's commitment to the Paris Agreement's goal of limiting global warming to 1.5 degrees Celsius. Despite the challenges posed by the pandemic, sustainability remains a priority in European energy plans. Renewables are leading the low-carbon push, already contributing 38% of the EU's electricity in 2020. While diversification and interconnection of energy sources are important for security, phasing out coal remains a pressing issue.

The recent invasion of Russia on Ukraine and disruptions in the global energy market further emphasized the need for action, prompting the European Commission to create the REpowerEU plan (Figure 15).

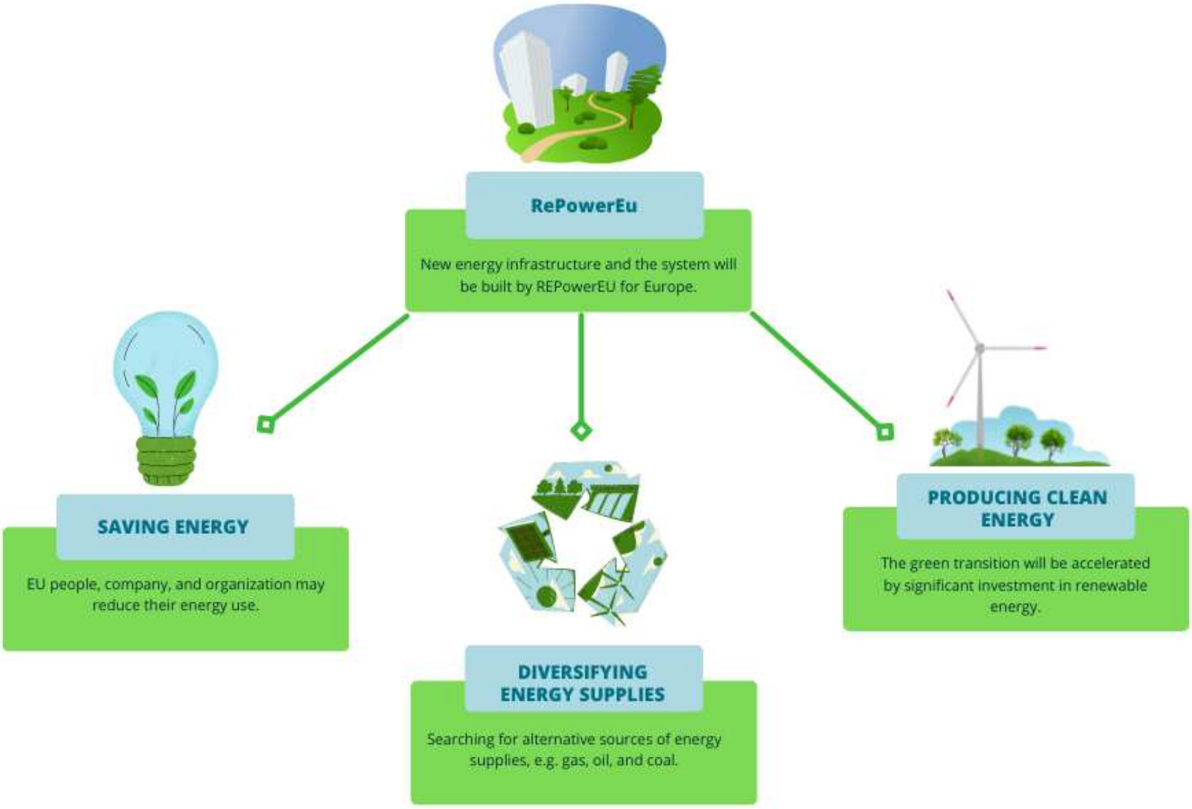

Figure 15: REPowerEU in action: a graphical overview of the key measures.

Source: Authored in response to the REPowerEU plan (European Commission 2022).

The European Union confronts a critical hurdle in securing its energy supply while heavily reliant on Russian imports. This dependence is not just a security threat but also hinders the EU's progress towards its ambitious Green Deal goals (European Commission, 2022).

Fossil fuels dominate the EU's import landscape, with petroleum products alone accounting for nearly two-thirds in 2019. This reliance creates vulnerabilities, leaving the EU's energy system exposed in the long term.

To address this challenge, the EU's REPowerEU plan proposes a three-pronged strategy. Firstly, it aims to reduce overall energy consumption across all sectors – households, businesses, and industries. Secondly, it seeks to diversify import sources, breaking free from dependence on single suppliers. Finally, it emphasizes the rapid adoption of clean energy sources such as solar and wind power, aiming to permanently replace fossil fuels. This multifaceted approach strives to achieve a secure, affordable, and sustainable energy future for Europe (Máté et al., 2020; Rokicki & Perkowska, 2020).

Implementing these measures would offer a double benefit. It would not only enhance energy security but also align perfectly with the Green Deal's objectives of sustainability and climate action. The current geopolitical situation underscores the urgency of this transformation – a more resilient and sustainable energy future for Europe is no longer a possibility, but a necessity.

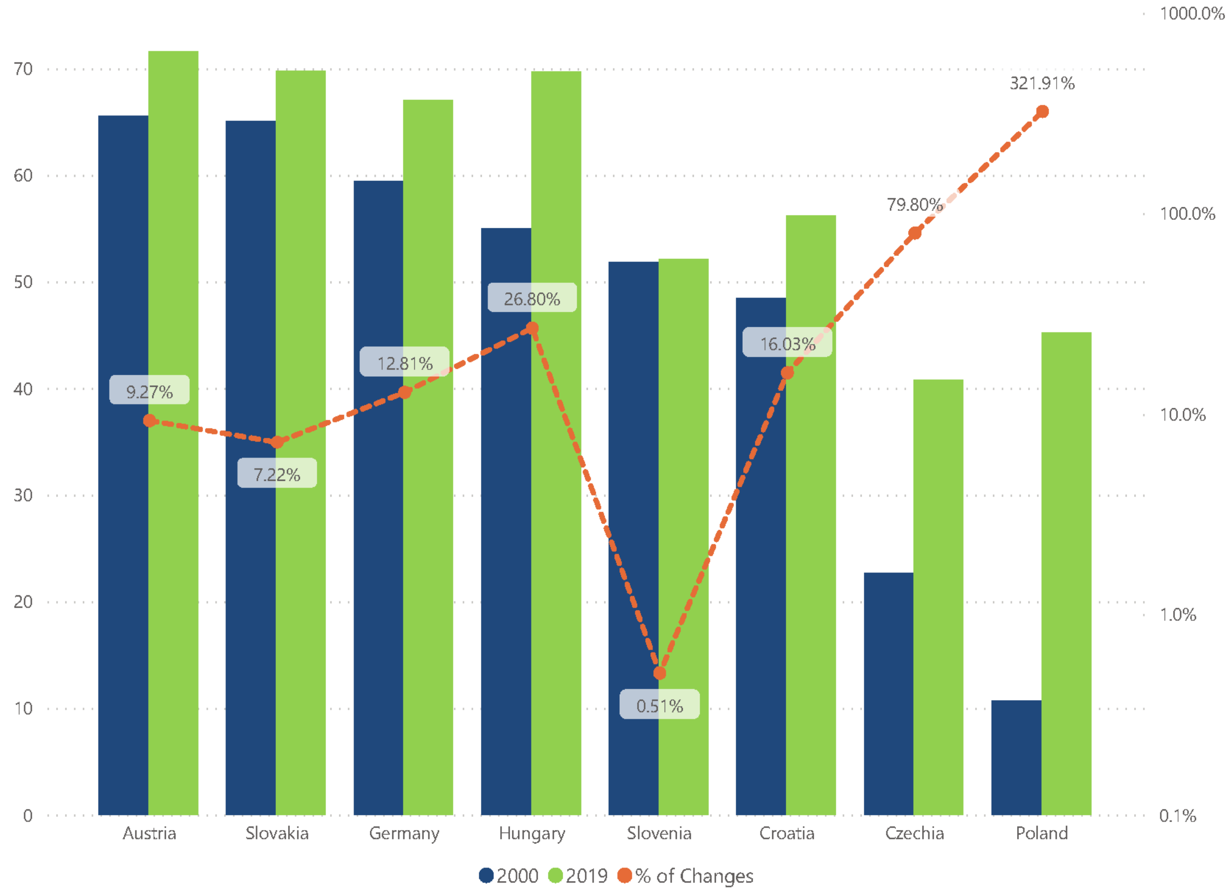

Figure 16: European energy dependency rates (%) by country in 2021.

Source: Developed based on Eurostat 2019 (Eurostat, 2021).

The EU relies heavily on energy imports, with over 60% of its energy needs met through imports in 2019. This reliance has increased since 2000, when it was only 56% (European Commission, 2021).

Among EU countries, Austria, Czechia, and Hungary are the most reliant on Russia for crude oil, natural gas, and solid fuels, with import shares exceeding 69%. Notably, Poland's dependence on Russian energy imports has skyrocketed by over 300% since 2000. While the EU is striving to reduce its import dependency, several countries remain heavily reliant on external energy sources. This highlights the need for diversification and increased domestic energy production to ensure energy security and sustainability. Despite this energy import reliance, the EU is actively seeking to reduce its dependence on imported energy and achieve greater energy independence (Box 2).

Box 2: Accelerating transformation: EU makes significant strides in the energy sector

Progress:

- **Cleaner skies:** The EU has slashed its greenhouse gas emissions by a third since 1990!
- **Renewables on the rise:** Renewable energy sources are surpassing fossil fuels in electricity generation, currently reaching 38%.
- **Energy efficiency wins:** Primary energy consumption in the EU dropped in 2019, indicating smarter usage.
- **Coal on the decline**: Many EU states have already ditched coal or set firm phase-out dates.

Challenges to address:

- **Import dependence:** The EU relies heavily on energy imports, reaching 60.6% in 2019.
- **Energy affordability:** Energy prices have surged, and millions in the EU struggle with energy poverty.
- **Renewables need a boost:** Despite growth, further efforts are needed to reach the 22% target for renewable energy.
- **Electricity demand grows:** More efficient use is crucial to meet rising electricity needs.

Source: European Commission (2021)

The EU plans to ditch its dependence on Russian fossil fuels through the ambitious REPowerEU initiative. Currently, about 22% of the EU's energy comes from renewables, meaning they import a hefty 60%. Notably, in 2021, Russia supplied a significant portion of this import: 40% of gas, 27% of oil, and 46% of coal, amounting to €99 billion.

REPowerEU aims for complete independence from Russian fossil fuels by 2030. Its key strategies involve dramatically increasing renewable energy sources and boosting energy efficiency. This two-pronged approach is predicted to achieve a 55% reduction in greenhouse gas emissions by 2030.

Specifically, the plan proposes raising the EU's renewable energy target from 40% to 45% and energy efficiency from 9% to 13% by 2030 (European Commission, 2022). To achieve this, EU legislation is streamlining permitting processes for renewable projects like wind farms and solar panels. Additionally, the EU Solar Energy Strategy aims to double current solar capacity by 2025, installing over 320 GW of new solar photovoltaics.

Furthermore, the hydrogen strategy focuses on producing and importing 10 million tons of clean hydrogen each by 2030. This shift towards cleaner energy sources will not only enhance energy security but also accelerate progress towards climate goals (European Commission, 2022).

The EU prioritizes sustainability, affordability, and secure energy supplies in its energy policy. Achieving these goals is crucial for energy security, as high dependence on external sources leads to price volatility and disruptions (Jun et al., 2009).

The Energy Union strategy pursued five interlocking goals launched in 2015: enhancing energy security through diversification, facilitating seamless energy flow across the EU, lowering demand through smart usage, transitioning to renewables for decarbonization, and fostering innovation. Its focus on renewables has paid off, with renewable energy now exceeding fossil fuels in the EU, demonstrating its potential to ensure energy independence, particularly in the face of external shocks like the pandemic (Dobreva et al., 2016).

The EU is tackling its energy needs and climate goals through various initiatives: expediting technical standards for clean hydrogen, aiming for 35 billion cubic meters of biomethane production by 2030 through the Industrial Biogas and Bio-methane Partnership, and phasing out Russian fossil fuels by 2027 with a €210 billion investment plan (European Commission, 2021).

EU countries are transitioning to renewable energy at different paces. This reflects their individual needs and priorities regarding energy security, leading to diverse foreign energy policies within the Energy Union (Mata Pérez et al., 2019). However, shifting to renewable enery offers a global pathway away from fossil fuels and towards a zero-carbon future. Despite ongoing efforts, curbing carbon emissions and preventing climate change require further action. Energy efficiency improvements and RE deployment hold the potential to reduce emissions by 90% (IRENA, 2022; Rabbi, Hasan, et al., 2021). Moreover, embracing renewable energy is crucial for achieving energy security and sustainability. While the transition presents significant challenges for the EU and beyond, its repercussions extend far beyond the clean energy package targets. As highlighted in Box 3, renewable energy impacts the economy, society, and politics in multifaceted ways.

Box 3: Is green energy easy? examining the roadblocks to renewables.

Challenges of large-scale renewable energy:

- **Land use:** Both solar and wind farms require significant acreage, potentially impacting animal habitats and competing with other land uses.
- **End-of-life management:** Wind turbines utilize various materials like metal and concrete that, after their lifespan (20-26 years), need responsible recycling or disposal to avoid adding to solid waste burdens.
- **Community acceptance:** Large-scale renewable projects often face public opposition due to concerns about visual aesthetics and potential disruptions to local lifestyles.
- **Intermittency:** Wind and solar power are weather-dependent, necessitating efficient energy storage solutions for them to serve as primary energy sources.
- **Cost and policy:** While renewable technologies are becoming more affordable, government support and cost reduction efforts are still crucial for wider adoption.

Source: Harjanne et al. (Harjanne & Korhonen, 2019)

While installing renewable energy systems presents challenges, "smart grid" technology offers a solution for effectively managing and integrating renewable sources like solar, wind, and hydrogen. This interconnected network of distributed energy resources can deliver both economic growth and improved electricity distribution thanks to the growing demand for sustainable technologies worldwide (IEEE, 2019). Moreover, to fully realize the benefits of this transition, we need to minimize the environmental impact of renewable energy projects and increase public acceptance. Fortunately, renewable sources like solar, wind, and water offer the potential for rapid expansion, paving the way for a global energy system powered entirely by clean, renewable energy (Box 4).

Box 4: Powering a sustainable future: 100% renewables by 2050.

- **Cleaner Air, Healthier Lives:** Transitioning to renewable energy could save millions of lives annually, preventing pollution-related deaths and illnesses.
- **Climate Champions:** By slashing greenhouse gas emissions near zero, renewable energy offers a path to escape the worst impacts of climate change.
- **Jobs Boom:** Not only will renewable energy create over 24 million new jobs, it can also replace all those lost in the fossil fuel industry.
- **Stable Prices, Lower Costs:** While ensuring global energy stability, a renewable future could mean cheaper energy bills for consumers.
- **Power to the People:** The transition can bring electricity access to billions currently facing energy poverty.
- **Security Enhanced:** Decentralized renewable energy systems reduce the risk of terrorism and minimize the vulnerabilities of massive, centralized power plants.

Source: Jacobson et al. (2017)

The world is shifting away from fossil fuels towards renewable energy to combat climate change and air pollution. This transition promises not just environmental benefits but also major economic, social, and political transformations. Many European countries, including the Netherlands, are leading the charge with ambitious goals like achieving carbon neutrality by 2050. Barbir (2009) suggest that renewable energy-based systems offer a more sustainable future compared to fossil fuels, even for countries with abundant traditional energy sources. This shift will reshape relationships between energy producers and consumers, demanding innovative approaches to manage these complex transitions (El-kharouf & Serhad, 2019).

The war in Ukraine threatens the energy performance of several EU countries heavily reliant on Russian imports. This presents a double challenge: ensuring energy security while maintaining the bloc's ambitious climate goals.

Figure 17 proposes a three-pronged strategy for climate neutrality: 1) prioritizing energy efficiency and renewable, 2) investing in clean energy technologies, and 3) promoting energy conservation. This aligns with goals for accessible, affordable energy (Iqbal et al., 2021), while boosting technology advancements (Zou et al., 2021) and encouraging individual responsibility (Huang et al., 2022) to create a comprehensive solution. Additionally, the European Green Deal emphasizes the need for a fully integrated, interconnected, and digitalized EU energy market.

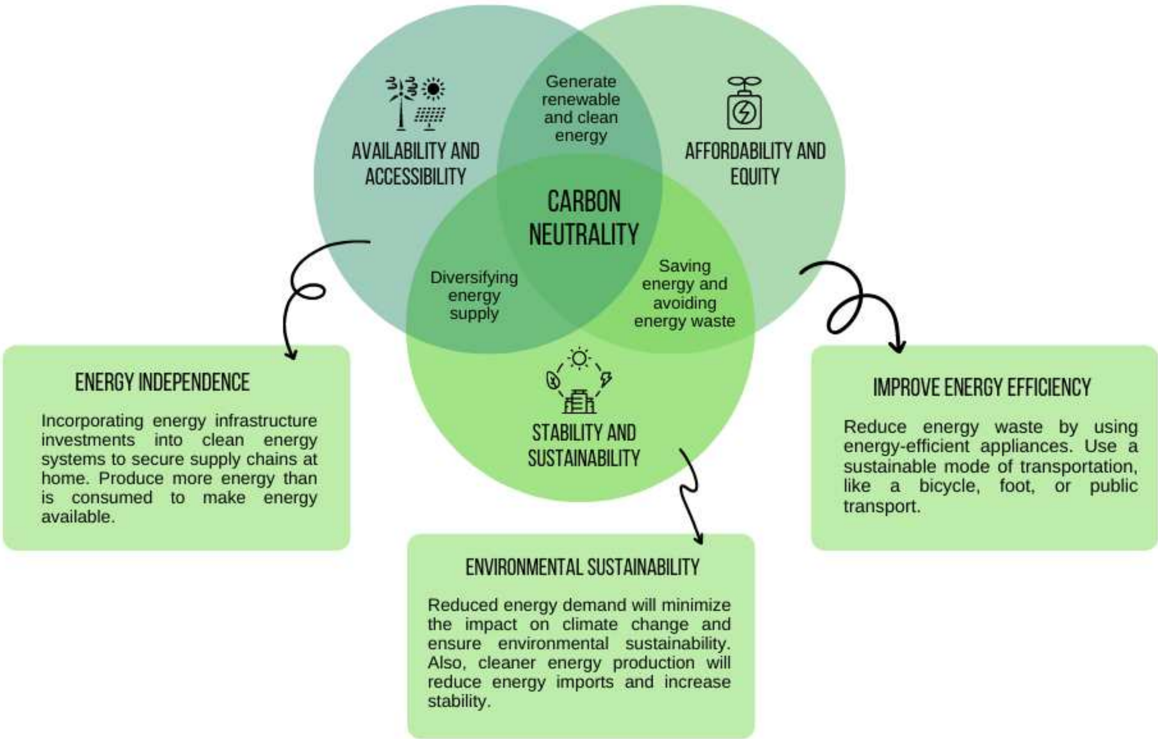

Figure 17: Building a zero-carbon future: actionable model for energy transition.

Source: Authored by drawing on the principles of energy security and the RePowerEU plan.

However, concerns remain about the reliability of renewables compared to fossil fuels. Their relative novelty presents uncertainties and requires tailored solutions. Public awareness and understanding of renewable energy's long-term benefits are also crucial. Building upon the 2015 Energy Union agenda, ten specific policies and strategies are proposed to facilitate the EU's transition to renewables (Dobreva et al., 2016).

5.3. Environmental security (Study 3)

This study revealed a nuanced picture of CO_2 emissions across the EU's food system (2010-2021). While some areas showed progress, others demanded attention. However, the study found that the emissions from pesticide production have generally declined, except in Austria and Belgium. Additionally, on-farm energy use and agri-food waste disposal have decreased in most countries. However, food processing emissions remain stable, and packaging emissions have mostly risen. Food transport emissions have also climbed in most nations.

In contrast, household food consumption, transport, and retail. Significant emissions were emitted from on-farm energy use and waste disposal. Emissions from pesticide production, processing, and packaging required further focus. The current investigation urged immediate action to tackle emissions across all stages. This requires a multi-pronged approach: reducing food waste, boosting energy efficiency, and embracing sustainable packaging.

The EU's food system significantly impacts the environment, particularly through greenhouse gas emissions. Household food consumption is the largest contributor, responsible for nearly 25% of the total CO_2 emissions. Processing and on-farm energy use follow closely behind, at around 21% and 18.5% respectively.

This highlights the need for a more sustainable food system. By implementing targeted interventions throughout the supply chain, the EU can achieve this goal.

Studies by Wawrzyniak (2020) have shown a decrease in CO_2 emissions in recent years. Visegrad countries, for example, reduced emissions by 20% between 1993 and 2016. However, challenges remain. Several factors influence emission rates. Soil acidification, increased nitrogen supply, and deforestation all contribute to the problem. Land-use changes, such as converting forests to farmland, can have adverse effects.

Soil plays a crucial role in storing a significant amount of carbon. Soil quality and organic matter content impact the rate of carbon and nitrogen mineralization. Temperature and the addition of fresh organic matter also influence soil decomposition. Understanding these factors is essential for mitigating climate change (Thiessen et al., 2013).

Organic matter amendments can be a double-edged sword. While they may enhance net primary productivity, they can also increase greenhouse gas emissions. Changes in organic matter content can significantly alter soil conditions, potentially leading to higher CO_2 emissions (Conant et al., 2011). Complementary strategies are needed to address these challenges. These include soil management practices, nitrification inhibitors, and the use of organic or inorganic fertilizers that minimize CO_2 emissions.

Centralized climate change policies in some European countries may not be as effective as a more localized approach that considers local expertise and resources. Long-term solutions likely lie in renewable energy technologies such as biomass, wind, solar, and geothermal.

The EU's food system significantly impacts the environment, particularly through greenhouse gas emissions. Household food consumption is the largest emitter, responsible for nearly 25% of the total CO_2 emissions (Figure 11). Food processing and on-farm energy use follow closely behind, at around 21% and 18.5% respectively.

This necessitates a more sustainable food system. The EU can achieve this goal by implementing targeted interventions throughout the supply chain.

A detailed analysis (Figure 10) reveals positive strides in reducing emissions across the EU's agri-food systems from 2010 to 2021. Germany has been a leader, achieving significant declines in various sectors: on-farm energy use (32%), pesticide manufacturing (59%), food processing (21%), packaging (23%), and retail (23%). Waste disposal saw the most significant drop in Hungary (59%).

However, challenges remain. Food transport emissions rose in all nations except Hungary, with the Netherlands experiencing the largest increase (13%). Similarly, food consumption decreased in most countries, with Hungary and Poland behind, while Germany again took the lead with a 20% reduction.

These findings highlight progress in sustainability but also point towards areas that require further attention. Food transport remains a challenge, particularly in countries like the Netherlands. Additionally, consumption patterns in other selected European countries need to be addressed.

To develop targeted reduction strategies, policymakers and stakeholders need to understand the emitters within the agri-food sector (Figure 11). Household food consumption is the largest culprit (24.8%), followed by food processing (21.2%) and on-farm energy use (18.5%). Food transport, food retail, agri-food systems waste disposal, pesticide manufacturing, and food packaging contribute the remaining 34.1%.

Understanding the breakdown of emissions within the agri-food sector (Figure 11) is crucial for crafting effective solutions. Household activities like cooking and food storage are the biggest contributors (24.8%), followed closely by food processing (21.2%) and on-farm energy use (18.5%). The remaining emissions stem from food transport, retail, waste disposal, pesticide manufacturing, and packaging.

The EU has made strides in reducing emissions, with Germany leading the charge. However, challenges remain, particularly in areas like food transport emissions (up in all countries except Hungary) and consumption patterns in selected European countries. To address these issues and create a more sustainable food system, the EU can focus on reducing food waste, improving energy efficiency throughout the supply chain, promoting sustainable farming practices, shortening food transport distances, encouraging plant-based diets, and developing eco-friendly packaging materials. By implementing these strategies, the EU can minimize its environmental footprint while ensuring food security for its citizens.

This research shows that, in certain European countries, food eaten at home is the biggest source of carbon dioxide emissions linked to food, making up almost a quarter (25%) of the total. This emphasizes the need for individuals and households to be more conscious and adopt sustainable consumption patterns to reduce their environmental impact.

However, the study also highlights the significant contribution of other aspects of the food system. On-farm energy use (18.5%) and food transportation (13.8%) are also major contributors to emissions. Implementing energy-efficient practices and technologies in agriculture, such as optimizing machinery and adopting renewable energy sources, can significantly minimize the environmental footprint of food production. Additionally, optimizing transportation logistics, embracing local food systems, and promoting sustainable supply chain practices are crucial to reducing emissions associated with food movement.

These findings align perfectly with the urgency of achieving Sustainable Development Goal 13 (Climate Action). By focusing on key areas like household consumption, on-farm energy use, and food transportation, policymakers and stakeholders can align their efforts with SDG 13 targets and actively contribute to combating climate change. This necessitates a multi-pronged approach that encompasses sustainable food consumption and production practices, alongside promoting renewable energy and improving transportation efficiency. By doing so, we can move closer to achieving SDG 13 and building a more sustainable and resilient future for all.

Building upon the identified drivers of food-related emissions, further research is necessary to delve deeper into the specific factors influencing consumer choices, agricultural practices, and supply chain logistics. Understanding the motivations behind unsustainable consumption patterns, inefficiencies within agricultural production, and environmentally detrimental practices in the food chain is crucial for crafting effective interventions.

This deeper understanding can pave the way for targeted policy measures, educational campaigns, and technological advancements. Policymakers could incentivize sustainable food choices by implementing carbon labeling or introducing subsidies for local and organic produce. Educational campaigns could raise awareness about the environmental impact of food choices and promote responsible consumption practices like reducing food waste and adopting plant-based alternatives.

On the production side, research can inform the development of new technologies and practices that optimize energy use and minimize emissions in agricultural settings. Precision agriculture techniques, for instance, can contribute to this goal by promoting targeted resource utilization and reducing reliance on chemical inputs. Additionally, fostering knowledge exchange and collaboration between farmers and researchers can accelerate the adoption of sustainable agricultural practices.

Furthermore, food-related emissions pose a significant challenge, necessitating a multifaceted research agenda. By comprehensively exploring this complex issue, policymakers, stakeholders, and researchers can collaborate effectively to develop and implement solutions. This collaboration is critical for achieving the ambitious goals of Sustainable Development Goal 13 (SDG 13), which aims to ensure a sustainable and resilient future for all. Researchers, environmentalists, and policymakers each hold crucial responsibilities in mitigating climate change by reducing greenhouse gas concentrations. Specifically, EU farmers must become aware of environmentally harmful cultivation practices. By adopting practices that mitigate CO_2 and nitrous oxide emissions, they can not only enhance their productivity but also contribute meaningfully to achieving the EU's climate goals. This combined effort, encompassing research, policy development, and implementation at the farm level, offers the potential for a substantial and lasting positive impact on our planet's health and sustainability.

5.4. Food, Energy, and Environment security (Study 4)

This study dives into the intricate interplay between climate change, energy consumption, and food security across selected 8 EU member states. Multiple Factor Analysis (MFA) unveils a comprehensive picture, considering diverse variables and pinpointing unique positions for each country.

The analysis confirms a complex web of relationships. High food consumption and import reliance are linked to increased energy intensity, further exacerbating air pollution, soil erosion, and rising temperatures. This underscores the critical need for the EU to embrace sustainable food and energy practices.

The MFA's two-dimensional map effectively visualizes regional variations. A clear divide emerges. Countries like Austria, Germany, and Switzerland boast high renewable energy usage, strong food security, and diverse diets. Conversely, the Visegrad Group (V4) of Hungary, Poland, Slovakia, and the Czech Republic grapple with energy intensity, climate change, and aspects of food security.

FEE analysis provides detailed profiles for each EU member state. The V4 group appears more susceptible to energy and climate change issues, while also lagging in renewable energy investment. Hungary faces heightened vulnerability due to climate change's impact on agriculture. Meanwhile, Slovakia and Poland struggle with urbanization affecting food availability, while the Czech Republic exhibits deficiencies in dietary quality.

Austria, Germany, and Switzerland stand out for their exceptional performance in both renewable energy consumption and generation, alongside robust food security. This suggests a potential model for the EU's sustainable development goals.

The Netherlands has emerged as a leader in environmental protection and sustainable food policy. This success can be attributed to several factors. First, the country's geography makes it less vulnerable to the effects of climate change, allowing them to focus on sustainable practices without facing immediate existential threats. Second, they've prioritized improving the protein quality of their food systems, ensuring people get the nutrients they need without relying heavily on environmentally damaging sources. Finally, the Netherlands promotes greater dietary diversity, encouraging a wider range of healthy and sustainable food options. These combined efforts showcase a successful approach to balancing economic growth with environmental and social well-being. By focusing on resilience, responsible protein sources, and dietary variety, the Netherlands has created a model for sustainable food production that benefits both people and the planet.

The findings offer crucial guidance for EU policymakers. The urgent need for increased investment in renewable energy sources and sustainable agricultural practices is evident. The V4 group would benefit from targeted strategies to address their specific vulnerabilities. Learning from leading countries like the Netherlands can provide valuable insights for improving food security and environmental protection across the EU.

This MFA analysis effectively sheds light on the complex relationships between climate change, energy consumption, and food security within the EU. The research highlights regional variations and identifies both challenges and opportunities for sustainable development across member states. By fostering collaboration and knowledge exchange, the EU can leverage these findings to develop and implement effective policies that ensure a secure and sustainable future for all its citizens.

Furthermore, the analysis reveals regional disparities within the European Union (EU) regarding sustainable development, particularly in areas like energy, environment, and food security. These observations align with several Sustainable Development Goals (SDGs) including SDG2 (Zero Hunger), SDG7 (Affordable and Clean Energy), SDG12 (Responsible Consumption and Production), and SDG13 (Climate Action).

A two-dimensional map generated using Multi-Factor Analysis (MFA) effectively illustrates these regional variations. Countries like Austria, Germany, and Switzerland exhibit high levels of renewable energy usage, robust food security measures, and diverse dietary patterns. In contrast, the Visegrad Group (V4) countries - Hungary, Poland, Slovakia, and the Czech Republic - face challenges related to energy intensity, climate change vulnerability, and aspects of food security.

SDG7, aiming to ensure access to affordable, reliable, sustainable, and modern energy for all, holds relevance. The disparity in renewable energy investment and usage between the V4 and the advanced economies highlights the need for targeted efforts to enhance clean energy adoption in lagging regions. Additionally, Hungary's vulnerability to climate change's impact on agriculture underscores the importance of SDG13, which calls for urgent action to combat climate change and its impacts.

SDG2, aiming to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture, is also implicated in the analysis. The challenges faced by Slovakia and Poland regarding urbanization affecting food availability, and dietary quality deficiencies observed in the Czech Republic, emphasize the multifaceted nature of food security issues within the EU.

Furthermore, SDG12, promoting sustainable consumption and production patterns, is highly relevant. The exemplary performance of Austria, Germany, and Switzerland in both renewable energy consumption and generation, coupled with robust food security measures, suggests a potential model for achieving sustainable development goals within the EU. Emphasizing responsible consumption and production practices can significantly contribute to addressing the outlined challenges and advancing progress towards a more sustainable future.

Overall, the findings highlight the importance of holistic approaches to sustainable development that address the interconnected challenges of energy, environment, and food security. By aligning strategies with the targets outlined in SDGs 2, 7, 12, and 13, policymakers can work towards narrowing regional disparities and fostering more inclusive and sustainable development across the European Union.

5.5. Building a secure future: model-driven policy solutions

Sustainable food security is a broad phenomenon that necessitates careful consideration of a variety of factors when devising a strategy to achieve it. Food availability, accessibility, utilization, and stability are the main pillars of food security that are believed to be vital to the long-term viability (Barrett, 2010b; Coates, 2013; Kannan et al., 2000; Pinstrup-Andersen, 2009).

In this current study, the conceptual research framework was developed based on the theoretical background of the four pillars of FEE security where SDG 2 was considered as supporting food security, SDG 7 worked for energy security, and SDG 13 supported environmental eecurity.

Several studies previously measured water, food, and energy security by using four pillars (Beck & Villarroel Walker, 2013; Machell et al., 2015; Mc Carthy et al., 2018b). But there was less evidence to the measurement of environmental security by using the same pillars.

The proposed model was developed based on the FEE security theory and supporting several targets of SDG 2, 7 and 13 by complying with the ‘Paris Agreement. The Paris Convention was adopted at the end of 2015 by the UN Framework Convention on climate change. The parties who signed the Paris Agreement agreed to reinforce a global solution to climate change by increasing adaptability and fostering climate adaptation and generation of low-grade greenhouse gas emissions in ways that do not affect food production (UNFCCC, 2015).

The conceptual framework in Figure 18 encompassing FEE security that has been derived from a widely accepted theoretical foundation. In this context, a visual representation depicting the interconnection between sustainable FEE security, as well as its alignment with the SDGs, was established. The examination seeks to contextualise SDG 2, 7 and 13 within the context of sustainable systems.

These three SDGs play a vital role in addressing pressing global challenges and promoting sustainable development. SDG 2, also known as zero hunger, holds great significance in the context of sustainable development. It aims to eradicate hunger, achieve food security, improve nutrition, and promote sustainable agriculture. By addressing issues related to hunger and malnutrition, SDG 2 contributes to poverty reduction, economic growth, and overall human well-being. It recognises the importance of sustainable agricultural practises, resilient food systems, and equitable access to nutritious food for all. SDG 7, which focuses on affordable and clean energy, is another crucial goal within the sustainable development framework. It aims to ensure universal access to reliable, affordable, and modern energy services while promoting the use of renewable energy sources. By transitioning to clean energy sources, such as solar and wind power, SDG 7 contributes to mitigating climate change.

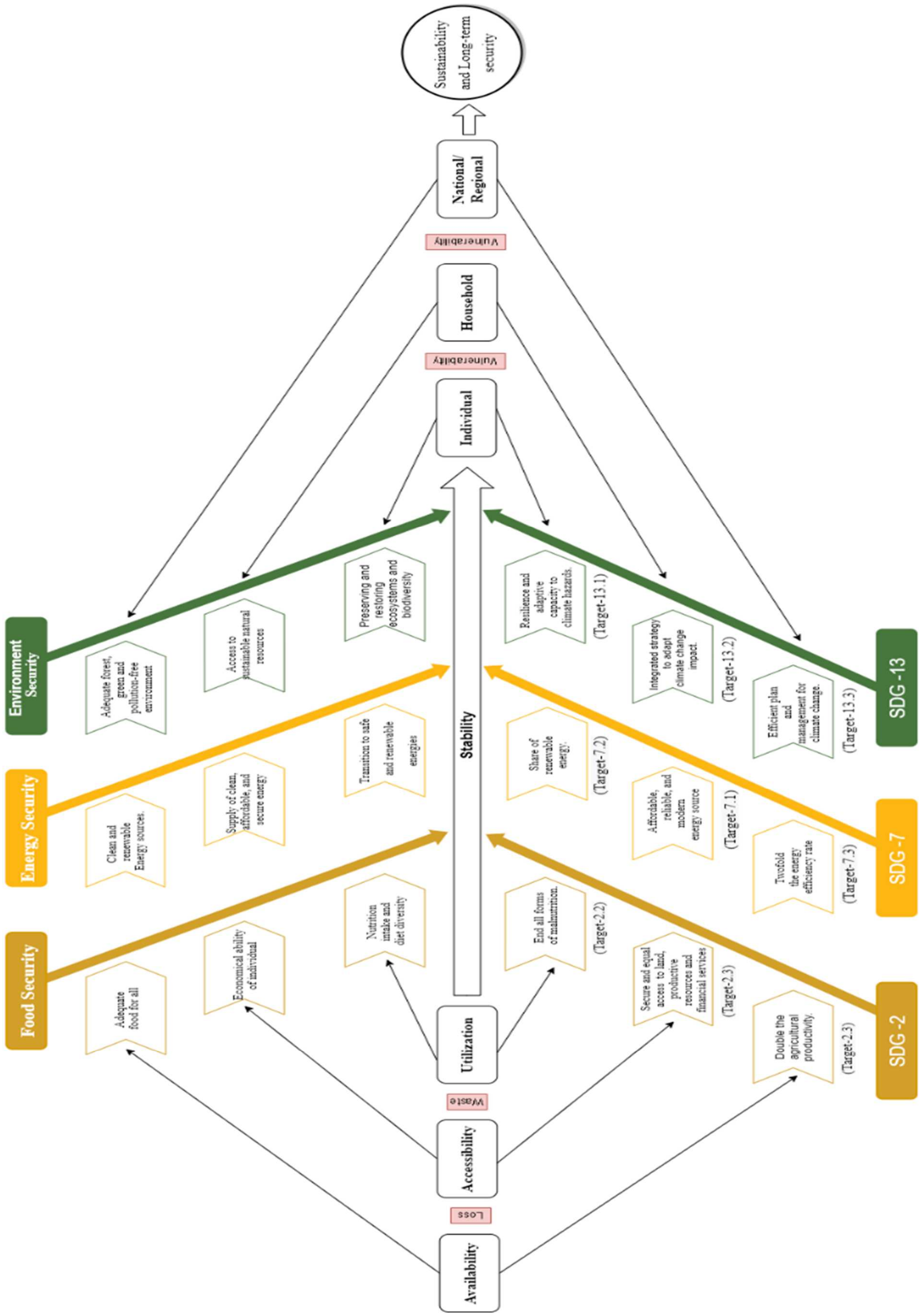

Figure 18: Building sustainable systems for FEE security: an SDG-guided approach

Source: Author's construction

Figure 18 presented a novel strategy to accomplish SDG 2, 7, and 13 targets for FEE security simultaneously. The dependent variable in this study was sustainable and long-term security, whereas the independent variables were food security (SDG 2), energy security (SDG 7), and environment security (SDG 13). These independent variables were utilised to examine the linkages and assess the model fit. The objective of this study was to examine the potential contributions of accomplishing SDGs pertaining to FEE security towards the attainment of sustainable and enduring security. The research framework aimed to evaluate the overall model fit by analysing the connections between the independent variables and the dependent variable. The forthcoming analysis aimed to offer significant insight into the intricate interconnections among different dimensions of security, emphasising the crucial role of sustainable development in ensuring enduring security.

Recognizing the interconnectedness of FEE issues, SDG 2, 7, and 13 tackle these challenges through three key approaches: 1) securing access and availability of food and energy while maintaining a healthy, forested environment; 2) promoting sustainable practices by combining efficient resource management with effective governance; and 3) addressing and mitigating FEE challenges. This aligns with FEE's framework of "security," "efficiency," "sustainability," and "resilience," highlighting the shared goals and integrated approach needed to overcome these complex issues. In addition, Figure 18 depicted the intricate relationship between FEE security, highlighting their crucial role in achieving the UN's SDGs 2, 7, and 13. Each element rests on four pillars: availability, accessibility, utilization, and stability. For food security, availability means enough nutritious food for all, accessible natural resources, and eliminating malnutrition. Accessibility requires economic means, affordable and reliable energy, and financial services. Utilization emphasizes proper nutrition and dietary diversity, while stability demands resilience against climate shocks.

Energy security mirrors this structure. Availability requires clean, renewable sources and sustainable resource management. Accessibility focuses on affordable, reliable energy access, while utilization emphasizes efficient use and climate-friendly practices. Finally, stability demands resilience against climate disruptions.

Environmental security follows the same pattern. Availability demands healthy forests, clean air, and thriving ecosystems. Accessibility highlights the right to clean water, sanitation, and environmental resources. Utilization emphasizes sustainable resource use and biodiversity conservation, while stability requires resilience against environmental shocks.

Figure 18 illustrated how these elements intertwine. Food production requires energy, which can impact the environment. Thus, sustainable development requires considering all three aspects holistically. The SDGs offer a roadmap to achieve this. Figure 18 illustrated the critical links between FEE security and the pursuit of SDGs, specifically Zero Hunger (SDG 2), Affordable and Clean Energy (SDG 7), and Climate Action (SDG 13). By working towards these goals, a more sustainable future can be built for all. This scenario calls for a rapid response. Interventions in governance (cohesion and efficiency) are needed in addition to social action (improving capabilities while broadening access and fairness), economic action (providing incentives and making use of resources), and environmental action (evaluating the value of and taking steps to conserve ecological services).

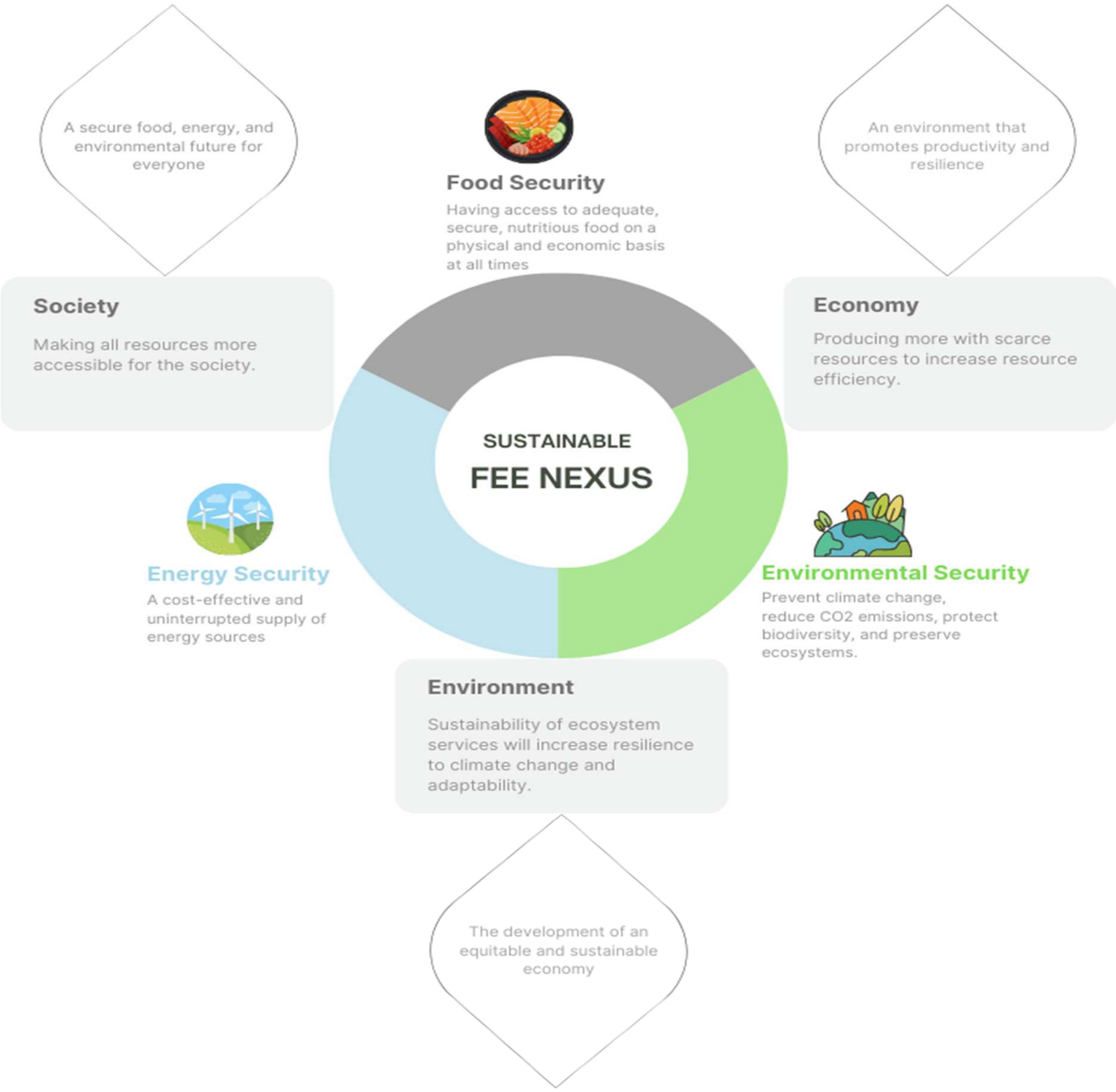

Figure 19: Optimizing the triple bottom line: a systems approach to sustainable FEE security

Source: Author's construction

Globally, one of the biggest problems is the shortage of essential resources, which negatively affects stainability. The UN predicts that by 2030, the global population would need 30% more water, 45% more energy, and 50% more food than it does today. FEE sustainability has emerged as a central topic in the field of environmental research. Because of the lack of global indicators to track progress towards FEE sustainability, this study was initiated. Figure 19 suggested a novel framework that aims to combine the nexus of FEE security with the three (environmental, social, and economic) dimensions of sustainability.

Food, water, and energy are vital to human survival, economic growth, and sustainable development. SDGs have shifted their attention worldwide to the task of ensuring the long-term viability of FEE. FEE of society's problems is as intertwined, convoluted, and pressing as this. The SDGs are the primary indicators used in this research. Being a global leader, these metrics should enable forecasting statements with substantial policy consequences for the coming decade. Coordination across disciplines is necessary for addressing the FEE problems and achieving the SDGs (Rasul, 2016). There are three useful objectives: SDG 2 is to put an end to hunger, achieve food security, enhance nutrition, and promote sustainable agriculture. SDG 7 is to ensure that everyone has access to affordable, dependable, and sustainable energy. SDG 13 is to increase resilience and adaptation capability in all countries to climate-related risks and natural catastrophes. FEE sustainability indicators are baseline data for tracking the 2030 agenda's progress.

The sustainable FEE nexus is a concept that represents the interconnectedness of Food, Energy, and Environment. It emphasizes that these three domains can be managed collaboratively to ensure a secure future for all.

The diagram highlights several key aspects of the FEE Nexus. Food security, for example, is achieved by making all resources more accessible to society. This means having enough nutritious food for everyone, all the time. Energy security, on the other hand, requires a steady and affordable supply of energy sources. The diagram pointed out that this can be achieved through cost-effective and uninterrupted energy sources. Finally, environmental security involves protecting the environment from harm. The diagram emphasized that this can be done by preventing climate change, reducing CO_2 emissions, protecting biodiversity, and preserving ecosystems.

The diagram also highlighted the importance of society and the economy in achieving the FEE Nexus. It stated that an equitable and sustainable economy is necessary for the development of the FEE Nexus. This means that everyone has access to the resources they need to live a good life and that the economy does not harm the environment.

Overall, the FEE Nexus is a framework for understanding the complex relationships between Food, Energy, and Environment. It can be used to guide decision-making and investment to create a more sustainable future for all. While it is a relatively new concept, and there is still ongoing research on how to best implement it, the FEE nexus has the potential to make a significant contribution to achieving sustainable development.

6. CONCLUSIONS

6.1. Implications

This research revealed the intricate link between FEE security, emphasizing the impact of actions at all levels, from individual households to international partnerships. Interventions in one area can cascade into others, highlighting the need for comprehensive and coordinated strategies. For instance, large-scale energy projects might affect local biofuel plants and regional environmental security. Similarly, global trade regulations can influence regional agricultural production and distribution networks.

Tackling these complex challenges requires a multifaceted approach. Policymakers must prioritize sustainable practices throughout the production, consumption, and environmental spheres, advocating for circular economies and embracing renewable resources. Moreover, ensuring worker well-being through fair labour policies, particularly for marginalized farmers, is vital. Responsible management of domestic resources is crucial for bolstering overall food security. Effective management of domestic materials and attainment of inclusive food security goals necessitate collaboration among all stakeholders, including governments, industries, and consumers.

The research also unveiled discrepancies in European countries' energy transition efforts, with some leading in renewable energy adoption while others fall behind. Tailoring solutions to each country's specific needs is key, focusing on expanding renewable energy capacity, strengthening cross-border energy grid connections, and fostering regional cooperation. The study identifies technology and system integration as crucial drivers for advancing renewable energy integration and enhancing energy efficiency.

The research further identified targeted strategies for reducing CO_2 emissions in the agri-food sector, emphasizing the importance of energy efficiency and sustainable practices across the entire supply chain. Collaboration among policymakers, producers, retailers, and consumers is crucial for implementing comprehensive solutions, including consumer education, and incentivizing sustainable practices. Continued investment in research and development of innovative technologies is critical for emission reduction and building resilience in the food system.

Methodologically, the research stressed the need to consider the multidimensional aspects of sustainable development initiatives when quantifying and analyzing global concerns. These findings resonate deeply with policymakers worldwide, as the demand for safe and clean food, along with sustainable energy, continues to rise alongside the growing global population.

6.2. Limitations and future research directions

The study's limitations stemmed from methodological choices and variable selection. The arbitrary selection of key variables introduces bias, particularly omitted variable bias. Additionally, the study's broad scope necessitates numerous indicators, potentially hindering representativeness. Future research should employ a multidisciplinary approach encompassing economics, circular economy, sustainability, resource management, and climate theories. This comprehensive approach is crucial for developing accurate indicators reflecting global realities and future trajectories.

While the energy security study offers valuable insights into EU electricity patterns, it lacks depth. It primarily focuses on demand and generation, neglecting crucial factors like energy prices, policies, technological advancements, and socio-economic dynamics. Furthermore, the 2010-2022 timeframe restricts capturing crucial long-term trends and cycles. A more comprehensive and extended analysis incorporating these neglected aspects would yield a deeper understanding of the EU energy market evolution.

The environmental security study's findings may lack representativeness due to focusing on only eight countries, ignoring variations in practices, conditions, policies, and infrastructure. While identifying emission reduction opportunities, it doesn't evaluate specific mitigation strategies or policy interventions. Further research is necessary to assess the effectiveness of emissions reduction initiatives and sustainability objectives.

Further research is crucial to overcome these limitations and move forward. Deep dives into specific regions facing significant challenges, like the V4 countries, can provide a clearer understanding of their unique circumstances. Analyzing existing policies and exploring their potential for adaptation or transfer across the EU can lead to more effective solutions. Investigating innovative solutions in areas like renewable energy and sustainable agriculture offers promising avenues for addressing identified challenges. Furthermore, understanding public perceptions and behavior concerning sustainable development in different regions is crucial for developing targeted interventions and communication strategies that promote responsible practices. Finally, conducting longitudinal studies will allow for tracking progress over time and assessing the effectiveness of implemented policies in achieving long-term sustainable development goals across the entire EU.

This research also highlighted the need to improve educational approaches for sustainable food production, climate change, and energy issues. Redesigning programs to align with sustainable engineering principles necessitates integrating rigorous energy-saving system maintenance, big data science, and decision analysis techniques. This requires collaboration between STEM researchers and social science professionals to understand the socio-cultural, economic, regional, and political contexts of environmental challenges. Furthermore, expanding engineering curricula to include global issues and their interconnectedness is crucial.

6.3. Main findings of the study

Instead of taking a simplistic view of FEE security, as has been done in the past, the dissertation focused on the nuances essential for delving into the relationships between FEE and other social, economic, and environmental factors. The examination concluded that the various aspects of food security are expected to have varying effects on the different parts of SDGs. Specifically, the following findigs were discovered:

Table 13: Empirical findings aligned with research hypotheses of the study.

Sl. No	Findings	Suporintg Hypothesis
01.	The study on food security in selected EU countries revealed a regional disparity and identified challenges in access, affordability, and quality. Urbanization and economic factors affect access, while consumption habits and import reliance impact affordability. Diet quality, including protein intake, is also a concern.	The finding provides evidence that food security is indeed linked to regional disparities, higher urbanization, and (implicitly) economic growth, supporting Hypothesis 1 (H1).
02.	This research proved food security and sustainability demand a strategy focused on efficient domestic material consumption (DMC), sustainable intensification, upgraded road, rail, and port infrastructure, dietary diversity, and waste reduction.	The research finding highlights specific strategies that contribute to the core elements of Hypothesis 2 (H2): efficient production, better infrastructure, diverse diets, and reduced waste. By implementing these strategies,

		we can achieve a more sustainable food future.
03.	The study demonstrated a 204.34% increase in renewable energy consumption from 2010-2022. This growth underscored the effectiveness of sustainability policies and investments in accelerating the shift towards a greener energy sector.	The growth in renewable energy consumption is seen as a positive step towards a more diverse energy mix. This alignment with the core concept of Hypothesis 3 (H3) strengthens the hypothesis.
04.	This research revealed that household food consumption is the primary driver (24.8%) of food-related CO_2 emissions in selected European countries, followed by on-farm energy use (18.5%) and food transportation (13.8%).	The finding strongly supports Hypothesis 4 (H4) by highlighting that several stages within the food system, heavily influenced by food production practices and energy consumption patterns, are significant contributors to CO_2 emissions.

Source: Author's compilation

6.4. New and novel results

While previous research explored facets of global food security, none holistically examined the interconnected variables crucial for its long-term sustainability. This dissertation addressed this gap by analyzing the impact of various factors on maintaining FEE security, offering fresh insights into a comprehensive approach.

A review of relevant literature revealed numerous factors that, if unaddressed, hinder food security strategies. As demonstrated, the proposed model for sustainable food security necessitated careful consideration of these factors when developing strategic action plans.

The selected EU member states exhibited diverse energy transitions. Some countries embraced renewables, while others relied mainly on fossil fuels. To achieve a secure, sustainable, and affordable energy future for all, tailored policies and collaborative efforts are essential.

Understanding these divergent paths is critical for effective interventions. Countries like Austria, Belgium, and the Netherlands exemplify the power of supportive policies in driving renewable energy growth. However, challenges like import dependence and nuclear power decline in some regions demand innovative solutions.

Enhancing interconnection and regional cooperation can address these hurdles by facilitating resource exchange and grid stability. Aligning national strategies with EU goals, while respecting individual circumstances, is crucial. Additionally, investing in technological innovation, system integration, and smart grids enables greater flexibility and integration of renewables. The research novel results were as follows:

Table 14: Novelty: contributions of the research

1.	The findings succinctly captured how SDGs 2, 7, and 13 influence FEE security across the selected EU countries, stressing the need for regionally tailored policies to address these interconnected challenges.
2.	The research explored a novel energy transition concept based on energy security pillars and RePowerEU principles, aiming to achieve carbon neutrality.
3.	An integrated FEE model was developed and linked to SDG 2, 7, and 13, seeking dual security and sustainability.
4.	Th investigation led to the development of a novel framework that seamlessly integrates sustainability dimensions with FEE security considerations.

Source: Author's compilation

By tackling these challenges and seizing existing opportunities, Europe can achieve its energy and climate objectives while ensuring energy security, affordability, and resilience for all member states. The path forward requires both individual action and collective effort, paving the way for a sustainable energy future for the entire continent.

Analyzing CO_2 emissions in the EU's agri-food sector identified opportunities for targeted intervention. Tailored policies and practices can reduce emissions from specific areas like food packaging and household consumption. Prioritizing sectors with high emissions, such as food processing and on-farm energy use, can yield significant reductions.

Promoting sustainable practices throughout the supply chain, from pesticide use to packaging materials, is crucial. Collaboration among stakeholders, including producer education, is essential for implementing comprehensive solutions. Continued investment in research and development of new technologies and practices is vital for achieving meaningful emissions reductions and building a more resilient and environmentally sustainable food system in the EU.

7. SUMMARY

This research investigated the interconnected web of FEE security, requiring a holistic approach to address its complexities. The introduction emphasized the importance of understanding how these domains are linked, particularly within the framework of SDG 2, 7, 12, and 13. Key terms were defined for clarity, and the study's objectives were outlined. By analyzing the impact of these SDGs on FEE, the research filled a critical gap in comprehending their interdependencies. The literature review explored existing research on each security domain individually, followed by an analysis of existing literature exploring their interconnections. It identified gaps in knowledge and justified further investigation. Additionally, the research contributed to theory by proposing a novel framework that integrated sustainability dimensions with FEE security considerations, deepening understanding of these intricate issues.

A new conceptual framework was developed, merging concepts from each security domain. This framework illuminated how factors like climate change, land use, and energy production influence system stability and resilience. The research also presented a novel energy transition concept based on energy security pillars and RePowerEU principles, aiming for carbon neutrality and offering a comprehensive strategy for transitioning to sustainable energy systems. The methodology section detailed the research design, data collection methods, and analysis techniques. The chosen approach was justified, and any limitations or constraints were transparently discussed. This transparency strengthened the research methodology's rigor and enhanced the credibility of the findings. The dissertation also proposed an integrated FEE model targeting SDG 2, 7, and 13, aiming for dual security and sustainability. This model provided a comprehensive analytical tool for assessing the sustainability and resilience of these systems.

The analysis and findings section presented the empirical results, meticulously analyzing data to uncover patterns, trends, and relationships between variables. Various statistical methods were employed to shed light on the implications of these findings for understanding and addressing the challenges inherent in securing FEE. Additionally, the section integrated results with the potential to address Europe's specific challenges, providing practical solutions. Three unique models were incorporated to offer FEE security solutions. These models provided valuable insight into the practical implications of the research, highlighting lessons learned and potential strategies for enhancing security in these crucial areas. Finally, the research culminated with a comprehensive summary of its key findings and contributions to the field. Future research directions were proposed, paving the way for continued exploration and inquiry into these vital issues.

8. REFERENCES

Abdi, H., Williams, L. J., & Valentin, D. (2013). Multiple factor analysis: principal component analysis for multitable and multiblock data sets. *Wiley Interdisciplinary Reviews: Computational Statistics*, *5*(2), 149–179. https://doi.org/10.1002/wics.1246

Abouelenin, M., & Hu, Y. (2024). Food insecurity and affective well-being during COVID-19 in the Middle East and North Africa. *Journal of Affective Disorders*, *350*, 741–745. https://doi.org/10.1016/j.jad.2024.01.103

Ackrill, R. (2005). Food for thought: towards a future for farming. By Patrick Herman and Richard Kuper (London: Pluto Press, 2003, pp. 156+xx). *Journal of International Development*, *17*(8), 1095–1097. https://doi.org/10.1002/jid.1145

Ahmad, W. S., Kaloop, M. R., Jamal, S., Taqi, M., Hu, J. W., & Abd El-Hamid, H. (2024). An analysis of LULC changes for understanding the impact of anthropogenic activities on food security: a case study of Dudhganga watershed, India. *Environmental Monitoring and Assessment*, *196*(1), 105. https://doi.org/10.1007/s10661-023-12264-9

Alińska, A., Filipiak, B., & Kosztowniak, A. (2018). The Importance of the Public Sector in Sustainable Development in Poland. *Sustainability*, *10*(9), 3278. https://doi.org/10.3390/su10093278

Allen, D. M. (1974). The Relationship Between Variable Selection and Data Augmentation and a Method for Prediction. *Technometrics*, *16*(1), 125–127. https://doi.org/10.1080/00401706.1974.10489157

Ang, B. W., Choong, W. L., & Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, *42*, 1077–1093. https://doi.org/10.1016/j.rser.2014.10.064

Appiah-Twumasi, M., & Asale, M. A. (2022). Crop diversification and farm household food and nutrition security in Northern Ghana. *Environment, Development and Sustainability*, *26*(1), 157–185. https://doi.org/10.1007/s10668-022-02703-x

ASIA PACIFIC ENERGY RESEARCH CENTRE. (2007). *A Quest for Energy Security in the 21st Century*.

Azabdaftari, F. (2019). Pillars of Sustainable Development. *Annals of Social Sciences & Management Studies*, *4*(3), 92–93. https://doi.org/10.19080/ASM.2019.04.555640

Barbir, F. (2009). Transition to renewable energy systems with hydrogen as an energy carrier☆. *Energy*, *34*(3), 308–312. https://doi.org/10.1016/j.energy.2008.07.007

Barrett, C. B. (2010a). Measuring Food Insecurity and Hunger. In *Measuring Food Insecurity and Hunger* (Issue February 2010). National Academies Press. https://doi.org/10.17226/11227

Barrett, C. B. (2010b). Measuring Food Insecurity and Hunger. In *Measuring Food Insecurity and Hunger* (Issue February 2010). National Academies Press. https://doi.org/10.17226/11227

Beck, M. B., & Villarroel Walker, R. (2013). On water security, sustainability, and the water-food-energy-climate nexus. *Frontiers of Environmental Science & Engineering*, *7*(5), 626–639. https://doi.org/10.1007/s11783-013-0548-6

Berning, J., Bonanno, A., & Cleary, R. (2024). Disparities in food insecurity among Black and White households: An analysis by age cohort, poverty,

education, and home ownership. *Applied Economic Perspectives and Policy*, *46*(1), 234–254. https://doi.org/10.1002/aepp.13332
Bhandari, M. P. (2022). Reducing Inequalities Towards Sustainable Development Goals. In *Reducing Inequalities Towards Sustainable Development Goals*. River Publishers. https://doi.org/10.1201/9781003339250
Bhatti, U. A., Bhatti, M. A., Tang, H., Syam, M. S., Awwad, E. M., Sharaf, M., & Ghadi, Y. Y. (2024). Global production patterns: Understanding the relationship between greenhouse gas emissions, agriculture greening and climate variability. *Environmental Research*, *245*, 118049. https://doi.org/10.1016/j.envres.2023.118049
BIOEAST. (2021). *BIOEAST Foresight Exercise - Sustainable Bioeconomies towards 2050* (Issue October).
Bodirsky, B. L., Dietrich, J. P., Martinelli, E., Stenstad, A., Pradhan, P., Gabrysch, S., Mishra, A., Weindl, I., Le Mouël, C., Rolinski, S., Baumstark, L., Wang, X., Waid, J. L., Lotze-Campen, H., & Popp, A. (2020). The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. *Scientific Reports*, *10*(1), 19778. https://doi.org/10.1038/s41598-020-75213-3
Borowski, P. F., & Patuk, I. (2021). Environmental, social and economic factors in sustainable development with food, energy and eco-space aspect security. *Present Environment and Sustainable Development*, *15*(1), 153–169. https://doi.org/10.15551/pesd2021151012
Borowy, I. (2021). The social dimension of sustainable development at the UN: from Brundtland to the SDGs. In *The Struggle for Social Sustainability* (pp. 89–108). Policy Press. https://doi.org/10.1332/policypress/9781447356103.003.0005
Boutin, J.-P., Gervasoni, G., Hlep, R., Seyboth, K., Lamers, P., Ratton, M., McCormick, K., Mundaca, L., & Plepys, A. (2006). ALTERNATIVE ENERGY SOURCES IN TRANSITION COUNTRIES. THE CASE OF BIO-ENERGY IN THE UKRAINE. *Environmental Engineering and Management Journal*, *5*(3), 471–486. https://doi.org/10.30638/eemj.2006.037
Brundtland, G. H. (1987). Report of the World Commission on Environment and Development : note / by the Secretary-General. In *United Nations*.
Burlinson, A., Davillas, A., Giulietti, M., & Price, C. W. (2024). Household energy price resilience in the face of gas and electricity market crises. *Energy Economics*, *132*, 107414. https://doi.org/10.1016/j.eneco.2024.107414
Campi, M., Dueñas, M., & Fagiolo, G. (2021). Specialization in food production affects global food security and food systems sustainability. *World Development*, *141*(June), 105411. https://doi.org/10.1016/j.worlddev.2021.105411
Chatterjee, S., Kar, A. K., & Mustafa, S. Z. (2021). Securing IoT devices in smart cities of India: from ethical and enterprise information system management perspective. *Enterprise Information Systems*, *15*(4), 585–615. https://doi.org/10.1080/17517575.2019.1654617
Chen, J. (2007). Rapid urbanization in China: A real challenge to soil protection and food security. *CATENA*, *69*(1), 1–15. https://doi.org/10.1016/j.catena.2006.04.019
Clapp, J., & Ruder, S.-L. (2020). Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability. *Global Environmental Politics*, *20*(3), 49–69. https://doi.org/10.1162/glep_a_00566

Coates, J. (2013). Build it back better: Deconstructing food security for improved measurement and action. *Global Food Security*, *2*(3), 188–194. https://doi.org/10.1016/j.gfs.2013.05.002

Cockx, L., Rancken, N., & Peiters, H. (2015). *Food and nutrition security in the European Union : Overview and case studies Food and nutrition security in the European Union : Overview and case studies*. *March*, 133. https://doi.org/http://dx.doi.org/10.13140/RG.2.1.3548.6245

Coff, C., Korthals, M., & Barling, D. (2008). Ethical Traceability and Informed Food Choice. In *Food Policy* (pp. 1–18). https://doi.org/10.1007/978-1-4020-8524-6_1

Conant, R. T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyvönen, R., Kirschbaum, M. U. F., Lavallee, J. M., Leifeld, J., Parton, W. J., Megan Steinweg, J., Wallenstein, M. D., Martin Wetterstedt, J. Å., & Bradford, M. A. (2011). Temperature and soil organic matter decomposition rates - synthesis of current knowledge and a way forward. *Global Change Biology*, *17*(11), 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Costa, J., Cancela, D., & Reis, J. (2021). Neverland or Tomorrowland? Addressing (In)compatibility among the SDG Pillars in Europe. *International Journal of Environmental Research and Public Health*, *18*(22), 11858. https://doi.org/10.3390/ijerph182211858

Dalampira, E. S., & Nastis, S. A. (2020). Back to the future: Simplifying Sustainable Development Goals based on three pillars of sustainability. *International Journal of Sustainable Agricultural Management and Informatics*, *6*(3), 226–240. https://doi.org/10.1504/IJSAMI.2020.112089

de Backer, E., Aertsens, J., Vergucht, S., & Steurbaut, W. (2009). Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA). *British Food Journal*, *111*(10), 1028–1061. https://doi.org/10.1108/00070700910992916

Dobreva, A., Svasek, M., & Erbach, G. (2016). *Energy supply and energy security* (Issue July).

Duane, A., Trasobares, A., Górriz, E., Casafont, L., & Maltoni, S. (2022). *The FIRE-RES Project: Innovative Technologies and Socio-Ecological–Economic Solutions for FIRE RESilient Territories in Europe*. 100. https://doi.org/10.3390/environsciproc2022017100

Dwyer, J. (2016). New Approaches to Revitalise Rural Economies and Communities-Reflections of a Policy Analyst. *European Countryside*, *8*(2), 175–182. https://doi.org/10.1515/euco-2016-0014

EC. (2020). *From Farm to Fork: Our food, our health, our planet, our future* (Issue May).

EIA. (2019). *Energy security - Areas of work - IEA*. IEA. https://www.iea.org/areas-of-work/ensuring-energy-security

El-kharouf, M. A. Q. A., & Serhad, S. and H. (2019). The Economics and Politics of China's Energy Security Transition. In M. Al Qubeissi, A. El-kharouf, & H. Serhad Soyhan (Eds.), *Renewable Energy - Resources, Challenges and Applications*. Elsevier. https://doi.org/10.1016/C2017-0-01392-7

Elmadfa, I., & Meyer, A. (2009). Trends in nutrition in Europe. *Acta Alimentaria*, *38*(2), 153–159. https://doi.org/10.1556/AAlim.38.2009.2.3

Energy Policy Review of Indonesia. (2008). In *International Energy Agency*.

Escofier, B., & Pages, J. (1994). Multiple factor analysis (AFMULT package). *Computational Statistics & Data Analysis*, *18*(1), 121–140. https://doi.org/10.1016/0167-9473(94)90135-X

EU. (2021). *Fighting climate change starts on your plate | European Youth Portal*. https://europa.eu/youth/get-involved/sustainable development/fighting-climate-change-starts-your-plate_en
European Commission. (2016). European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Regional Committee. Next Steps to a European Sustainable Future. In *EUR-Lex*.
European Commission. (2019). *Common Agricultural Policy : Key graphs & figures*. *July*, 2019.
European Commission. (2021). *State of the Energy Union 2021 – Contributing to the European Green Deal and the Union's recovery*.
European Commission. (2022). *REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition*.
European Commission (EC). (2022). *REPowerEU Plan*.
European Intelligence Units. (n.d.). *Global Food Security Index (GFSI)*.
Eurostat. (2020a). *Energy Database*. Energy Database.
Eurostat. (2020b). *Eurostat Energy Database*. Energy Database.
Eurostat. (2021). *Data Browser - Energy imports dependency*. Eurostat. https://ec.europa.eu/eurostat/databrowser/view/NRG_IND_ID__custom_938402/bookmark/table?lang=en,en&bookmarkId=f1ab4519-82df-4a89-a329-1b8d0a5925f7
Fadare, O., Srinivasan, C., & Zanello, G. (2024). Livestock diversification mitigates the impact of farmer-herder conflicts on animal-source foods consumption in Nigeria. *Food Policy*, *122*, 102586. https://doi.org/10.1016/j.foodpol.2023.102586
Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., & Vandewoestijne, S. (2017). Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environmental Research*, *159*(August 2017), 509–518. https://doi.org/10.1016/j.envres.2017.08.032
FAO. (2020). *FAOSTAT*.
FAO, IFAD, UNICEF, WFP, W. (2019a). The State of Food Security and Nutrition in the World 2019. In *Rome, FAO*.
FAO, IFAD, UNICEF, WFP, W. (2019b). The State of Food Security and Nutrition in the World 2019. In *Rome, FAO*.
FAOSTAT. (n.d.). Retrieved March 5, 2020, from http://www.fao.org/faostat/en/#data/GC
Farre, G., Twyman, R. M., Zhu, C., Capell, T., & Christou, P. (2011). Nutritionally enhanced crops and food security: scientific achievements versus political expediency. *Current Opinion in Biotechnology*, *22*(2), 245–251. https://doi.org/10.1016/j.copbio.2010.11.002
Fernandes, R. C., & Höfelmann, D. A. (2024). Simultaneity of health-related behaviors and food insecurity among pregnant women. *Health Care for Women International*, *0*(0), 1–16. https://doi.org/10.1080/07399332.2024.2317334
Fetanat, A., Tayebi, M., & Mofid, H. (2021). Water-energy-food security nexus based selection of energy recovery from wastewater treatment technologies: An extended decision making framework under intuitionistic fuzzy environment. *Sustainable Energy Technologies and Assessments*, *43*(November 2020), 100937. https://doi.org/10.1016/j.seta.2020.100937
Fontanet, A., & Cauchemez, S. (2020). COVID-19 herd immunity: where are we? *Nature Reviews Immunology*, *20*(10), 583–584. https://doi.org/10.1038/s41577-020-00451-5

Fortuna, G. (2020). *Food security is no longer an issue in the EU, says Commissioner – EURACTIV.com*. Euractiv. https://www.euractiv.com/section/agriculture-food/news/food-security-is-no-longer-an-issue-in-the-eu-says-commissioner/
Franz, M., Schlitz, N., & Schumacher, K. P. (2018). Globalization and the water-energy-food nexus – Using the global production networks approach to analyze society-environment relations. *Environmental Science & Policy*, *90*(December), 201–212. https://doi.org/10.1016/j.envsci.2017.12.004
Franzluebbers, A. J., & Gastal, F. (2019). Building Agricultural Resilience With Conservation Pasture-Crop Rotations. In *Agroecosystem Diversity* (pp. 109–121). Elsevier. https://doi.org/10.1016/B978-0-12-811050-8.00007-8
Friel, S., Dangour, A. D., Garnett, T., Lock, K., Chalabi, Z., Roberts, I., Butler, A., Butler, C. D., Waage, J., McMichael, A. J., & Haines, A. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *The Lancet*, *374*(9706), 2016–2025. https://doi.org/10.1016/S0140-6736(09)61753-0
Garren, S. J., & Brinkmann, R. (2018). Sustainability Definitions, Historical Context, and Frameworks. In S. J. Brinkmann Robert and Garren (Ed.), *The Palgrave Handbook of Sustainability* (pp. 1–18). Springer International Publishing. https://doi.org/10.1007/978-3-319-71389-2_1
Garson, G. D. (2016). *Partial Least Squares: Regression and Structural Models* (2016th ed.). Statistical Associates Publishers.
Geissler, C. H., Ryu, J., & Maravelias, C. T. (2024). The future of biofuels in the United States transportation sector. *Renewable and Sustainable Energy Reviews*, *192*, 114276. https://doi.org/10.1016/j.rser.2023.114276
Global Panel. (2018). Preventing Nutrient Loss and Waste across the Food System: Policy Actions for High-Quality Diets. In *Policy Brief* (Issue 12).
Godde, C. M., Mason-D'Croz, D., Mayberry, D. E., Thornton, P. K., & Herrero, M. (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. *Global Food Security*, *28*, 100488. https://doi.org/10.1016/j.gfs.2020.100488
Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, *327*(5967), 812–818. https://doi.org/10.1126/science.1185383
González, A., Mc Guinness, S., Murphy, E., Kelliher, G., & Hagin-Meade, L. (2023). Priorities, Scale and Insights: Opportunities and Challenges for Community Involvement in SDG Implementation and Monitoring. *Sustainability*, *15*(6), 4971. https://doi.org/10.3390/su15064971
Greco, C., Campiotti, A., de Rossi, P., Febo, P., & Giagnacovo, G. (2020). Energy consumption and improvement of energy efficiency for the European agricultural-food system. *Rivista Di Studi Sulla Sostenibilita*, *2020*(1), 92–103. https://doi.org/10.3280/RISS2020-001006
Guan, D.-X., Menezes-Blackburn, D., & Li, G. (2024). The Importance of Mineral Elements for Sustainable Crop Production. *Agronomy*, *14*(1), 209. https://doi.org/10.3390/agronomy14010209
Guo, C., Zhang, X., & Iqbal, S. (2024). Does oil price volatility and financial expenditures of the oil industry influence energy generation intensity? Implications for clean energy acquisition. *Journal of Cleaner Production*, *434*, 139907. https://doi.org/10.1016/j.jclepro.2023.139907

Hall, R. D., Brouwer, I. D., & Fitzgerald, M. A. (2007). Plant metabolomics and its potential application for human nutrition. *Physiologia Plantarum*, *132*(2), 071115143317004-??? https://doi.org/10.1111/j.1399-3054.2007.00989.x

Hammer, Øyvind, Harper, David A.T., and P. D. R. (2001). *Past: Paleontological Statistics Software Package for Education and Data Analysis* (Vol. 4, Issue 1).

Harjanne, A., & Korhonen, J. M. (2019). Abandoning the concept of renewable energy. *Energy Policy*, *127*(September 2018), 330–340. https://doi.org/10.1016/j.enpol.2018.12.029

Hasan, M., Abedin, M. Z., Amin, M. Bin, Nekmahmud, M., & Oláh, J. (2023). Sustainable biofuel economy: A mapping through bibliometric research. *Journal of Environmental Management*, *336*(March), 117644. https://doi.org/10.1016/j.jenvman.2023.117644

Hassan, Q., Viktor, P., J. Al-Musawi, T., Mahmood Ali, B., Algburi, S., Alzoubi, H. M., Khudhair Al-Jiboory, A., Zuhair Sameen, A., Salman, H. M., & Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, *48*, 100545. https://doi.org/10.1016/j.ref.2024.100545

Hertel, T. W. (2016). Food security under climate change. *Nature Climate Change*, *6*(1), 10–13. https://doi.org/10.1038/nclimate2834

HLPE. (2014). Food losses and waste in the context of sustainable food systems. In *A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. of Sustainable Food Systems* (Issue June).

HLPE. (2020a). Food Security and Nutrition: Building a Global Narrative towards 2030. In *High Level Panel of Experts*.

HLPE. (2020b). *Food Security and Nutrition Building a Global Narrative Towards 2030*.

Huang, C., Wang, W., Madonski, R., Lyu, J., Yue, G., & Ni, W. (2022). Novel Energy Saving Technologies for Thermodynamic Systems with Carbon Neutrality Goal. *SSRN Electronic Journal*, *8*, 9541–9553. https://doi.org/10.2139/ssrn.4034169

Husson, F., Josse, J., & Lê, S. (2008). FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software*, *25*. https://doi.org/10.18637/jss.v025.i01

Ibukun, C. O., & Adebayo, A. A. (2021). Household food security and the COVID-19 pandemic in Nigeria. *African Development Review*, *33*(S1), S75–S87. https://doi.org/10.1111/1467-8268.12515

IEA. (2014). *World Energy Outlook 2014*.

IEA. (2017). *Energy intensity – SDG7: Data and Projections – Analysis - IEA*. https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity

IEEE. (2019). *The Smart Grid and Renewable Energy*. I.E.E.E. https://innovationatwork.ieee.org/smart-grid-transforming-renewable-energy/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. (2018). (2018a). *The IPBES assessment report on land degradation and restoration.* (Issue July 2018). https://doi.org/https://doi.org/10.5281/zenodo.3237392

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. (2018). (2018b). *The IPBES assessment report on land degradation and restoration.* (Issue July 2018). https://doi.org/https://doi.org/10.5281/zenodo.3237392

Iqbal, N., Abbasi, K. R., Shinwari, R., Guangcai, W., Ahmad, M., & Tang, K. (2021). Does exports diversification and environmental innovation achieve carbon neutrality target of OECD economies? *Journal of Environmental Management*, *291*(February), 112648. https://doi.org/10.1016/j.jenvman.2021.112648

IRENA. (n.d.). *Energy Transition*. International Renewable Energy Agency. Retrieved January 24, 2022, from https://www.irena.org/energytransition

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A. F., Goodman, S. C., Chapman, W. E., Cameron, M. A., Bozonnat, C., Chobadi, L., Clonts, H. A., Enevoldsen, P., Erwin, J. R., Fobi, S. N., Goldstrom, O. K., Hennessy, E. M., Liu, J., Lo, J., Meyer, C. B., Morris, S. B., Moy, K. R., … Yachanin, A. S. (2017). 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, *1*(1), 108–121. https://doi.org/10.1016/j.joule.2017.07.005

Jewell, J., Cherp, A., & Riahi, K. (2014). Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy*, *65*, 743–760. https://doi.org/10.1016/j.enpol.2013.10.051

Johan Helland, G. M. S. (2014). Food security and social conflict. In *Chr. Michelsen Institute*. Chr. Michelsen Institute.

Johnston, J. L., Fanzo, J. C., & Cogill, B. (2014). Understanding Sustainable Diets: A Descriptive Analysis of the Determinants and Processes That Influence Diets and Their Impact on Health, Food Security, and Environmental Sustainability. *Advances in Nutrition*, *5*(4), 418–429. https://doi.org/10.3945/an.113.005553

Jun, E., Kim, W., & Chang, S. H. (2009). The analysis of security cost for different energy sources. *Applied Energy*, *86*(10), 1894–1901. https://doi.org/10.1016/j.apenergy.2008.11.028

Kandel, G. P., Bavorova, M., Ullah, A., & Pradhan, P. (2024a). Food security and sustainability through adaptation to climate change: Lessons learned from Nepal. *International Journal of Disaster Risk Reduction*, *101*, 104279. https://doi.org/10.1016/j.ijdrr.2024.104279

Kandel, G. P., Bavorova, M., Ullah, A., & Pradhan, P. (2024b). Food security and sustainability through adaptation to climate change: Lessons learned from Nepal. *International Journal of Disaster Risk Reduction*, *101*, 104279. https://doi.org/10.1016/j.ijdrr.2024.104279

Kannan, K. P., Dev, S. M., & Sharma, A. N. (2000). Concerns on Food Security. *Economic And Political Weekly*, *35*(45), 3919–3922. https://doi.org/10.2307/4409916

Kearney, J. (2010). Food consumption trends and drivers. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2793–2807. https://doi.org/10.1098/rstb.2010.0149

Khorev, A. I., Ovchinnikova, T. I., Belyaeva, G. V., Bulgakova, I. N., & Lebedeva, E. V. (2020). *Social and Labour Challenges of Regional Economic Development*. https://doi.org/10.2991/aebmr.k.200730.074

Kitole, F. A., & Sesabo, J. K. (2024). The Heterogeneity of Socioeconomic Factors Affecting Poverty Reduction in Tanzania: A Multidimensional Statistical Inquiry. *Society*. https://doi.org/10.1007/s12115-024-00957-x

Kłoczowski, J. (2004). Actualité des grandes traditions de la cohabitation et du dialogue des cultures en Europe du Centre-Est. In *L'heritage historique de la Res Publica de Plusieurs Nations* (pp. 29.-30.). Lublin.

Kobylińska, M., Antosik, K., Decyk, A., & Kurowska, K. (2022). Malnutrition in Obesity: Is It Possible? *Obesity Facts*, *15*(1), 19–25. https://doi.org/10.1159/000519503

Koff, H., & Maganda, C. (2020). Coherence and cooperation as pillars of sustainable development. *Regions and Cohesion*, *10*(1), iv–vi. https://doi.org/10.3167/reco.2020.100101

Kohavi, R. (2001). A Study of Cross-Validation and Bootstrap for Accuracy Estimation and Model Selection. *Proceedings of the Fourteenth International Joint Conference on Artificial Intelligence.*, *14*.

Koralesky, K. E., Tworek, H. J. S., von Keyserlingk, M. A. G., & Weary, D. M. (2024). "Frequently Asked Questions" About Genetic Engineering in Farm Animals: A Frame Analysis. *Food Ethics*, *9*(1), 7. https://doi.org/10.1007/s41055-024-00143-z

Köse, N., & Ünal, E. (2022). The effects of the oil price and temperature on food inflation in Latin America. *Environment, Development and Sustainability*, *26*(2), 3269–3295. https://doi.org/10.1007/s10668-022-02817-2

Kummu, M., Fader, M., Gerten, D., Guillaume, J. H., Jalava, M., Jägermeyr, J., Pfister, S., Porkka, M., Siebert, S., & Varis, O. (2017). Bringing it all together: linking measures to secure nations' food supply. *Current Opinion in Environmental Sustainability*, *29*, 98–117. https://doi.org/10.1016/j.cosust.2018.01.006

Ladha-Sabur, A., Bakalis, S., Fryer, P. J., & Lopez-Quiroga, E. (2019). Mapping energy consumption in food manufacturing. *Trends in Food Science and Technology*, *86*, 270–280. https://doi.org/10.1016/j.tifs.2019.02.034

Lamichhane, S., Eğilmez, G., Gedik, R., Bhutta, M. K. S., & Erenay, B. (2021). Benchmarking OECD countries' sustainable development performance: A goal-specific principal component analysis approach. *Journal of Cleaner Production*, *287*, 125040. https://doi.org/10.1016/j.jclepro.2020.125040

Le Blanc, D. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustainable Development*, *23*(3), 176–187. https://doi.org/10.1002/sd.1582

Leisner, C. P. (2020). Review: Climate change impacts on food security- focus on perennial cropping systems and nutritional value. *Plant Science*, *293*, 110412. https://doi.org/10.1016/j.plantsci.2020.110412

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012). International trade drives biodiversity threats in developing nations. *Nature*, *486*(7401), 109–112. https://doi.org/10.1038/nature11145

Louman, B., Keenan, R. J., Kleinschmit, D., Atmadja, S., Sitoe, A. A., Nhantumbo, I., de Camino Velozo, R., & Morales, J. P. (2019). SDG 13: Climate action-Impacts on forests and people. In *Sustainable Development Goals: Their Impacts on Forests and People* (pp. 419–444). Cambridge University Press. https://doi.org/10.1017/9781108765015.015

Love, P. (2016). Debate the Issues: New Approaches to Economic Challenges. In *OECD Insights*. Organisation for Economic Cooperation and Development. https://doi.org/10.1787/9789264264687-en

MacFeely, S. (2019). The Big (data) Bang: Opportunities andChallenges for Compiling SDG Indicators. *Global Policy*, *10*(S1), 121–133. https://doi.org/10.1111/1758-5899.12595

Machell, J., Prior, K., Allan, R., & Andresen, J. M. (2015). The water energy food nexus – challenges and emerging solutions. *Environmental Science: Water Research & Technology*, *1*(1), 15–16. https://doi.org/10.1039/C4EW90001D

Maistry, N., & Annegarn, H. (2016). Using energy profiles to identify university energy reduction opportunities. *International Journal of Sustainability in Higher Education*, *17*(2), 188–207. https://doi.org/10.1108/IJSHE-09-2014-0129

Marino, A., & Pariso, P. (2020). Comparing European countries' performances in the transition towards the Circular Economy. *Science of The Total Environment*, *729*, 138142. https://doi.org/10.1016/j.scitotenv.2020.138142

Marshall, D. (2001). Food Availability and The European Consumer. In *Food, People and Society* (pp. 317–338). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-04601-2_20

Mata Pérez, M. de la E., Scholten, D., & Smith Stegen, K. (2019). The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security. *Energy Strategy Reviews*, *26*(October), 100415. https://doi.org/10.1016/j.esr.2019.100415

Máté, D., Rabbi, M. F., Novotny, A., & Kovács, S. (2020a). Grand Challenges in Central Europe: The Relationship of Food Security, Climate Change, and Energy Use. *Energies*, *13*(20), 5422. https://doi.org/10.3390/en13205422

Máté, D., Rabbi, M. F., Novotny, A., & Kovács, S. (2020b). Grand Challenges in Central Europe: The Relationship of Food Security, Climate Change, and Energy Use. *Energies*, *13*(20), 5422. https://doi.org/10.3390/en13205422

Mc Carthy, U., Uysal, I., Badia-Melis, R., Mercier, S., O'Donnell, C., & Ktenioudaki, A. (2018a). Global food security – Issues, challenges and technological solutions. *Trends in Food Science & Technology*, *77*(August 2017), 11–20. https://doi.org/10.1016/j.tifs.2018.05.002

Mc Carthy, U., Uysal, I., Badia-Melis, R., Mercier, S., O'Donnell, C., & Ktenioudaki, A. (2018b). Global food security – Issues, challenges and technological solutions. *Trends in Food Science & Technology*, *77*(August 2017), 11–20. https://doi.org/10.1016/j.tifs.2018.05.002

Mensah, J., & Enu-Kwesi, F. (2019). Implications of environmental sanitation management for sustainable livelihoods in the catchment area of Benya Lagoon in Ghana. *Journal of Integrative Environmental Sciences*, *16*(1), 23–43. https://doi.org/10.1080/1943815X.2018.1554591

Moldan, B., Janoušková, S., & Hák, T. (2012). How to understand and measure environmental sustainability: Indicators and targets. *Ecological Indicators*, *17*, 4–13. https://doi.org/10.1016/j.ecolind.2011.04.033

Monforti, F., & Dallemand, J. F. (2015). *Energy use in the EU food sector: State of play and opportunities for improvement Energy from Waste in Croatia View project*. https://doi.org/10.2790/158316

Morton, S., Pencheon, D., & Squires, N. (2017). Sustainable Development Goals (SDGs), and their implementation. *British Medical Bulletin*, *124*(1), 1–10. https://doi.org/10.1093/bmb/ldx031

Mostova, A., & Hutorov, A. (2023). Food security in the countries of Central and Eastern Europe: state and strategic directions of provision. *Ekonomika APK*, *30*(1), 20–29. https://doi.org/10.32317/2221-1055.202301020

Moyo, P. (2024). The Political Economy of Zimbabwe's Food Crisis, 2019–2020. *Journal of Asian and African Studies*, *59*(2), 640–655. https://doi.org/10.1177/00219096221120923

Neves Freiria, C., Arikawa, A., Van Horn, L. T., Pires Corona, L., & Wright, L. Y. (2024). Food Insecurity Among Older Adults Living in Low- and Middle-Income Countries: A Scoping Review. *The Gerontologist*, *64*(1). https://doi.org/10.1093/geront/gnac161

Nogueira, C., Marques, J. F., & Pinto, H. (2024). Intentional sustainable communities and sustainable development goals: from micro-scale implementation to scalability of innovative practices. *Journal of Environmental Planning and Management*, *67*(1), 175–196. https://doi.org/10.1080/09640568.2022.2106553
Nuttall, W. J., & Manz, D. L. (2008). A new energy security paradigm for the twenty-first century. *Technological Forecasting and Social Change*, *75*(8), 1247–1259. https://doi.org/10.1016/j.techfore.2008.02.007
Odhiambo, V. O., Hendriks, S. L., & Mutsvangwa-Sammie, E. P. (2021). The effect of an objective weighting of the global food security index's natural resources and resilience component on country scores and ranking. *Food Security*. https://doi.org/10.1007/s12571-021-01176-6
Ozturk, I. (2015). Sustainability in the food-energy-water nexus: Evidence from BRICS (Brazil, the Russian Federation, India, China, and South Africa) countries. *Energy*, *93*, 999–1010. https://doi.org/10.1016/j.energy.2015.09.104
Pagès, J. (2014). Multiple factor analysis and procrustes analysis. In *Multiple factor analysis by example using R*. Chapman and Hall.
Pagés, J., & Husson, F. (2005). Multiple factor analysis with confidence ellipses: a methodology to study the relationships between sensory and instrumental data. *Journal of Chemometrics*, *19*(3), 138–144. https://doi.org/10.1002/cem.916
Pandey, S., Olsen, A., Perez-Cueto, F. J. A., & Thomsen, M. (2023). Nudging Toward Sustainable Food Consumption at University Canteens: A Systematic Review and Meta-Analysis. *Journal of Nutrition Education and Behavior*, *55*(12), 894–904. https://doi.org/10.1016/j.jneb.2023.09.006
Pham, N. M., Huynh, T. L. D., & Nasir, M. A. (2020). Environmental consequences of population, affluence and technological progress for European countries: A Malthusian view. *Journal of Environmental Management*, *260*(December 2019), 110143. https://doi.org/10.1016/j.jenvman.2020.110143
Pinstrup-Andersen, P. (2009). Food security: definition and measurement. *Food Security*, *1*(1), 5–7. https://doi.org/10.1007/s12571-008-0002-y
Popp, J., Lakner, Z., Harangi-Rákos, M., & Fári, M. (2014). The effect of bioenergy expansion: Food, energy, and environment. *Renewable and Sustainable Energy Reviews*, *32*, 559–578. https://doi.org/10.1016/j.rser.2014.01.056
Pradhan, P., Kriewald, S., Costa, L., Rybski, D., Benton, T. G., Fischer, G., & Kropp, J. P. (2020). Urban Food Systems: How Regionalization Can Contribute to Climate Change Mitigation. *Environmental Science & Technology*, *54*(17), 10551–10560. https://doi.org/10.1021/acs.est.0c02739
Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5
Quisumbing, A. R., Brown, L. R., Feldstein, H. S., Haddad, L., & Peña, C. (1996). Women: The Key to Food Security. *Food and Nutrition Bulletin*, *17*(1), 1–2. https://doi.org/10.1177/156482659601700116
Rabbi, M. F., Ben Hassen, T., El Bilali, H., Raheem, D., & Raposo, A. (2023). Food Security Challenges in Europe in the Context of the Prolonged Russian–Ukrainian Conflict. *Sustainability*, *15*(6), 4745. https://doi.org/10.3390/su15064745

Rabbi, M. F., Hasan, M., & Kovács, S. (2021). Food Security and Transition towards Sustainability. *Sustainability*, *13*(22), 12433. https://doi.org/10.3390/su132212433

Rabbi, M. F., Oláh, J., Popp, J., Máté, D., & Kovács, S. (2021a). Food Security and the COVID-19 Crisis from a Consumer Buying Behaviour Perspective—The Case of Bangladesh. *Foods*, *10*(12), 3073. https://doi.org/10.3390/foods10123073

Rabbi, M. F., Oláh, J., Popp, J., Máté, D., & Kovács, S. (2021b). Food Security and the COVID-19 Crisis from a Consumer Buying Behaviour Perspective—The Case of Bangladesh. *Foods*, *10*(12), 3073. https://doi.org/10.3390/foods10123073

Rabbi, M. F., Popp, J., Máté, D., & Kovács, S. (2022a). Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energies*, *15*(21), 8126. https://doi.org/10.3390/en15218126

Rabbi, M. F., Popp, J., Máté, D., & Kovács, S. (2022b). Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energies*, *15*(21), 8126. https://doi.org/10.3390/en15218126

Rakotomalala, R. (2005). TANAGRA: a Free Software for Research and Academic Purposes. *Proceedings of EGC*, *2*, 697–702.

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development*, *18*, 14–25. https://doi.org/10.1016/j.envdev.2015.12.001

Read, Q. D., Brown, S., Cuéllar, A. D., Finn, S. M., Gephart, J. A., Marston, L. T., Meyer, E., Weitz, K. A., & Muth, M. K. (2020). Assessing the environmental impacts of halving food loss and waste along the food supply chain. *Science of The Total Environment*, *712*, 136255. https://doi.org/10.1016/j.scitotenv.2019.136255

Rebelatto, B. G., Lange Salvia, A., Reginatto, G., Daneli, R. C., & Brandli, L. L. (2019). Energy efficiency actions at a Brazilian university and their contribution to sustainable development Goal 7. *International Journal of Sustainability in Higher Education*, *20*(5), 842–855. https://doi.org/10.1108/IJSHE-01-2019-0023

Reisch, L., Eberle, U., & Lorek, S. (2013). Sustainable food consumption: an overview of contemporary issues and policies. *Sustainability: Science, Practice and Policy*, *9*(2), 7–25. https://doi.org/10.1080/15487733.2013.11908111

Renewable energy. (2023). European Environment Agency. https://www.eea.europa.eu/en/topics/in-depth/renewable-energy

Riseh, R. S., Vazvani, M. G., Hassanisaadi, M., & Thakur, V. K. (2024). Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. *Industrial Crops and Products*, *208*, 117904. https://doi.org/10.1016/j.indcrop.2023.117904

Rodríguez-Fernández, L., Fernández Carvajal, A. B., & Ruiz-Gómez, L. M. (2020). Evolution of European Union's energy security in gas supply during Russia–Ukraine gas crises (2006–2009). *Energy Strategy Reviews*, *30*(February), 100518. https://doi.org/10.1016/j.esr.2020.100518

Rokicki, T., & Perkowska, A. (2020). Changes in Energy Supplies in the Countries of the Visegrad Group. *Sustainability*, *12*(19), 7916. https://doi.org/10.3390/su12197916

Rokicki, T., Perkowska, A., Klepacki, B., Bórawski, P., Bełdycka-Bórawska, A., & Michalski, K. (2021). Changes in energy consumption in agriculture in the eu countries. *Energies*, *14*(6). https://doi.org/10.3390/en14061570

Rounsevell, M.; Fischer, M.; Rando, A. T. M.; Mader, A. (2018). *The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia*. https://doi.org/10.5281/zenodo.3237428

Royo-Bordonada, M. Á. (2016). Setting up childhood obesity policies in Europe. *The Lancet*, *388*(10059), 2475. https://doi.org/10.1016/S0140-6736(16)32175-4

Russell-Bennett, R., Rosenbaum, M. S., Fisk, R. P., & Raciti, M. M. (2024). SDG editorial: improving life on planet earth – a call to action for service research to achieve the sustainable development goals (SDGs). *Journal of Services Marketing*, *38*(2), 145–152. https://doi.org/10.1108/JSM-11-2023-0425

Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19703–19708. https://doi.org/10.1073/pnas.0701976104

Screti, C., Edwards, K., & Blissett, J. (2024). Understanding family food purchasing behaviour of low-income urban UK families: An analysis of parent capability, opportunity and motivation. *Appetite*, *195*, 107183. https://doi.org/10.1016/j.appet.2023.107183

Shahbaz, M., Raghutla, C., Chittedi, K. R., Jiao, Z., & Vo, X. V. (2020). The effect of renewable energy consumption on economic growth: Evidence from the renewable energy country attractive index. *Energy*, *207*, 118162. https://doi.org/10.1016/j.energy.2020.118162

Shaw, D. J. (2007). World Food Summit, 1996. In *World Food Security* (Vol. 95, Issue 1, pp. 347–360). Palgrave Macmillan UK. https://doi.org/10.1057/9780230589780_35

Shen, G., Ru, X., Wang, K., Li, Z., Yu, M., Chen, L., Han, J., & Guo, Y. (2024). Influence of labor migration on rural household food waste in China: Application of propensity score matching (PSM). *Journal of Environmental Management*, *351*, 119840. https://doi.org/10.1016/j.jenvman.2023.119840

Shrestha, S., Babel, M. S., & Pandey, V. P. (2014). Climate Change and Water Resources. In S. Shrestha, M. S. Babel, & V. P. Pandey (Eds.), *Climate Change and Water Resources* (Issue March 2016). CRC Press. https://doi.org/10.1201/b16969

Snyder, B. F. (2020). The genetic and cultural evolution of unsustainability. *Sustainability Science*, *15*(4), 1087–1099. https://doi.org/10.1007/s11625-020-00803-z

Solorio, I. (2011). Bridging the Gap between Environmental Policy Integration and the EU's Energy Policy: Mapping out the "Green Europeanisation" of Energy Governance. *Journal of Contemporary European Research*, *7*, 396–416.

Sotarauta, M. (2012). Leadership and Change in Sustainable Regional Development. In M. Sotarauta, I. Horlings, & J. Liddle (Eds.), *Leadership and Change in Sustainable Regional Development*. Routledge. https://doi.org/10.4324/9780203107058

Sousa, R. de, Bragança, L., da Silva, M. V., & Oliveira, R. S. (2024). Challenges and Solutions for Sustainable Food Systems: The Potential of Home Hydroponics. *Sustainability*, *16*(2), 817. https://doi.org/10.3390/su16020817

STEWART, J. (2003). MOVING FOOD. *African Security Review*, *12*(1), 17–27. https://doi.org/10.1080/10246029.2003.9627567

Stone, M. (1977). An Asymptotic Equivalence of Choice of Model by Cross-Validation and Akaike's Criterion. *Journal of the Royal Statistical Society: Series B (Methodological)*, *39*(1), 44–47. https://doi.org/10.1111/j.2517-6161.1977.tb01603.x

Suantika, G., Situmorang, M. L., Saputra, F. I., Putri, S. L. E., Putri, S. P., Aditiawati, P., & Fukusaki, E. (2020). Metabolite profiling of whiteleg shrimp Litopenaeus vannamei from super-intensive culture in closed aquaculture systems: a recirculating aquaculture system and a hybrid zero water discharge–recirculating aquaculture system. *Metabolomics*, *16*(4), 49. https://doi.org/10.1007/s11306-020-01675-1

Subramaniam, Y., Masron, T. A., & Azman, N. H. N. (2020). Biofuels, environmental sustainability, and food security: A review of 51 countries. *Energy Research & Social Science*, *68*(203), 101549. https://doi.org/10.1016/j.erss.2020.101549

Suhardono, S., Fitria, L., Suryawan, I. W. K., Septiariva, I. Y., Mulyana, R., Sari, M. M., Ulhasanah, N., & Prayogo, W. (2024). Human activities and forest fires in Indonesia: An analysis of the Bromo incident and implications for conservation tourism. *Trees, Forests and People*, *15*, 100509. https://doi.org/10.1016/j.tfp.2024.100509

Sun, F., Dai, Y., & Yu, X. (2017). Air pollution, food production and food security: A review from the perspective of food system. *Journal of Integrative Agriculture*, *16*(12), 2945–2962. https://doi.org/10.1016/S2095-3119(17)61814-8

Tamargo, J. (2022). Food values in Europe. *Food, Culture & Society*, *25*(4), 763–765. https://doi.org/10.1080/15528014.2021.1876487

The World Bank. (2020). *World Development Indicators | DataBank*.

Thiessen, S., Gleixner, G., Wutzler, T., & Reichstein, M. (2013). Both priming and temperature sensitivity of soil organic matter decomposition depend on microbial biomass – An incubation study. *Soil Biology and Biochemistry*, *57*, 739–748. https://doi.org/10.1016/j.soilbio.2012.10.029

Thow, A. M., Greenberg, S., Hara, M., Friel, S., duToit, A., & Sanders, D. (2018). Improving policy coherence for food security and nutrition in South Africa: a qualitative policy analysis. *Food Security*, *10*(4), 1105–1130. https://doi.org/10.1007/s12571-018-0813-4

Thurstone, L. L. (1931). Multiple factor analysis. *Psychological Review*, *38*(5), 406–427. https://doi.org/10.1037/h0069792

Tosun, J., & Leininger, J. (2017). Governing the Interlinkages between the Sustainable Development Goals: Approaches to Attain Policy Integration. *Global Challenges*, *1*(9), 1700036. https://doi.org/10.1002/gch2.201700036

Tötösy, S. (2002). *Comparative Central European Culture* (Steven Tötösy de Zepetnek, Ed.). Purdue University Press.

UN. (2020a). *The Sustainable Development Goals Report 2020*.

UN. (2020b). *The Sustainable Development Goals Report 2020*.

UNDG. (2017). *Mainstreaming the 2030 Agenda for Sustainable Development Reference Guide to UN Country Teams*. 137. https://doi.org/10.1016/j.landusepol.2015.05.019

UNFCCC. (2015). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United Nations. (n.d.). *THE 17 GOALS | Sustainable Development*. Retrieved March 8, 2022, from https://sdgs.un.org/goals

United Nations. (1987). *The World Commission on Environment and Development*.

United Nations. (2015). United Nations General Assembly. Transforming our world: The 2030 agenda for sustainable development. In *United Nations*.
United Nations. (2024a). *Goal 2 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal2
United Nations. (2024b). *Goal 7 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal7
United Nations. (2024c). *Goal 12 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal12
United Nations. (2024d). *Goal 13 | Department of Economic and Social Affairs*. https://sdgs.un.org/goals/goal13
UNITED NATIONS General Assembly. (n.d.).
Vann Yaroson, E., Chowdhury, S., Mangla, S. K., Dey, P., Chan, F. T. S., & Roux, M. (2024). A systematic literature review exploring and linking circular economy and sustainable development goals in the past three decades (1991–2022). *International Journal of Production Research*, *62*(4), 1399–1433. https://doi.org/10.1080/00207543.2023.2270586
Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. I. (2012). Climate Change and Food Systems. *Annual Review of Environment and Resources*, *37*(1), 195–222. https://doi.org/10.1146/annurev-environ-020411-130608
Videira, N., Schneider, F., Sekulova, F., & Kallis, G. (2014). Improving understanding on degrowth pathways: An exploratory study using collaborative causal models. *Futures*, *55*, 58–77. https://doi.org/10.1016/j.futures.2013.11.001
Vysochyna, A., Stoyanets, N., Mentel, G., & Olejarz, T. (2020). Environmental Determinants of a Country's Food Security in Short-Term and Long-Term Perspectives. *Sustainability*, *12*(10), 4090. https://doi.org/10.3390/su12104090
Wagh, M. S., S, S., Nath, P. C., Chakraborty, A., Amrit, R., Mishra, B., Mishra, A. K., & Mohanta, Y. K. (2024). Valorisation of agro-industrial wastes: Circular bioeconomy and biorefinery process – A sustainable symphony. *Process Safety and Environmental Protection*, *183*, 708–725. https://doi.org/10.1016/j.psep.2024.01.055
Wahbeh, S., Anastasiadis, F., Sundarakani, B., & Manikas, I. (2022). Exploration of Food Security Challenges towards More Sustainable Food Production: A Systematic Literature Review of the Major Drivers and Policies. *Foods*, *11*(23), 3804. https://doi.org/10.3390/foods11233804
Walker, T. R. (2021). (Micro)plastics and the UN Sustainable Development Goals. *Current Opinion in Green and Sustainable Chemistry*, *30*, 100497. https://doi.org/10.1016/j.cogsc.2021.100497
Wawrzyniak, D. (2020). CO2 Emissions in the Visegrad Group Countries and the European Union Climate Policy. *Comparative Economic Research. Central and Eastern Europe*, *23*(1), 73–91. https://doi.org/10.18778/1508-2008.23.05
Wenban-Smith, H., Faße, A., & Grote, U. (2016). Food security in Tanzania: the challenge of rapid urbanisation. *Food Security*, *8*(5), 973–984. https://doi.org/10.1007/s12571-016-0612-8
Wilcoxon, F. (1945). Individual Comparisons by Ranking Methods. *Biometrics Bulletin*, *1*(6), 80. https://doi.org/10.2307/3001968
WOLD, H. (1975). Path Models with Latent Variables: The NIPALS Approach. In *Quantitative Sociology*. https://doi.org/10.1016/b978-0-12-103950-9.50017-4

Wold, S., Sjöström, M., & Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemometrics and Intelligent Laboratory Systems*, *58*(2), 109–130. https://doi.org/10.1016/S0169-7439(01)00155-1
WTO. (2020). *Tariff Download Facility: WTO tariff database*.
WWAP. (2014). *The United Nations World Water Development Report 2014: Water and Energy.* (Vol. 1).
Yao, H., Alhussam, M. I., Abu Risha, O., & Memon, B. A. (2020). Analyzing the Relationship between Agricultural FDI and Food Security: Evidence from Belt and Road Countries. *Sustainability*, *12*(7), 2906. https://doi.org/10.3390/su12072906
Young, S. L., Frongillo, E. A., Jamaluddine, Z., Melgar-Quiñonez, H., Pérez-Escamilla, R., Ringler, C., & Rosinger, A. Y. (2021). Perspective: The Importance of Water Security for Ensuring Food Security, Good Nutrition, and Well-being. *Advances in Nutrition*, *12*(4), 1058–1073. https://doi.org/10.1093/advances/nmab003
Yue, Q., & Guo, P. (2021). Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. *Agricultural Water Management*, *252*(April), 106899. https://doi.org/10.1016/j.agwat.2021.106899
Zhang, H.-Y., Ji, Q., & Fan, Y. (2013). An evaluation framework for oil import security based on the supply chain with a case study focused on China. *Energy Economics*, *38*, 87–95. https://doi.org/10.1016/j.eneco.2013.03.014
ZOU, C., XIONG, B., XUE, H., ZHENG, D., GE, Z., WANG, Y., JIANG, L., PAN, S., & WU, S. (2021). The role of new energy in carbon neutral. *Petroleum Exploration and Development*, *48*(2), 480–491. https://doi.org/10.1016/S1876-3804(21)60039-3
Zurlini, G., & Müller, F. (2008). Environmental Security. In A. Gheciu & W. C. Wohlforth (Eds.), *Encyclopedia of Ecology* (Issue 2001, pp. 1350–1356). Elsevier. https://doi.org/10.1016/B978-008045405-4.00707-2

9. LIST OF PUBLICATIONS

UNIVERSITY of DEBRECEN

UNIVERSITY AND NATIONAL LIBRARY
UNIVERSITY OF DEBRECEN
H-4002 Egyetem tér 1, Debrecen
Phone: +3652/410-443, email: publikaciok@lib.unideb.hu

Registry number: DEENK//2023.PL
Subject: PhD Publication List

Candidate: Mohammad Fazle Rabbi
Doctoral School: Károly Ihrig Doctoral School of Management and Business
MTMT ID: 10074243

List of publications related to the dissertation

Articles, studies (8)

1. Kristia, K., Kovács, S., Bács, Z., **Rabbi, M. F.**: A Bibliometric Analysis of Sustainable Food Consumption: Historical Evolution, Dominant Topics and Trends.
   Sustainability. 15 (11), 1-24, 2023. ISSN: 2071-1050.
   DOI: http://dx.doi.org/10.3390/su15118998
   IF: 3.9 (2022)

2. Atikur Rahaman, M., Amin, M. B., Taru, R. D., Rasel Ahammed, M., **Rabbi, M. F.**: An analysis of renewable energy consumption in Visegrád countries.
   Environmental Research Communications. [Epub ahead of print] (-), 1-16, 2023. EISSN: 2515-7620.
   DOI: http://dx.doi.org/10.1088/2515-7620/acff40
   IF: 2.9 (2022)

3. Kristia, K., **Rabbi, M. F.**: Exploring the Synergy of Renewable Energy in the Circular Economy Framework: A Bibliometric Study.
   Sustainability. 15 (17), 1-27, 2023. ISSN: 2071-1050.
   DOI: http://dx.doi.org/10.3390/su151713165
   IF: 3.9 (2022)

4. **Rabbi, M. F.**, Hassen, T. B., El Bilali, H., Raheem, D., Raposo, A.: Food Security Challenges in Europe in the Context of the Prolonged Russian-Ukrainian Conflict.
   Sustainability. 15 (6), 1-20, 2023. ISSN: 2071-1050.
   DOI: http://dx.doi.org/10.3390/su15064745
   IF: 3.9 (2022)

5. **Rabbi, M. F.**: An assessment of food loss and waste in the Hungarian agri-food supply chain: Encouraging sustainable and conscious consumption.
   Prosperitas. 9 (3), 1-10, 2022. ISSN: 2064-759X.
   DOI: http://dx.doi.org/10.31570/prosp_2022_0026

6. Nekmahmud, M., **Rabbi, M. F.**, Hassan, A.: Evaluation of COVID-19's Effects and Opportunities for Bangladesh's Sustainable Tourism.
   In: The Emerald Handbook of Destination Recovery in Tourism and Hospitality. Ed.: Hassan, Azizul; Kennell, James; Sharma, Anukrati; Mohanty, Priyakrushna, Emerald Group Publishing Limited, West Yorkshire, 87-104, 2022. ISBN: 9781802620740

7. **Rabbi, M. F.**: Carbon dioxide emission trends and environmental problems in Central Europe.
   Apstract. 15 (1-2), 45-54, 2021. ISSN: 1789-221X.
   DOI: http://dx.doi.org/10.19041/APSTRACT/2021/1-2/6

8. **Rabbi, M. F.**, Nekmahmud, M.: Medical Tourism in Bangladesh: Issues, Opportunities and Strategic Marketing Plan Model for Growth and Development.
   In: Tourism in Bangladesh: Investment and Development Perspectives. Ed.: Hassan Azizul, Springer Singapore, Singapore, 191-208, 2021. ISBN: 9789811618581

List of other publications

<u>Articles, studies</u> (7)

9. **Rabbi, M. F.**, Popp, J., Máté, D., Kovács, S.: Energy Security and Energy Transition to Achieve Carbon Neutrality.
   Energies. 15 (21), 1-18, 2022. ISSN: 1996-1073.
   DOI: http://dx.doi.org/10.3390/en15218126
   IF: 3.2

10. Máté, D., **Rabbi, M. F.**, Novotny, Á., Kovács, S.: Grand Challenges in Central Europe: The Relationship of Food Security, Climate Change, and Energy Use. Utánközlés másodközlés,
    In: Economic and Policy Challenges of the Energy Transition in CEE Countries. Ed.: Jacek Kaminski, MDPI, Basel, 421-436, 2022. ISBN: 9783036534978

11. **Rabbi, M. F.**, Oláh, J., Popp, J., Máté, D., Kovács, S.: Food Security and the COVID-19 Crisis from a Consumer Buying Behaviour Perspective: The Case of Bangladesh.
    Foods. 10 (12), 1-20, 2021. EISSN: 2304-8158.
    DOI: http://dx.doi.org/10.3390/foods10123073
    IF: 5.561

12. **Rabbi, M. F.**, Hasan, M. M., Kovács, S.: Food Security and Transition towards Sustainability.
    Sustainability. 13, 1-21, 2021. ISSN: 2071-1050.
    DOI: https://doi.org/10.3390/su132212433
    IF: 3.889

13. Kovács, S., **Rabbi, M. F.**, Máté, D.: Global Food Security, Economic and Health Risk Assessment of the COVID-19 Epidemic.
    Mathematics. 9 (19), 1-16, 2021. EISSN: 2227-7390.
    DOI: https://doi.org/10.3390/math9192398
    IF: 2.592

14. Máté, D., **Rabbi, M. F.**: How to make food security sustainable related to economic crisis and pandemic recovery.
    SEA - Practical Application of Science. 9 (25), 59-66, 2021. EISSN: 2360-2554.

15. Máté, D., **Rabbi, M. F.**, Novotny, Á., Kovács, S.: Grand Challenges in Central Europe: The Relationship of Food Security, Climate Change, and Energy Use.
    Energies. 13 (20), 1-16, 2020. ISSN: 1996-1073.
    DOI: http://dx.doi.org/10.3390/en13205422
    IF: 3.004

Total IF of journals (all publications): 32,846
Total IF of journals (publications related to the dissertation): 14,6

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

24 October, 2023

10. List of the Tables

11. List of the Figures

12. List of the Boxes

13. List of the most frequently used abbreviations

Abbreviation	Definition
AFI	Agricultural Factor Income
DIM	Dimension
DMC	Domestic Material Consumption
EC	European Commission
EU	European Union
FAC	Food accessibility
FAF	Food affordability
FAO	Food and Agriculture Organization
FEE	Food, Energy, and Environment(al)
FQ	Food quality
FLW	Food Loss and Waste
GDP	Gross Domestic Product
GFSI	Global Food Security Index
GHG	Greenhouse Gas
MFA	Multifactor Analysis
NPP	Net Primary Productivity
OECD	Organisation for Economic Co-operation and Development
PC and PCA	Principal Component and Principal Component Analysis
PLSR	Partial Least Squares Regression
RE	Renewable energy
RMSE	Root Mean Squared Error
R&D	Research And Development
SDG	Sustainable Development Goal
SSPs	Shared Socioeconomic Pathways
UN	United Nations
WB	World Bank
WEF	Water-Energy-Food
WTO	World Trade Organization

14. Dedication

To my family, whose unwavering support and endless encouragement nourished my journey into the interconnected worlds of food, energy, and environmental security.

To my mentors, whose wisdom and guidance illuminated the complexities of European sustainability efforts, challenging me to explore and grow.

To the countless researchers, policymakers, activists, and individuals weaving a tapestry of sustainable solutions - your dedication inspires me.

This dissertation is dedicated to those who strive tirelessly to bridge the gap between human needs and environmental preservation, forging a path towards a more sustainable and secure future for generations to come.

15. Acknowledgement

First and foremost, I express my gratitude to the divine entity for bestowing upon me the fortitude, perseverance, and resolve necessary to understand government. I am grateful to both the Hungarian Government and Debrecen University for granting me the opportunity to pursue my doctoral studies. This research endeavour afforded me an exceptional opportunity, encompassing both intellectual and personal growth.

My deepest appreciation goes to Dr. Habil Kovács Sándor for his invaluable guidance, mentorship, and unwavering patience throughout this process. His confidence in me has been instrumental to my success.

I am also grateful to Dr. József Popp and Dr. Domicián Máté for their unwavering support during my pursuit of this academic achievement.

Finally, I extend my heartfelt thanks to my family, colleagues, and friends who have provided me with encouragement and assistance throughout this journey. I am especially grateful to those who offered insightful feedback that enhanced the quality of this dissertation.