Quantitative Assessment on Water-Energy-Food Nexus in South Korea

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Abstract

With the exponential increase in the demand for water, energy, and food (WEF) resources due to various factors, such as climate change, economic development, population growth, pandemics, and geopolitical instability, WEF security and sustainability are simultaneously threatened. To address this issue, the WEF nexus, which explores the interactions among different WEF sectors as an integrated system, can distinguish between different influencing indicators of WEF security. However, existing WEF nexus research using a quantitative approach at the national scale is lacking, and studies that simultaneously consider WEF security and sustainability require improvement.

Hence, this dissertation aims to address the WEF nexus in the national context (South Korea) and evaluate the interactions of selected indicators in WEF security by applying a conceptual and quantitative analysis framework and considering sustainability aspects together with external factors (society, economy, and environment). To achieve this objectives and overcome the limitations of previous studies, the following specific goals were formulated:

(1) To explore existing WEF nexus concepts, indicator frameworks, and models

(2) To analyze the interactive relationships of the WEF nexus at the country level, author demonstrate that WEF security is interconnected.

(3) To investigate specific interactions in the sustainable national WEF nexus by considering external factors and sustainability.

(4) To suggest a policy for sustainable resource management from a WEF nexus perspective.

The results show that WEF security is closely related not only to each other, but also to external factors and sustainability. Moreover, the interactions between WEF security and sustainability can be managed efficiently if resource management policies based on the nexus approach are introduced. Therefore, this study provides a roadmap for policymakers regarding efficient ways to improve sustainability and WEF security simultaneously.

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List of abbreviations

ABM	Agent-Based Model
AEZ	Agro-Ecological Zoning
CLEWs	Climate, Land-use, Energy and Water strategies
EKC	Environmental Kuznets Curve
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GFN	Global Footprint Network
GIMS	National Groundwater Information Management & Service Center
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KEEI	Korea Energy Economics Institute
KOSIS	Korean Statistical Information Service
KREI	Korea Rural Economic Institute
LCA	Life Cycle Assessment
LEAP	Long-range Energy Alternatives Planning tool
MAFRA	Ministry of Agriculture, Food and Rural Affair of South Korea
MOE	Ministry of Environment of South Korea
NIC	National Intelligence Council
OECD	Organization for Economic Cooperation and Development
ODI	Overseas Development Institute
ROK	Republic of Korea
SDGs	Sustainable Development Goals
SD	System Dynamics
SEM	Simultaneous Equation Model
SWAT	Soil and Water Assessment Tool
UK	United Kingdom
USD	United States Dollar
UN	United Nations
UNICEF	United Nations Children's Fund

WEAP	Water Evaluation and Planning tool
WEF	Water, Energy, and Food
2SLS	Two-Stage Least Squares
3SLS	Three-Stage Least Squares

Chapter 1. Introduction

This chapter provides an overview of the dissertation and handles the background and problem statements to deduce the research originality and objectives. It also presents the overall research trends, literature gaps, and research design. Moreover, it describes the significance of the study and a brief introduction to each thesis chapter.

1.1. Background

1.1.1 Status of WEF security

Water, energy, and food (WEF) resources are vital to humankind (Bizikova et al., 2013), and face enormous challenges worldwide. Despite all the bad conditions, the demand for water, energy, and food resources is predicted to soar worldwide by 80, 55, and 60%, respectively, in 2050, compared with 2005/07 levels (Flammini et al., 2014), owing to a surge in population, economy, urbanization, and an additional three billion middle-class people (Ferroukhi et al., 2015). Furthermore, the comprehensive impacts of climate change, the COVID-19 pandemic, and geopolitical instabilities (the Russia–Ukraine War and Israel–Hamas War) further aggravate resource security. Under these conditions, it is clear that WEF security will deteriorate at an unprecedented rate; the current status of each resource is as follows:

First, 2.4 billion people resided in water-stressed nations in 2020 (UN, 2023) and 2.2 billion people had insufficient access to safe water services (UNICEF, 2023). Global water security index (Figure 1.1), which consists of water availability, accessibility, safety and quality, and management (the value ‘0–1’ expresses ‘low-high’ security), shows inadequate situation of water security in the world, especially, in Africa and Asia (Gain et al., 2016).

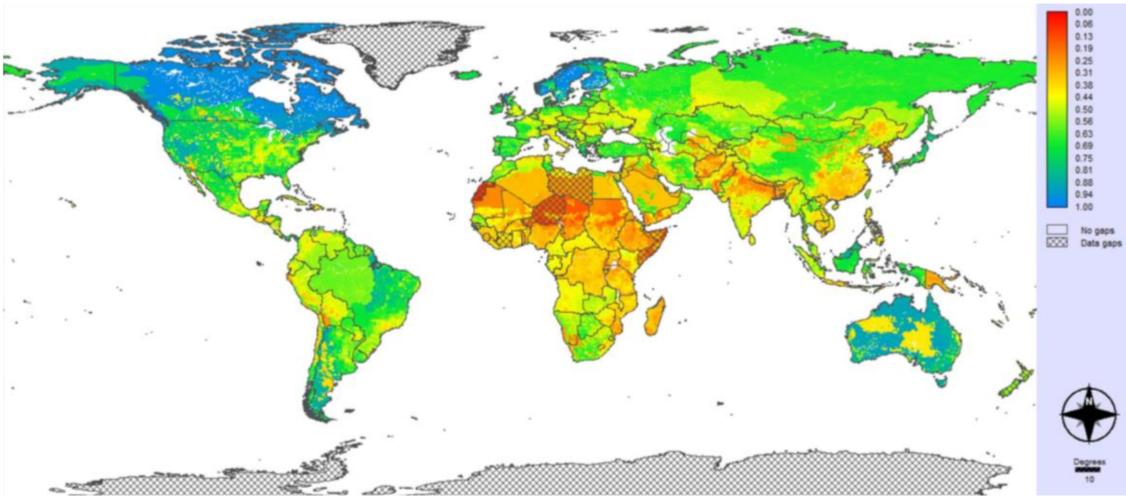


Figure 1.1 Global water security index

Source: Gain et al. (2016)

Second, according to IEA et al. (2023), 675 million people still lack access to electricity (Figure 1.2) and 2.3 billion people are limited use to clean cooking (Figure 1.3) as of 2021. More than 80% of the world's population lacks access to electricity and lives in sub-Saharan Africa, which remains a major obstacle to socioeconomic development in the region. Approximately 29% of the global population still employs polluting fuels and technologies to cook a large portion of their food.

Figure 1.2 Proportion of world population with access to electricity in 2021

Source: IEA et al. (2023)

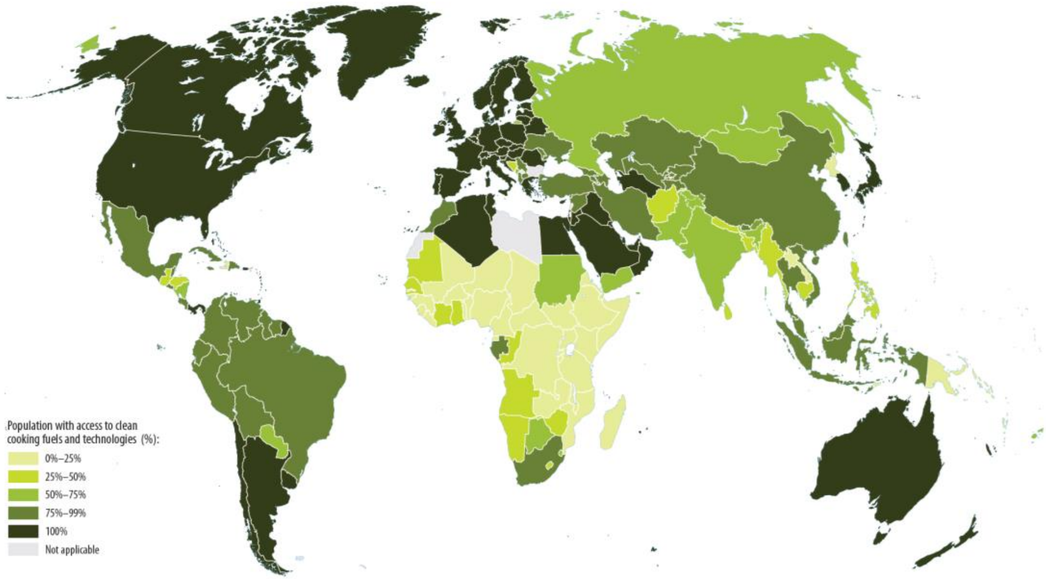


Figure 1.3 Proportion of world population with access to clean cooking fuels and technologies in 2021

Source: IEA et al. (2023)

Third, approximately 9.2 percent of the global population (735 million people) was chronically hungry during the same period (Figure 1.4).

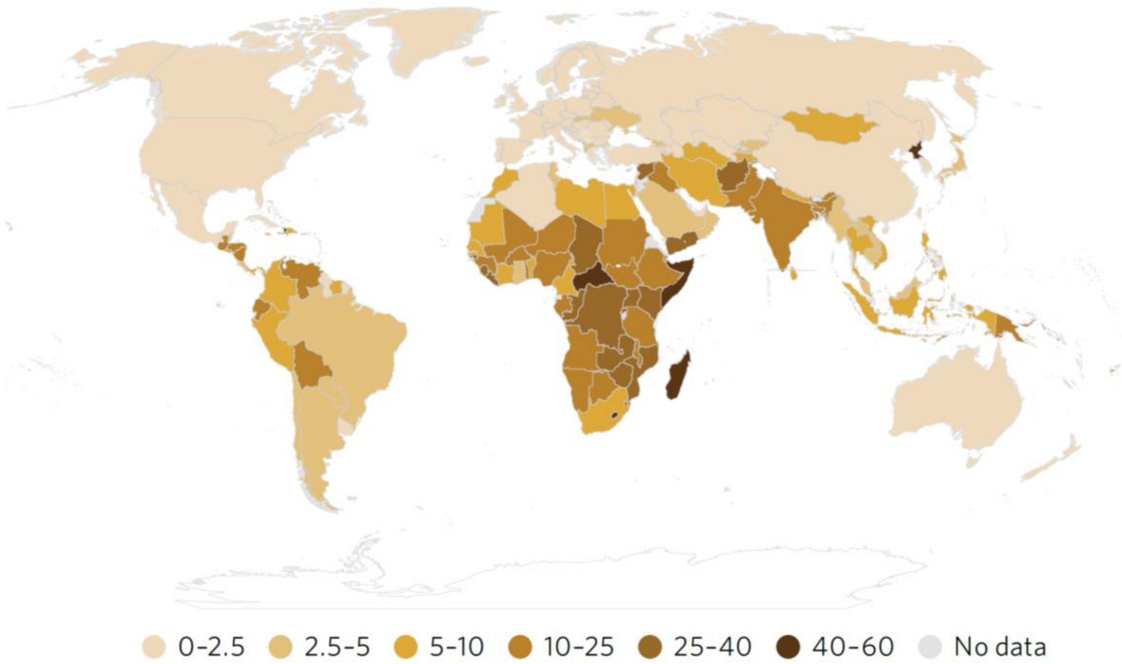


Figure 1.4 Prevalence of undernourishment from 2020 to 2022 on average (percentage)

Source: UN (2023)

Since 2015, the number of people experiencing food insecurity and hunger has increased, and the pandemic, conflicts, climate change, and widening disparities are worsening matters (UN 2023). Specifically, 29.6 percent of the world population (2.4 billion people) will not have access to appropriate food in 2022.

1.1.2 Definition of WEF nexus

Solutions to water, energy, and food security should be approached comprehensively, not separately, because water, energy, and food are inextricably connected with each other (Brears, 2018). For example, food production consumes approximately 70% of the total global freshwater and accounts for approximately 30% of global energy (FAO, 2017). Bio-crops (sugar cane and corn) are used not only as edible crops but also as bioenergy, which is a renewable energy source (IRENA, 2019a). The water sector, including the transfer, wastewater treatment, reuse, desalination, distribution, and supply sectors, consumes approximately 4% of the world's electricity, while primary energy production and power generation account for approximately 10% of the world's water withdrawals (IEA, 2016).

The concept of the WEF Nexus emerged to overcome the problem of resource security (Hoff, 2011), and is a holistic framework for analyzing the interactions between water, energy, and food (Albrecht et al., 2018) (Figure 1.5). In the classical sense, the etymology of the word "nexus" is derived from the Latin verb "connection; tie; link" (Oxford University Press, 2023).

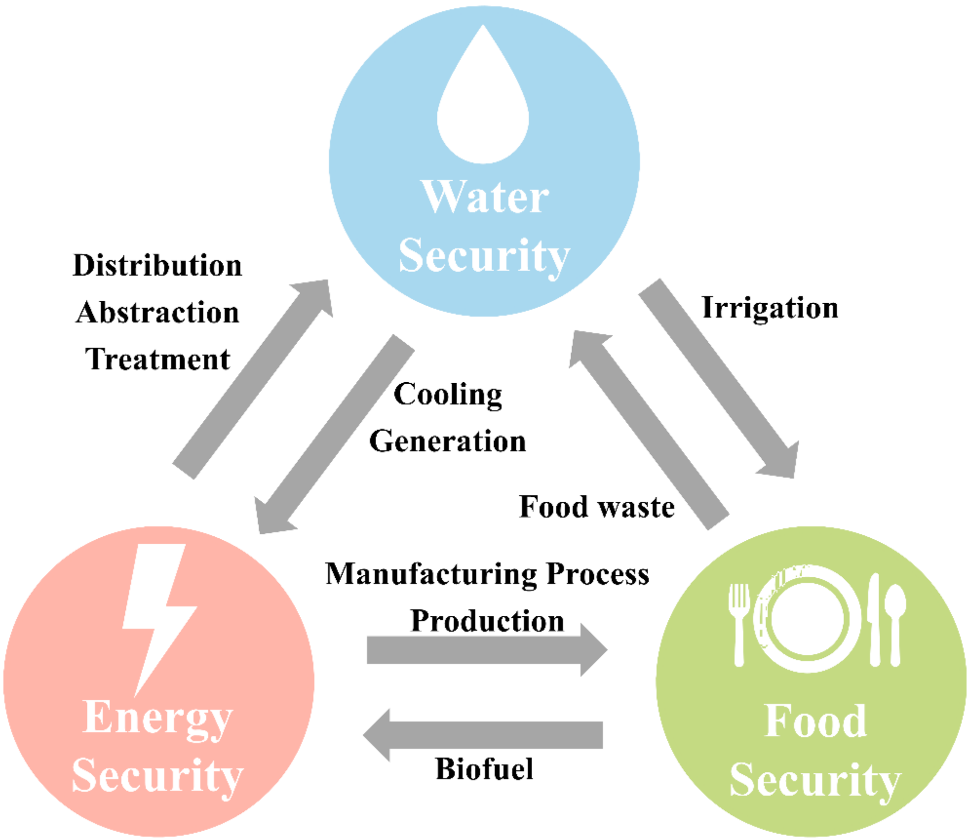


Figure 1.5 Structure of WEF nexus

Source: Hoff (2011), WEF (2011), Bizikova et al. (2013), FAO (2014).

Interactions can typically be considered synergies, wherein progress in one field stimulates advances in another, and trade-offs, wherein progress in one field hampers advances in another (Putra et al., 2020). For this reason, a choice made regarding the management of one of the three resources influences the choices made for the other two resources (Putra et al., 2020). This idea includes the perspective that the supply and demand chains for these resources are intimately intertwined (Bizikova et al., 2013; Ringler et al., 2013). Specifically, the WEF nexus suggests a mechanism to maximize synergy and minimize trade-offs by analyzing the tangled interactions among the three resources (World Economic Forum, 2011; Mukuve and Fenner, 2015). A comprehensive assessment will treat water, energy, and food as well as environmental, social, and economic drivers, which will also allow for the identification of interrelationships across sectors to guide WEF-related sustainable management and development activities (McCarl et al., 2017).

1.1.3 Relationships between WEF security and sustainable development

The sustainable development goals (SDGs) of the United Nations are interlinked, and achieving one goal may contribute to achieving other goals (Zhou and Moinuddion, 2017). The WEF nexus approach can help achieve the SDGs because SDGs 2 (zero hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) are closely related to water, energy, and food, respectively (Liu et al., 2018). Consequently, comprehending the interactions among the WEF sectors, maximizing synergies, and minimizing trade-offs could help develop overall WEF security while accomplishing the SDGs (Stephan et al., 2018; Terrapon-Pfaff et al., 2018) (Figure 1.6).

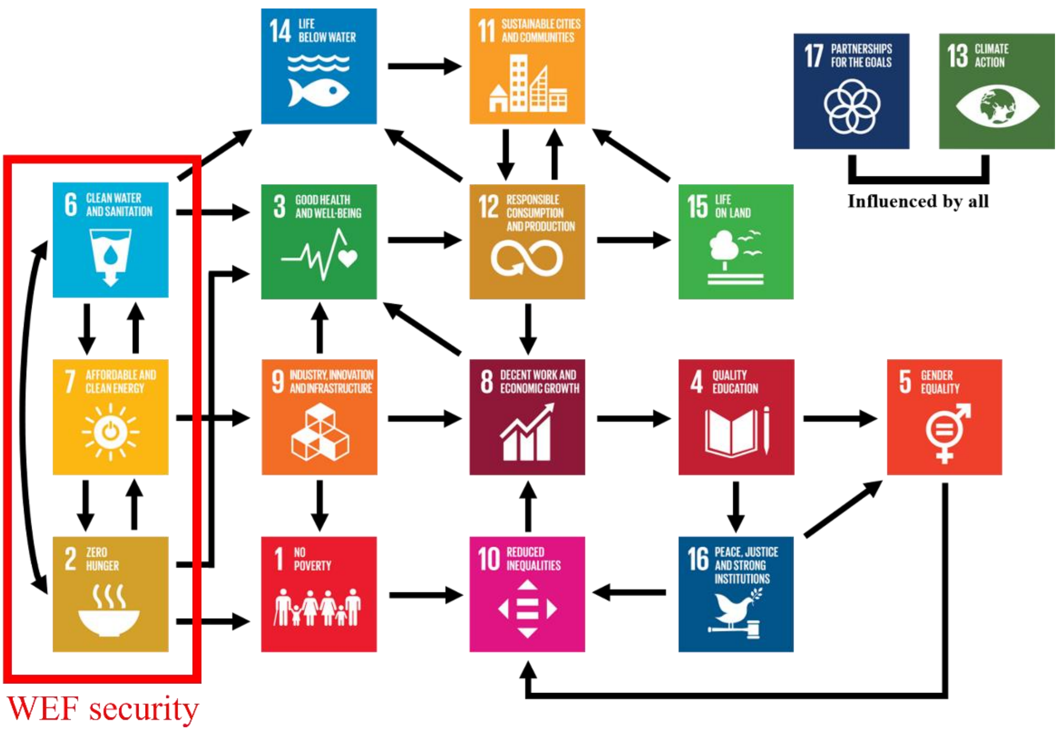


Figure 1.6 Interlinkage between SDGs and WEF security (example)

Source (symbol): UN (2015)

However, pressure on WEF security threatens the SDGs. For example, as water security becomes scarcer and stretched, its capability to support advances in some SDGs, especially in poverty, energy, hunger, health, sustainability, and the environment, is declining.

1.1.4 WEF security situation in South Korea

This study was conducted at the country level in South Korea, officially the Republic of Korea (ROK), which has a significant economic scale (1.67 trillion USD) and a population (52 million) as of 2022. The country has limited natural resources and thus faces challenges in ensuring WEF security, especially when the availability facet is vulnerable (Table 1.1). The Water-Energy-Food (WEF) Nexus Index, a comprehensive country-level indicator based on 21 WEF security-related indicators, shows that the availability of WEF security in South Korea is fragile (Figure 1.7) (Simpson et al., 2022).

Table 1.1 Current condition of resource security in South Korea

Type	Security situation
Water	Renewable water resources per capita (1,453 m^3); ranked 129th among 153 countries (2015)
Energy	Dependence on imported energy; import 94% of natural resources (2017)
Food	Food self-sufficiency (23%); global average 101% (2015–2017)

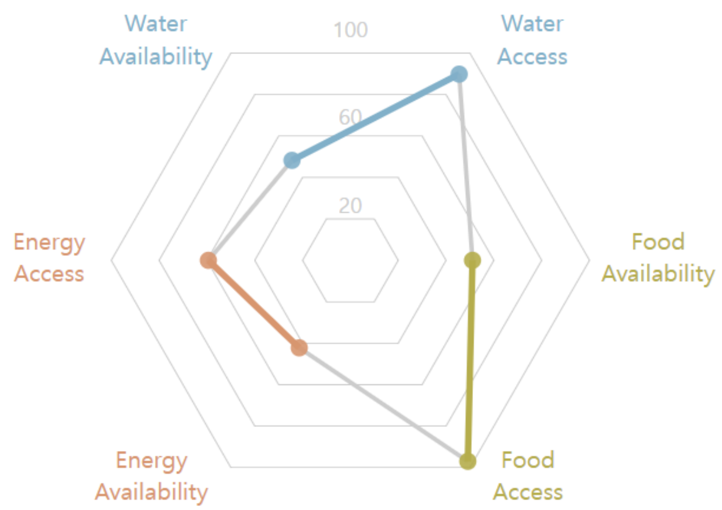


Figure 1.7 WEF Nexus Index of South Korea

Source: Simpson et al. (2022)

First, it has very few renewable water resources per capita (1,453 m^3) owing to its high population density (Ministry of Environment Korea Water Resources Corporation, 2020). Moreover, more than half of the annual precipitation is concentrated in summer, which makes water resource management difficult. Second, the dependence on energy resource imports is approximately 95% (Korea Energy Economics Institute, 2019). This is because, even though natural resources in South Korea are meager, the proportion of non-renewable energy in the energy mix exceeds 90%. Third, the food self-sufficiency rate is only 23% (Korea Rural Economic Institute, 2019), making it one of the countries with a high water footprint in the world (Hoekstra and Chapagain, 2011). Based on these situations, the nexus approach can help achieve sustainable resource management in society and understand the interactions in WEF security.

1.2. Research trends and gaps

1.2.1 Overall tendency

Many studies have been conducted on WEF nexus since "Bonn 2011 Conference: The Water Energy and Food Security Nexus – Solutions for the Green Economy" arranged by the German Federal Government (Leck et al., 2015). Research on the WEF nexus is broadly divided into five categories (Lazaro et al., 2022). With an emphasis on multidisciplinary and inter-sectoral studies, Table 1.2 demonstrates how the nexus approach is gradually developing into an integrative concept and adding new themes. This has led to the development of several methodologies for the WEF nexus research.

Table 1.2 Research tendency of WEF nexus

Period	Main topic
Trend 1 (2012–2016)	WEF nexus for water management and natural resource security
Trend 2 (2017–2018)	Connections among WEF nexus, sustainable development goals, and green economy
Trend 3 (2019)	WEF nexus governance and policy integration
Trend 4 (2020)	Application of the nexus concept on various scales
Trend 5 (2021)	Treatment of challenges on climate change and urbanization

Source: Lazaro et al. (2022)

As interest in WEF nexus research increases, the number of tools that analyze it will also increase by 2021 (Figure 1.8) (Taguta et al., 2022). This trend began to increase slowly in 2012 and rapidly in 2016.

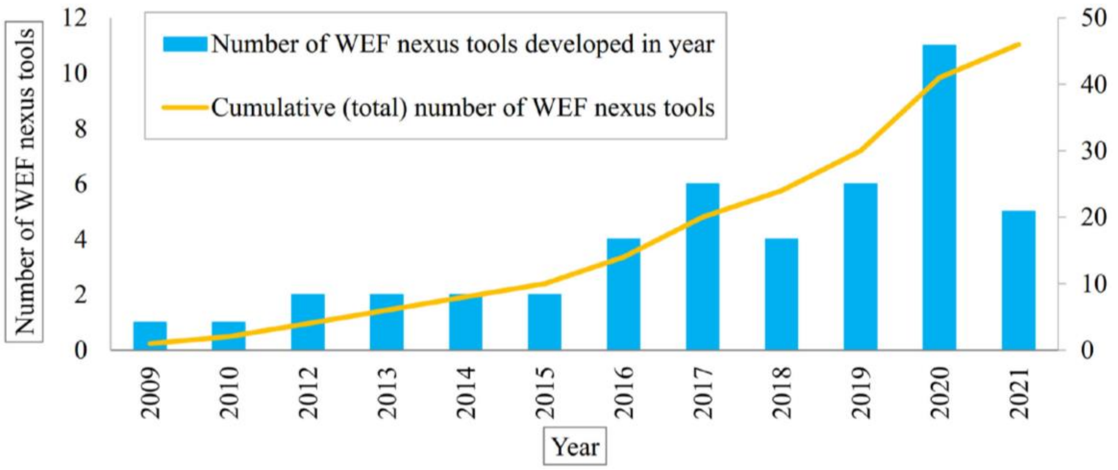


Figure 1.8 Tendency in the advancement of WEF nexus tools

Source: Taguta et al. (2022)

1.2.2 Literature gaps

Nonetheless, quantitative studies on the interaction among WEF sectors are scarce at the national scale (Albrecht et al., 2018) and the environmental science approach is predominant, whereas the social science approach is inadequate in nexus-related study disciplines (Newell et al., 2019). In particular, there remains a lack of application of nexus frameworks to policy recommendations regarding external drivers (environmental, economic, and social). In addition, although the WEF is intimately associated with sustainable development, there is a dearth of studies on sustainability. As mentioned in Section 1.1.4, South Korea, the target of this study, is experiencing challenges in ensuring WEF security, and there is a severe lack of research on the WEF nexus. A more specific literature review is presented in Section 2.

1.3. Research aims and design

1.3.1 Research objectives

Research on the WEF nexus could provide deep insights into how to handle resources efficiently, not only in South Korea but also in other countries suffering from resource shortages, by interpreting interactions in WEF security.

The main objective of this dissertation is to address the WEF nexus in a national context and evaluate the interactions of selected national-scale indicators in WEF security by applying a conceptual and quantitative analysis framework and considering sustainability aspects together with external factors. To achieve this goal and overcome the limitations of the aforementioned previous studies, the following specific objectives were formulated:

First, explore existing WEF nexus concepts, indicator frameworks, and models through an extended literature review (Chapter 2).

Second, analyze the interactive relationships of the WEF nexus at the country level to demonstrate that WEF security is interconnected using Spearman's rank correlation and network analyses (Chapter 3).

Third, investigate specific interactions in the sustainable national WEF nexus by considering external factors and sustainability, using a simultaneous equation model and the environmental Kuznets curve hypothesis (Chapter 4).

Fourth, suggest a policy for sustainable resource management from the perspective of the WEF nexus based on the results of the quantitative assessment (Chapter 5).

1.3.2 Conceptual framework

This dissertation is organized into five interconnected chapters to grasp all research objectives in Section 1.3, and the framework for the research design is shown in Figure 1.9. More than half of the chapters are based on or adapted from two peer-reviewed papers. Chapter 1 describes the background of this research, including overall research trends, literature gaps, research objectives, and conceptual framework. Chapter 2 provides an extended literature search of the history, concept, and current state of the WEF security and nexus, as well as a detailed analysis of the nexus frameworks and quantitative models. Chapter 3 discusses the interactions composed of synergies and trade-offs between the WEF sectors in the national context, using Spearman's rank correlation and network analyses. Chapter 4 develops a sustainable national WEF nexus framework and analyzes the interrelationships among water consumption, electricity demand, food production, and ecological footprint, considering the Environmental Kuznets Curve (EKC) hypothesis and external factors of the WEF nexus. Chapter 5 concludes the main findings of the entire dissertation, together with its contributions, suggests recommendations for the government to improve WEF security, and presents suggestions for further research.

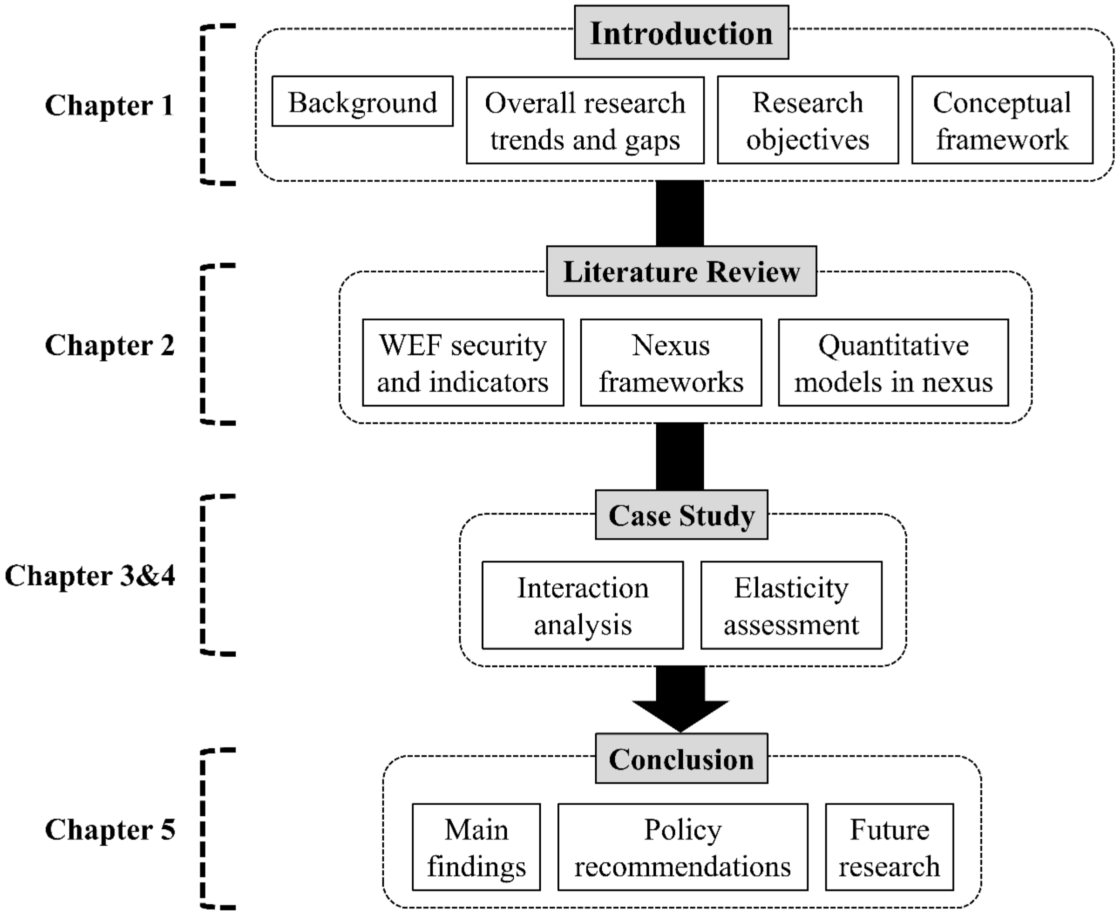


Figure 1.9 Outline of the dissertation

Chapter 2. Literature Review

This chapter provides a literature review of concepts and theories related to WEF security and the nexus approach. It begins with the origin of the definition of WEF security and its evolution, including its essential elements and characteristics. In addition, it discusses concepts, frameworks, and models.

2.1. WEF security

2.1.1 Water security

Since the 1990s, concerns over the supply consistency, safety, equity, quantity, quality, and environmental provisioning of water resources have been voiced through the idea of water security (Gerlak et al., 2018). In this context, water security has been defined more broadly, embracing multidimensional sustainability and an integrated systems approach, rather than a narrow focus on quantity, quality, access, and dangers, such as droughts and floods) (Wheater and Gober, 2015).

Global Water Partnership (2000) describes water security as the ‘‘sustainable use and protection of water resources, safeguarding access to water functions and services for humans and the environment, and protection against water-related hazards.” Grey and Sadoff (2007) characterized water security as “the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies”. Zeitoun (2011) introduced the ‘web’ of Water Security, which is a conceptual tool for policy and research. The sustainability of water security is determined by the degree of equity and equilibrium among the interdependencies of the associated security zones, which are influenced by a complex web of political and economic forces operating at various spatial levels (see Figure 2.1). Garrickk and Hall (2014) mentioned that water security is the opposite of water insecurity. Water insecurity refers “the conditions of the aquatic environment threaten the welfare and freedoms of individuals, communities, and societies”. This could result from the immediate impact of water-related disasters such as droughts, floods, pollution, landslides, and aridification. Gerlak et al. (2018)

systematically analyzed 124 articles, books, and book chapters from 2010 to 2015 to appraise research trends in place-based water security. They argued that water security is simultaneously a condition to be measured, a framework for decision-making, and a policy objective.

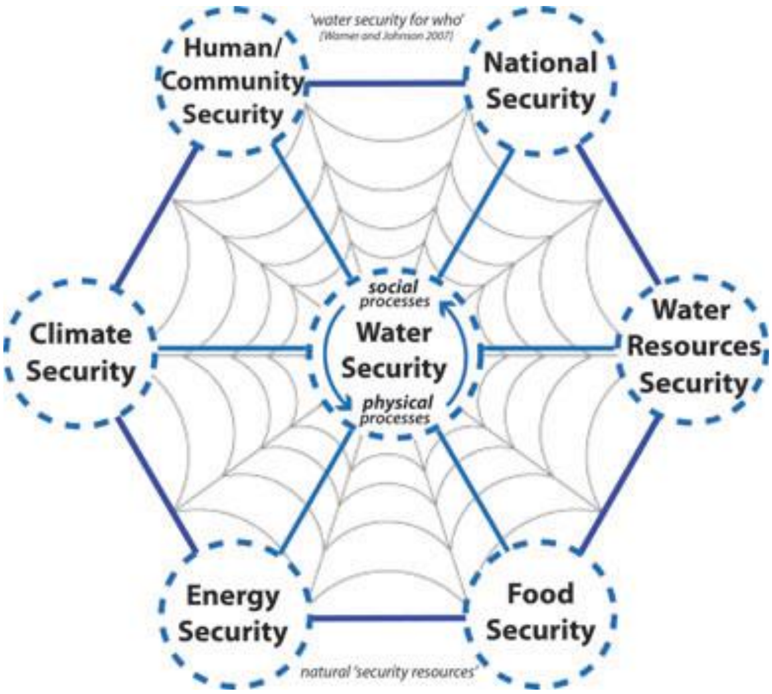


Figure 2.1 The ‘web’ of water security

Source: Zeitoun (2011)

2.1.2 Energy security

Since its inception in the wake of the oil crisis of the 1970s, research on energy security has grown to cover a wide range of energy sectors and challenges (Cherp and Jewell, 2014). Different ideas on energy security are often influenced by national styles, geology, geography, time, and institutional and personal viewpoints (Sovacool and Brown, 2010), thus it has become an umbrella term that covers various policy goals (Winzer, 2012). As a result of severe challenges, such as climate change and environmental degradation, and gathering uncertainty in the geopolitical sphere, the agenda of energy security has recently been increasing among decision makers around the world (Axon and Darton, 2021).

Many researchers have attempted to explain and analyze energy security through a selection of indicators (Table 2.1). According to the World Bank Group (2005), energy security is founded on three fundamental principles: energy efficiency, supply diversification, and price volatility minimization. Hughes (2009) presents a simple and flexible methodology, named four 'R' that can be applied to any energy security issue: understanding the problem (review), using less energy (reduce), shifting to secure sources (replace), and limiting new demand to secure sources (restrict). Kruyt et al. (2009) distinguished four elements of energy security that relate to availability, accessibility, affordability, and acceptability because this concept is deeply context-dependent. Moreover, they state that the application of diverse indicators could lead to a broader understanding of energy security. Sovacool and Brown (2010) argue that energy security is interconnected with the drivers of availability, affordability, efficiency, and environmental stewardship. Winzer (2012) defined energy security as the continuity of energy supply relative to demand.

Based on 104 studies published between 2001 and 2014, Ang et al. (2015) identify seven key themes or dimensions of energy security: energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. They stated that it should be reviewed regularly to ensure that the concept of energy security remains applicable. Energy security, being a context-dependent term, must be updated frequently to consider shifting priorities or newly discovered dangers arising from the constantly changing environment and new advancements in the energy sector. Radovanović et al. (2017) defined a new energy security indicator based on six indicators, which are energy intensity, final energy consumption, energy dependency, gross domestic product per capita, carbon intensity, and share of renewable and nuclear energy. Drawing on research interviews, questionnaire surveys, and an extensive literature review, Gasser (2020) suggested that energy security should consist of five aspects: availability, affordability, technology development, sustainability, and regulation. These five dimensions are divided into 20 components: supply and production, dependency, and diversification for availability; price stability, access and equity, decentralization, and low prices for affordability; innovation and research, safety and reliability, resilience, energy efficiency, and investment for technology development; land use, water, climate change, and air pollution for sustainability; and governance, trade, competition, and knowledge for sound regulation.

Cergibozan (2022) analyzed the influence of renewable energy on the energy security risk for 23 OECD countries using a second-generation panel dataset over 1985–2016. They found that wind, hydroelectric, and total renewable energy reduced energy security risks, whereas biomass and solar sources did not have a significant impact on energy security. Therefore, it is argued that OECD countries ought to enact laws designed to lessen the danger to their energy security, while taking into account their particular features. Doğan et al. (2023) investigated the role of energy security on environmental assessment, using data from the Newly Industrialized Countries. For example, the carbon emissions function includes several significant non-climatic factors, such as the uncertainty index, financial development, and quality of governance, in addition to energy security. They emphasized that to promote energy security and environmental conditions, there is a pressing need to discuss the roles of energy savings and discontinuing subsidies on traditional fuels.

Table 2.1 Energy security indicators

Authors	Indicator criterion
World Bank Group (2005)	Energy efficiency, diversification of supply, and minimization of price volatility
Hughes (2009)	Understanding the problem (review), using less energy (reduce), shifting to secure sources (replace), and limiting new demand to secure sources (restrict)
Kruyt et al. (2009)	Availability (supply and production, dependency, and diversification), accessibility (reliable and affordable access to both clean cooking facilities and to electricity), affordability (price stability, access and equity, decentralization, and low prices), and acceptability
Sovacool and Brown (2010)	Availability, affordability, efficiency, and environmental stewardship.
Winzer (2012)	Continuity of energy supplies relative to demand
Ang et al. (2015)	Energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency
Radovanović et al. (2017)	Energy intensity, final energy consumption, energy dependency, gross domestic product per capita, carbon intensity, and share of renewable and nuclear energy
Gasser (2020)	Availability, affordability, technology development (innovation and research, safety and reliability, resilience, energy efficiency, and investment), sustainability (land use, water, climate change, and air pollution), and regulation (governance, trade, competition, and

	knowledge)
Cergibozan (2022)	Generation of renewable energy
Doğan et al. (2023)	Carbon emissions, uncertainty index, financial development, and quality of governance

2.1.3 Food security

Food is fundamental to human well-being and human development is central to achieving food security (Misselhorn et al., 2012). Since the World Food Conference of 1974, the concept of "food security" has evolved, multiplied, settled and diversified (Maxwell, 1996). The most general concept of "food security" means "access by all people at all times to enough and appropriate food to provide the energy and nutrients needed to maintain an active and healthy life" (FAO, 2009). This definition comprises four key dimensions, each capturing a different aspect of food security: availability, stability, access, and utilization (FAO, 2017). Food security has advanced in three stages: (1) focusing on aggregate food availability; (2) emphasizing individual- and household-level access to food; and (3) placing food security in a broader framework of individual behavior (Barrett, 2002).

Global food security is under multiple pressures on both the supply and demand sides of food availability, access, and utilization (Table 2.2). Misselhorn et al. (2012) argued that a cross-sectoral approach is necessary to overcome these pressures because the dominant feature of 21st century food systems is inherently cross-level and cross-scale. For instance, an increase in weather extremes may lead to a higher frequency of multiple droughts or persistently high temperatures during the crucial phases of crop growth. Globally, the demand for animal-based foods is growing at a higher rate than that of vegetable-based foods.

Table 2.2 Main supply and demand side pressures on global food security

Pressures of supply side	Pressures of demand side
- Climate change - Urbanization - Globalization - Safety and quality - Land use change and competition	- Population increases - Urbanization - Changing demand in food types - Disease - Factors linked with under-development

Source: Misselhorn et al. (2012)

To support food security, Ingram et al. (2005) propose three major factors: food availability (production, distribution, and exchange), food access (affordability, allocation, and preference), and food utilization (nutritional, social, and food safety). Godfray et al. (2010) proposed the following solutions for ensuring food security: closing the yield gap, increasing production limits, reducing waste, changing diets, and expanding aquaculture practices. Lang and Barling (2012) suggested the main tensions of food security in the 21st century as farm versus food system focus, labor efficiency, the role of big business, Western levels of consumption, sustainability of diets, and power relations.

Food systems may be affected by climate change in several ways, including through direct effects on crop productivity, market modifications, pricing, and supply chain infrastructure (Gregory et al., 2005; Schmidhuber and Tubiello, 2007). Therefore, many researchers have linked climate change to food security. Lal (2013) identified challenges in global food security as population growth, climate change, soil degradation, decreased availability of water, land competition for urbanization, brick making, biofuel and non-agricultural uses, and preferences for animal-based diets. In particular, they emphasize the direct and indirect impacts of climate change on food security (Figure 2.2), mentioning that effective governance is needed to implement policies that promote restorative land use and recommended management practices.

Wheeler and Von Braun (2013) encourages that the need for considerable investment in adaptation and mitigation activities toward a “climate-smart food system”, which is more resilient to climate change influences on food security. Campbell et al. (2016) also argue that given the serious threats to food security, attention should shift to an action-oriented research agenda based on four main issues: changing the culture of research; deriving stakeholder-driven portfolios of options for farmers, communities, and countries; ensuring that adaptation actions are relevant to those most vulnerable to climate change; and combining adaptation and mitigation.

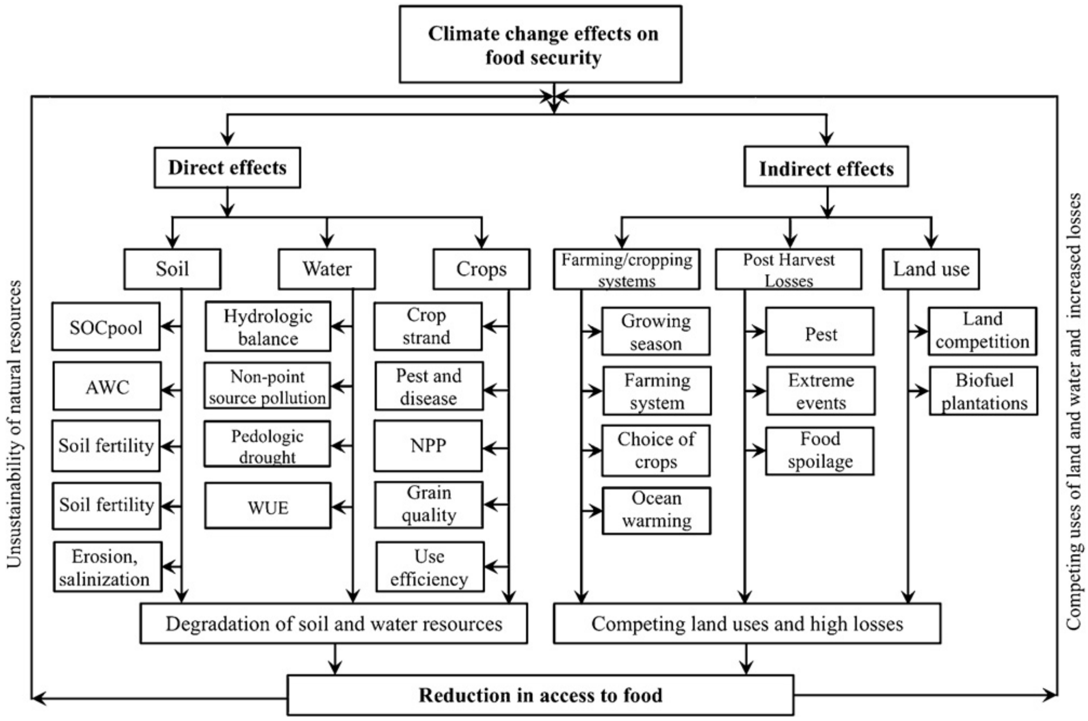


Figure 2.2 Direct and indirect impacts of climate change on food security

Sourece: Lal (2013)

Sustainability has also been studied in relation to food security. To position the concept of sustainability within the context of food security, it should be considered as a long-term dimension in the evaluation of food security (Berry et al., 2015). Smith (2013) examined sustainable intensification and considered alternatives, such as waste reduction and food demand. They concluded that sustainable intensification plays a role, but that this should be accompanied by basic changes to the global food system. Using circular and linear models, Wang et al. (2021) elucidated the connections between food loss and waste management, food security, and environmental sustainability.

2.2. Concepts, frameworks, and models of WEF nexus

2.2.1 Concepts

After the United Nations project on the energy–food nexus in the 1980s, the significance of the nexus concept began to appear to address interactions in resources (Sachs and Silk, 1990). The WEF nexus received significant attention at the "Bonn 2011

Nexus Conference", which is considered a milestone (Hoff, 2011). Since then, it has evolved into a widely known new paradigm for integrated and sustainable resource management focusing on WEF resources.

WEF resources are highly interconnected and thus should be consider as "together" rather than "individually" (Daher and Mohtar, 2015). Furthermore, the effects of an action on one of the WEF resources can be influenced by the other two resources (Hoff, 2011). Based on this theory, various nexus concepts have emerged. Hoff (2011) defined the nexus as a comprehensive approach for aggregating different managerial sectors to achieve a green economy. According to Ringler et al. (2013), the concept of integrated water resource management (IWRM), which served as the foundation for the nexus approach, is connected to the definition of nexus theory. FAO (2014) indicates that nexus approach could ensure food security and reach sustainable agricultural development. The International Renewable Energy Agency (IRENA) emphasizes that renewable energy can deal with some of the trade-offs between WEF resources, providing sustainable energy services using less resource-intensive systems (IRENA, 2015). Zhang et al. (2018) divided the WEF nexus into two categories. The first type was analyzed as interactions among different sectors within the system. The second is a novel approach for calibrating the connections between nexus nodes in different contexts. However, these can be consolidated using an integrated system evaluation. Albrecht et al. (2018) mentioned that the nexus has taken center stage as a means to better comprehend complex interactions among multiple resource systems.

2.2.2 Frameworks

According to the theories reviewed in Section 2.2.1, the main objectives of the WEF nexus framework are to promote action by providing a starting point for reducing trade-offs, building synergies, and encouraging the transition to a more sustainable society. These frameworks also shed light on the types of policies, measures, investments, and systems required to accomplish these goals (Bizikova et al., 2013).

Hoff (2011) presents a "Water-Energy-Food security nexus framework", which is centered on water supply, energy and food security, all connected to available water resources (Figure 2.3). Water works as a state variable as well as a control variable of change and is placed centrally in the WEF nexus. This framework interprets global trends in urbanization, population growth, and climate change. Considering finance, governance, and innovation, the aim is to promote WEF security for all, equitable and sustainable development, and a resilient and productive environment. This aim can be achieved through action fields by accelerating access and integrating the bottom of the pyramid (society), creating more with less (economy), and investing in sustaining ecosystem services (environment).

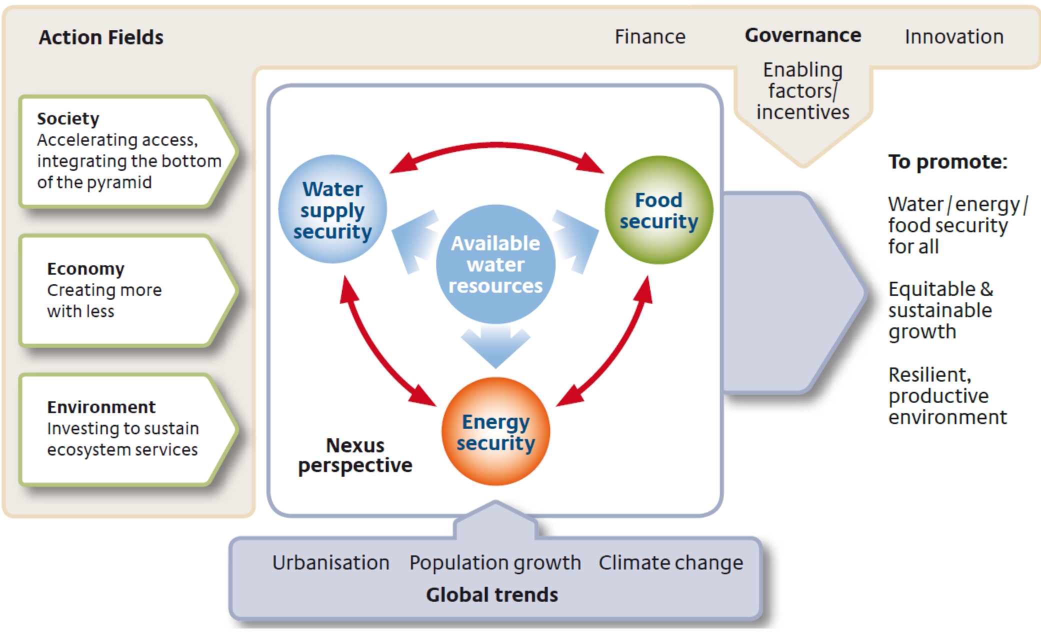


Figure 2.3 Water-Energy-Food security nexus framework

Source: Hoff (2011)

The World Economic Forum (2011) illustrates the nexus framework as a major risk field, along with economic disparities and macroeconomic imbalances (Figure 2.4) based on a set of direct and indirect impacts stemming from WEF security (Table 2.3). According to this framework, long-term water and food shortages and crises result from failures in global governance and economic inequality, which are linked to food and water security issues. Although energy scarcity is viewed as an economic danger, energy security is believed to impact societal stability and prosperity. Growth in the population, economy, and environmental pressures all impact the nexus. To enable preemptive actions and prompt mobilization during emergencies, this framework seeks to provide decision-makers with a better awareness of risks.

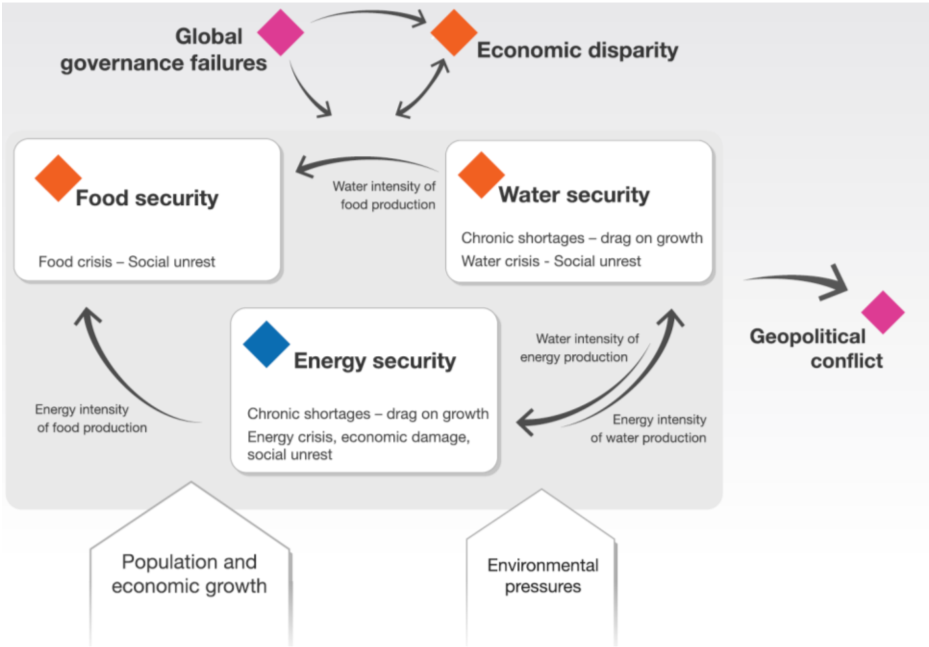


Figure 2.4 System diagram for risks related with Water-Food-Energy nexus

Source: World Economic Forum (2011)

Table 2.3 Impacts of risks related to Water-Energy-Food nexus

	Direct impacts	Indirect impacts
Impact on governments	- Stagnation in economic development - Political unrest - Cost of emergency food relief - Significantly reduced agricultural yields - Threats to energy security	- Increased social costs linked to employment and income loss as agriculture is negatively effected - National security risks/conflict over natural resources
Impact on society/populations	- Increased levels of hunger and poverty - Increased environmental degradation - Severe food and water shortages - Social unrest - Food price spikes	- Migration pressures - Irreparably damaged water sources - Loss of livelihoods
Impact on business	- Export constraints - Increased resource prices - Commodity price volatility as shortages ripple through global markets	- Lost investment opportunities

	- Energy and water restrictions	

Source: World Economic Forum (2011)

The FAO (2014) framework clearly addresses the interconnections and feedback between humans and natural systems (Figure 2.5). It centers on resources—biophysical and socioeconomic—that we rely on to meet our needs for food, energy, and water, as well as other social, environmental, and economic objectives. Interactions take effect within the background of external global drivers, as well as more site-specific internal drivers.

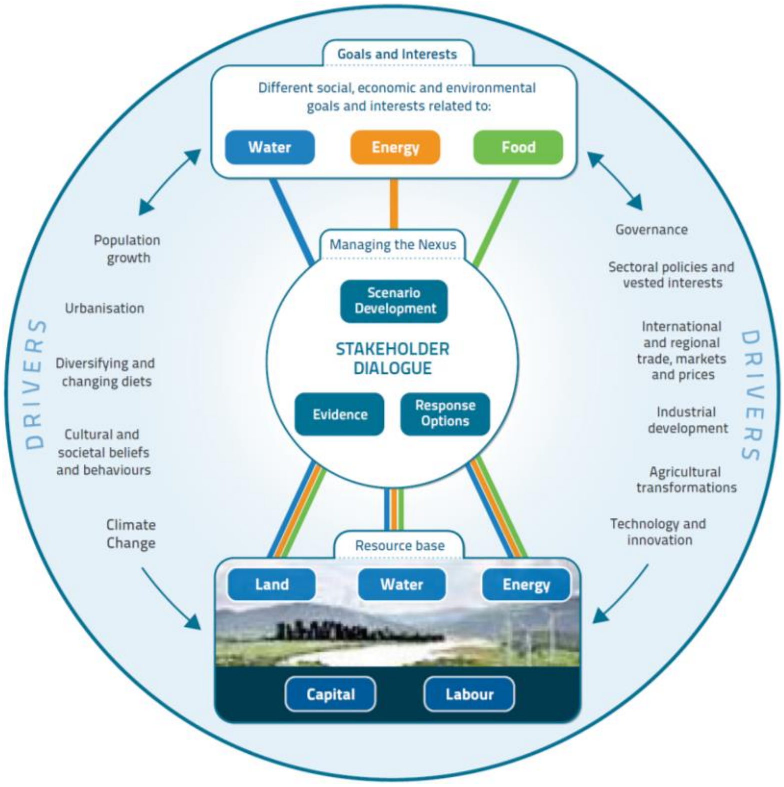


Figure 2.5 FAO's Water-Energy-Food nexus framework

Source: FAO (2014)

Some studies have attempted to expand the scope of the WEF nexus framework. By expanding from "food" to "land", ODI et al. (2012) presented Water-Energy-Land (WEL) nexus framework (Figure 2.6). Land includes not only food (agriculture), but also forests, biodiversity, human settlements, and infrastructure. WEL resources play a critical role as basic elements of economic systems, as well as parts of the natural cycle, and in adjusting the functions of ecosystems. As a feature of the WEL framework, inclusive and sustainable resource management requires a comprehensive approach that makes the links among different resources, uses, and users explicit.

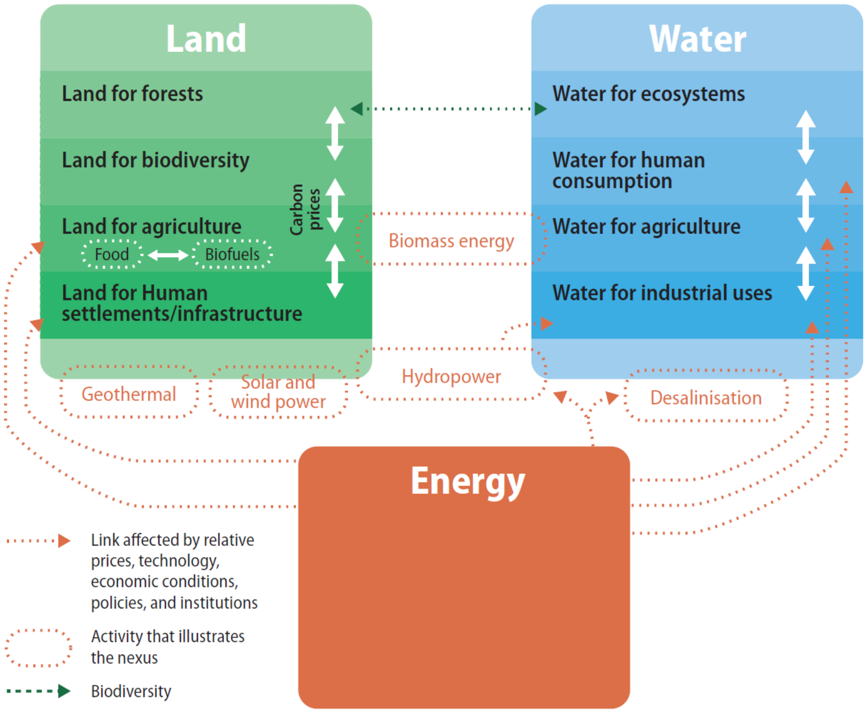


Figure 2.6 Water-Energy-Land (WEL) nexus framework

Source: ODI et al. (2012)

Melo et al. (2021) propose a hybrid framework called the (WEFF) nexus, which highlights the fundamental role of forests in achieving WEF security. It is a combination of forest and landscape restoration (FLR) and the WEF nexus, emphasizing three key principles (mainstream forest restoration, empowering local communities, and nature-based solutions) (Figure 2.7).

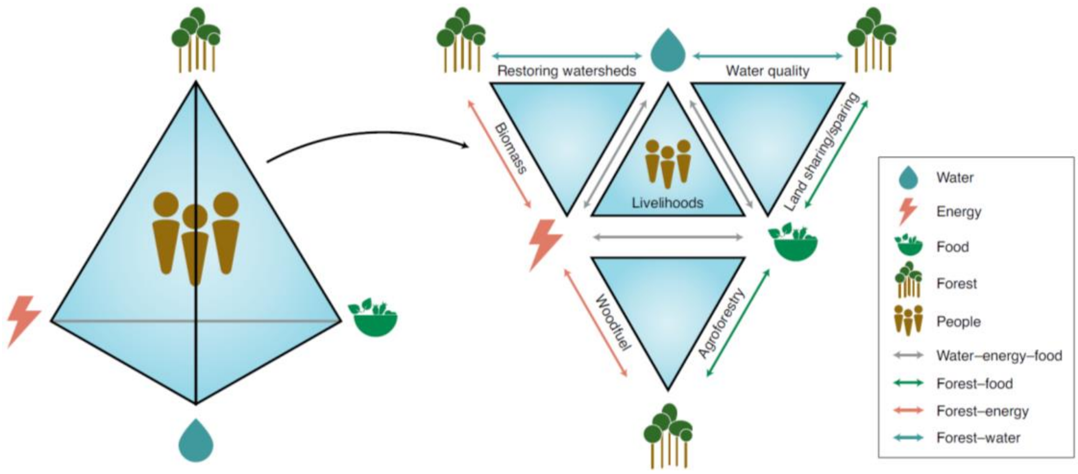


Figure 2.7 Water-energy-food-forest (WEFF) nexus framework

Source: Melo et al. (2021)

2.2.3 Models

Studies on the WEF nexus are becoming increasingly prevalent in the scholarly literature and policy contexts (Keairns et al., 2016). Since the milestone event at the Bonn 2011 Nexus Conference, numerous analytical models have been proposed and applied to explore the WEF nexus. The following paragraphs organize the models used in previous studies according to their different types. Table 2.4 tabulate and categorizes the WEF nexus models, focusing on quantitative methods.

(1) Integrated model

The fundamental concept of integrated models is that combining models from different subject areas captures the advantages of each model within a modeling suite. Howells et al. (2013) invented CLEWs the Climate, Land Use, Energy, and Water (CLEW) model, which consists of an energy model (Long-range Energy Alternatives Planning tool, LEAP), a water model (Water Evaluation and Planning tool, WEAP), and a land-use model (Agro-Ecological Zoning, AEZ) with climate change scenarios. They selected Mauritius for their case study because it is vulnerable to water availability and climate change. This model focuses on evaluating the interrelationships between resource systems to understand how the production and consumption of WEF resources may contribute to climate change, and how climate change may impact resource systems. The models also measure where pressure points exist and how to minimize trade-offs. Khan et al. (2017) integrated the agent-based model (ABM) and Soil and Water Assessment Tool (SWAT) to assess the effects of climate and demographic changes on the water, energy, food, and ecosystem sectors and characterize the resulting trade-offs through the aspect of the sustainability of water availability. It was tested in two transboundary river basins, the Mekong River Basin in Southeast Asia and the Niger River Basin in West Africa, where water consumption for ecosystem health competes with increasing human demand for food and energy resources. The human system is modeled as a decentralized water system model in this two-way coupled framework for modeling naturalhuman systems and is connected to a process-based, semi-distributed hydrologic model.

(2) System dynamics

System dynamics (SD) is a method that makes use of stocks, flows, internal feedback loops, table functions, and time delays to comprehend the nonlinear behavior of complex systems over time (Forrester, 1987). Complex behavioral interactions and their temporal evolution have been effectively illustrated using system dynamics modeling. Lee et al. (2018) evaluated the holistic impact of various rice self-sufficiency ratios (SSR) in Japan from a nexus perspective, focusing on the consumption change patterns of WEF resources, land-use trends, and CO_2 emissions. They analyzed the different impacts on resource management and environmental issues depending on the SSR level. Wicaksono and Kang (2019) introduced an SD model to calculate the supply, consumption, availability, and reliability of water, energy, and food resources on a national scale considering their interactions. Examining changes in energy policy in South Korea and capital investment planning of urban water systems in Indonesia, they simulated the nationwide resource nexus, estimated the reliability index of resources, and evaluated the feedback analysis. Bakhshianlamouki et al. (2020) assessed the impacts of possible restoration measures in a basin (Lake Urmia in Iran), considering a wide range of issues, including hydrological aspects, food production systems, and energy demand in the region, especially for agricultural use, touching on local livelihoods, and accounting for crucial interactions between these sectors. They search for win-win situations that can be leveraged and emphasize which implementations may lead to unexpected trade-offs. Wang et al. (2023) integrated society, economics, and environmental systems (SEE) into the WEF nexus to simulate a comprehensive environmental system. The WEF-SEE system assessed the trajectories from 2021 to 2035 of nine policies formulated by Hunan Province in China, and it contributed to reasonable policy recommendations, providing useful insights for the study area, particularly in light of potential trade-offs and synergies. Wu et al. (2023) evaluated six agricultural adaptations in terms of climate change (2021–2050) using the WEF nexus in Saskatchewan, Canada. These adaptations include agronomic measures (early planting date, reducing soil evaporation, irrigation expansion), genetic improvement (cultivars with larger growing degree day (GDD) requirements), and mixes of individual adaptations. Consequently, this study offers an approach for thoroughly assessing strategies designed to adapt agriculture to the challenges posed by climate change, providing valuable insights to guide decision-makers.

(3) Correlation analysis

Correlation analysis is used to indicate the association or relationship between two (or more) quantitative variables (Gogtay and Thatte, 2017). Its foundation lies in assuming a linear correlation between quantitative data. Putra et al. (2020) systematically analyzed the WEF nexus in South Asian countries (Bangladesh, India, Nepal, Pakistan, and Sri Lanka) using secondary data. They statistically analyzed the interactions between the WEF sectors, defining positive (synergies) and negative (trade-offs) correlations between the WEF security indicators. Their study showed proof for considering the WEF nexus as an integrated system, rather than just a combination of three independent sectors. Hao et al. (2022) assessed the level of WEF security in five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) from 2000 to 2014, and identified the drivers that positively or negatively determined WEF security, revealing the relationships among the three sectors. Moreover, the main factors influencing WEF security were analyzed using radar graphs.

(4) Scenario-based model

A scenario-based model analyzes how output data change depending on the input data in each scenario. Mohtar and Daher (2014) developed a holistic platform, which is a scenario-based approach to explicitly calibrate the interconnections among the three resources, reflecting the effects of changing populations, economies and policies, climate change, and other factors. It aims to help decision-makers detect sustainable resource management strategies from the perspective of the WEF nexus point of view and provide users with the ability to create different scenarios for a given country by considering portfolios of WEF security. Using this tool, the user can generate scenarios with various variations in these portfolios. For each scenario, the following outputs can be computed: water requirements, local energy requirements, local carbon emissions, land requirements, financial requirements, energy consumption through imports, and carbon emissions through imports. Yang et al. (2016) modeled the implications of the scope of climate change scenarios on the WEF nexus in the Indus Basin (Pakistan) and then assessed the possibility of diverse alternative water allocation scenarios and water infrastructure developments to handle growing WEF security problems. They presented a thorough analysis of how various environmental and socioeconomic scenarios affect the WEF nexus. For example, bitter temperatures and flexible water distribution policies lead to trade-offs between the use of surface water and energy, and can also lessen the effects of climate change.

(5) Economic model

A theoretical construct known as an economic model uses a set of variables along with a set of quantitative and/or logical linkages to depict economic processes (Friedman, 1953). This model is a simplified (often mathematical) framework designed to demonstrate complex processes by positioning structural parameters. Ozturk (2015) employed dynamic panel modeling and the generalized method of moments (GMM) to gauge the WEF nexus and to extract insights into sustainability from the BRICS (Brazil, Russian Federation, India, China, and South Africa) countries. They combined the WEF nexus and the EKC (Environmental Kuznets Curve) hypothesis to discuss sustainability. This study identified indications of an inverted U-shaped relationship between CO_2 emissions and economic growth within BRICS panel data, suggesting future policy implications from the integration of health, wealth, and the environment. Karnib (2017) proposed integrated quantitative assessments that consider all WEF intersectoral connections and the competing demand for WEF resources to estimate future development scenarios using input-output analysis. This analysis was conducted at the national level and has the advantage of being able to simultaneously analyzing the direct, indirect, and ripple effects of the variables. Daohan et al. (2020) adopted a two-stage least squares (2SLS) to calculate the elasticities between the WEF nexus-related factors using local-scale panel data of local scale (China) from 2005 to 2016. This model outperforms single-equation models in the analysis of indirect impacts, and has an advantage over structural equation models in investigating variable interactions. They defined the local WEF nexus as containing core, peripheral, and interactive sub-nexus, established a system to represent the local WEF nexus, and identified the main factors influencing the WEF subsystem in China.

(6) Life cycle assessment

Life cycle assessment (LCA) is a methodology for cradle-to-grave assessment to compute the environmental impacts and resources used throughout the life cycle of a product (Finnveden et al., 2009). The primary objective of an LCA is to evaluate the complete spectrum of environmental impacts attributed to products and services. This is achieved by quantifying all inputs and outputs of material flows and examining their environmental repercussions of these material flows. Al-Ansari et al. (2015) demonstrated the importance of integrated modelling in assessing the environmental impact of various WEF scenarios in the production process. The WEF-LCA nexus tool was used to estimate the environmental impact of expanding food production on Qatar's perceived level of food security. An understanding of the overall environmental impact of food consumption in Qatar was obtained by considering the emissions resulting from the lifecycle of imported products. Entrena-Barbero et al. (2023) suggested a standard procedure for the creation of an LCA for seafood products in connection with the computation of three environmental burdens (carbon, water, and energy footprints). They provided technical support for constructing a single WEF nexus index for ecolabeling seafood items in the Euro-Atlantic region. It is anticipated that this will result in the creation of a helpful communication channel between producers and consumers via an ecolabel that is simple to read.

(7) Optimization model

A mathematical method called optimization modeling is used to select the optimal solution from a range of options while considering certain restrictions and goals into account (Calafiore and Ghaoui, 2014). It is an effective instrument utilized in many different disciplines, such as engineering, economics, finance, operations research, and logistics. These models can reduce costs and increase operational efficiency throughout workflows by optimizing resource allocation, industrial processes, or logistics. Wicaksono et al. (2019) proposed an optimization module to support stakeholders in making informed decisions regarding sustainable resource management. By improving the priority index and water allocation choices, single- and multi-objective optimization modules were created to maximize the user reliability index for the WEF sector in South Korea. They applied the model to ascertain the best course of action for managing and allocating resources in plausible drought scenarios. Cansino-Loeza and Ponce-Ortega (2021) introduced a multi-objective optimization model for designing a WEF system that includes sustainable production of WEF resources in regions where the industrial, agricultural, and animal sectors share economic activity. A multi-stakeholder evaluation was also conducted to produce a set of options with varying priorities assigned to the stakeholders. This model could serve as a foundation for identifying sustainable interactions between resources and designing the WEF nexus at the regional level in Mexico with input from various stakeholders. Raya-Tapia et al. (2023) evaluated Mexico's WEF security and implemented actions to achieve sustainable development of the three resources by 2050 through deep learning (Long Short-Term Memory and Gated Recurrent Unit networks). The future quantification of WEF security made possible by this new methodology will assist decision-makers in managing, organizing, and implementing strategies to attain sustainability.

Table 2.4 Quantitative models in nexus field

Type	Specific method	Main point	Author
Integrated model	LEAP, WEAP, and AEZ	To measure where pressure points exist and how to minimize trade-offs	Howells et al. (2013)
	ABM and SWAT	To assess the effect of climate and demographic changes on the WEF and ecosystem sectors	Khan et al. (2017)
System dynamics (SD)	SD	To calculate the conditions of WEF resources according to the changes of policy	Wicaksono and Kang (2019)
	SD	To assess the impacts of possible restoration measures considering	Bakhshianlamouki et al. (2020)

		environment and WEF sectors	
	SD	To provide potential interactions, integrating society, economic, and environment systems into the WEF nexus	Wang et al. (2023)
	SD	To evaluate agricultural adaptations in terms of climate change via the lens of the WEF nexus	Wu et al. (2023)
	SD	To explore the holistic impact of various self-sufficiency ratio of rice	Lee et al. (2018)
Correlation analysis	Spearman's rank correlation	To analyze interactions between the WEF sectors, defining positive and negative correlations	Putra et al. (2020)
	Spearman's rank correlation	To recognize the drivers that positively or negatively determined WEF security	Hao et al. (2022)
Scenario-based model	Web-based tool	To calibrate the interconnections among the three resources, reflecting the effects of social, economic, and environmental factors.	Mohtar and Daher (2014)
	The Indus Basin Model Revise	To present a thorough analysis of the ways in which various impact of the WEF nexus	Yang et al. (2016)
Economic model	GMM	To gauge WEF nexus and to extract insights into sustainability	Ozturk (2015)
	Input-output analysis	To estimate future scenarios considering all the WEF intersectoral connections	Karnib (2017)
	2SLS	To calculate elasticities between WEF nexus related factors	Daohan et al. (2020)
Life cycle assessment (LCA)	LCA	To demonstrate the environmental impact of various WEF scenarios	Ansari et al. (2015)
	LCA	To provide technical support in order to construct a WEF nexus index for ecolabelling seafood items	Entrena-Barbero et al. (2023)
Optimization model	Single- and multi-objective optimization	To support stakeholders in making informed decisions regarding sustainable resource management	Wicaksono et al. (2019)
	Multi-objective optimization	To serve as a foundation for identifying sustainable interactions between resources	Cansino-Loeza and Ponce-Ortega (2021)
	Deep learning	To assist decision-makers in managing, organizing, and implementing strategies to attain sustainability	Raya-Tapia et al. (2023)

2.3. Summary

Resource security is under great pressure worldwide, and it should be considered holistically rather than approached separately because WEF security is deeply interrelated.

The WEF nexus has emerged as a comprehensive approach to alleviate these issues. According to the numerous previous studies, ‘WEF Nexus’ is following definitions: It is an approach that analyzes how synergies can be built and how trade-offs can be reduced by estimating the interactions in WEF security. Therefore, many researchers have attempted to explore these interconnections using various frameworks and methodologies.

The presented nexus frameworks explore not only the relationship between WEF security, but also the external factors related to it. Moreover, the range of elements covered has gradually expanded and developed beyond WEF security. Quantitative methodologies are useful for investigating the complex inter-relationships between WEF security and external drivers from a nexus perspective.

Nevertheless, the limitations of the existing literature should be noted. First, nexus case studies at the country level are lacking, particularly those related to Korea, which is a resource-poor country. Numerous analytical models (Table 2.4) have been proposed and applied mainly targeting regional, multi-national, and transboundary level. Second, despite the close relationship between sustainable development and WEF security, there is a paucity of research on sustainability. Third, there is a lack of nexus frameworks for policy suggestions concerning external drivers (environmental, economic, and social) and indirect impacts.

Chapter 3. Interaction Analysis in the WEF nexus

This chapter discusses the interactions composed of synergies and trade-offs between the WEF sectors in South Korea through Spearman's rank correlation and network analyses using secondary data at the national level. This provides important guidelines for prioritizing policies to implement sustainable resource management systems.

3.1. Introduction

Water, energy, and food (WEF) are essential resources for human survival (Adnan, 2013; Bizikova et al., 2013), and their demand is expected to increase worldwide by 80%, 55%, and 60%, respectively, by 2050 (Flammini et al., 2014) because of factors such as industrialization, urbanization, population explosion, and economic growth (Hoff, 2011). Consequently, the supply of corresponding resources can be disrupted, which, in turn, can diminish resource security (World Economic Forum, 2011). The concept of the WEF nexus, which is a holistic framework used to analyze the trade-offs and synergies between water, energy, and food, has emerged to address the problem of WEF security (Albrecht et al., 2018; Terrapon-Pfaff et al., 2018). Because the three components of the nexus are inextricably linked, they should be considered integratively (Brears, 2018). For example, food production consumes approximately 70% and 30% of the total global freshwater and energy, respectively (FAO, 2017). Moreover, bio-crops are not only food resources but can also be used as a renewable bioenergy source (IRENA, 2019). The water sector, which involves wastewater transfer, treatment, reuse, desalination, distribution, and supply, consumes approximately 4% of the world's electricity, while primary energy production and power generation consume approximately 10% (IEA, 2016).

The WEF nexus approach explores the interconnections among different WEF sectors, which can generally be regarded as synergies, wherein advances in one sector promote advances in another, and trade-offs, wherein advances in one sector hinder advances in another (Putra et al., 2020). Synergies enhance WEF security, whereas trade-offs undermine WEF security (Cai et al., 2018). A cross-sectoral nexus approach to the WEF sector provides an opportunity to achieve positive synergies and effectively manage trade-offs (Hoff, 2011). This approach can help achieve the sustainable development goals (SDGs) of the United Nations because SDGs 2 (zero hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) are closely related to water, energy, and food, respectively (Liu et al., 2018). Therefore, understanding the interactions among the WEF sectors, maximizing synergies, and minimizing trade-offs could improve overall WEF security while achieving the SDGs (Karnib, 2018; Stephan et al. (2018; Terrapon-Pfaff et al., 2018).

Previous studies on the WEF security nexus have emphasized global (Ringler et al., 2016), transboundary river basin (Amjath-Babu et al., 2019), local (Mroue et al., 2019), and regional (Mahlknecht et al., 2020; Saidmamatov et al., 2020) approaches. Since the 2011 Bon Nexus Conference, several studies have been conducted on WEF security since the Bon 2011 Nexus Conference (Leck et al., 2015; Endo et al., 2017). However, according to Albrecht et al. (2018), quantitative research on the relationships among the WEF sectors is limited at the national scale. Additionally, in nexus-related research, the environmental science approach is dominant, whereas the social science approach is insufficient (Newell et al., 2019).

South Korea does not have abundant natural resources and thus faces difficulties in ensuring WEF security. First, its renewable water resources per capita (1,453 m^3) rank 129 among 153 countries (MOE and K-water, 2019). Generally, managing water resources is easy and feasible if precipitation is uniformly distributed seasonally; however, in South Korea, precipitation is concentrated in the summer. Second, owing to the low abundance of natural resources, the country is highly dependent on imported natural resources for energy production, accounting for 94% (KEEI, 2019). Finally, the food self-sufficiency rate in South Korea is only 23%, with a major dependency on food resource imports (KREI, 2019). Based on these factors, a comprehensive investigation of the WEF security nexus can help achieve sustainable resource management. Further, understanding the interactions among the WEF indicators can not only provide a broader perspective of the relationship among the WEF sectors but can also help to establish a priority implementation strategy to address the WEF nexus security challenges (Huang et al., 2020). Wicaksono and Kang (2018) assessed the feedback analysis results and calculated the reliability index of resources resulting from energy policy changes in South Korea by examining the interlinkages between the WEF sectors. Wicaksono et al. (2019) proposed an optimization approach to maximize the reliability index of WEF security under plausible drought scenarios, and Lee et al. (2020) analyzed food-related interconnections in the WEF nexus under different scenarios of climate change and changes in irrigation management. Despite numerous studies and unpredictable resource security, there are few case studies of the WEF nexus targeting South Korea, and studies on the interactions between WEF security nexus indicators in South Korea are lacking.

To fill these research gaps, this chapter aimed to perform a quantitative analysis of the synergies and trade-offs identified between the WEF security indicators in South Korea using Spearman's rank correlation analysis and network analysis. The specific objectives are to (1) identify the interactions in WEF security indicators for South Korea, (2) analyze the most influential indicators in the WEF security nexus, and (3) provide policy priorities for effective resource management. The results can facilitate the identification of indicators for which improvements need to be prioritized by sector to ensure efficient WEF security. The systematic framework for assessing WEF interactions proposed in this study makes a fundamental contribution to policy implementation that can ensure effective management of water, energy, and food resources.

3.2. Materials and methods

3.2.1 Materials

To identify the indicators influencing the WEF security nexus, the indicators used in this study were selected based on criteria defined in previous studies. Simpson et al. (2020) developed a composite indicator that can effectively measure the WEF nexus using a method developed by the European Commission. Flammini et al. (2014) proposed comprehensive indices to determine the interactions among WEF sectors. Bizikova et al. (2013) defined utilization, access, and availability as core indicators of WEF security and further categorized them. For the SDGs indicators, SDGs 2 (zero hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) were considered by Liu et al. (2018) and Stephan et al. (2018). Based on these studies, 48 indicators, including 16 for water, energy, and food, were selected in the present study (Table 3.1; Appendix 1). These indicators consider the availability, accessibility, affordability, and productivity of the

WEF security in South Korea. Data for the selected 48 indicators were obtained for the period 2004–2018 from the SDG database (UN, 2021), International Energy Agency (2021), Food and Agriculture Organization Corporate Statistical Database (2021), World Bank (2021), Organization for Economic Cooperation and Development (2021), and statistics databases of the South Korean government (KEEI, 2019; MAFRA, 2020; GIMS, 2021; KOSIS, 2021; MOE, 2020; MOE, 2021). The research approach followed in this study was similar to that of Putra et al. (2020), who analyzed the interactions among the WEF sectors from five South Asian countries; however, in the present study, comparatively more indicators were considered with the focus on only one country, that is, South Korea.

Table 3.1 Indicators selected to investigate the water, energy, and food (WEF) security nexus of South Korea.

ID	Description	Sign	Source	ID	Description	Sign	Source
W1	Safe drinking water	1	SDG[1)] 6.1.1	E9	Electricity generation by biofuels	1	IEA
W2	Safe sanitation water	1	SDG 6.2.1	E10	Electricity generation by waste (renewable)	1	IEA
W3	Water use efficiency	1	SDG 6.4.1	E11	Electricity generation by coal	−1	IEA
W4	Level of water stress	−1	SDG 6.4.2	E12	Electricity generation by oil	−1	IEA
W5	Lake and river area	1	SDG 6.6.1	E13	Electricity generation by nature gas	−1	IEA
W6	Water usage per capita	−1	MOE[2)]	E14	Electricity generation by nuclear	−1	IEA
W7	Agricultural water consumption	−1	MOE	E15	Energy imports	−1	KEEI[7)]
W8	Industrial water consumption	1	MOE	E16	Budget for low-carbon energy technologies	1	IEA
W9	Municipal water consumption	1	MOE	F1	Stunning children	−1	SDG 2.2.1
W10	Annual precipitation	1	KOSIS[3)]	F2	Overweight children	−1	SDG 2.2.2
W11	Ground water	−1	GIMS[4)]	F3	Value-added	1	SDG

	for agriculture				management of agriculture		2.a.1
W12	Water supply service fee	−1	KOSIS	F4	Emission from agriculture sector	−1	MOE
W13	Water supply service rate	1	KOSIS	F5	Food production index	1	FAOSTAT[8)]
W14	Water withdrawals	−1	OECD[5)]	F6	Cereal production	1	KOSIS
W15	Wastewater treatment	1	OECD	F7	Arable land	1	World Bank
W16	Sewerage supply rate	1	KOSIS	F8	Cereal self-sufficiency rate	1	MAFRA[9)]
E1	Access to clean fuels for cooking	1	SDG 7.1.2	F9	Fertilizer usage	1	FAOSTAT
E2	Renewable energy consumption	1	SDG 7.2.1	F10	Crops and livestock products import	−1	FAOSTAT
E3	Energy intensity	−1	SDG 7.3.1	F11	Consumer food price index	−1	OECD
E4	Emission from energy sector	−1	MOE	F12	Non-arable land	1	MAFRA
E5	Energy usage in agriculture	1	IEA[6)]	F13	Agricultural productivity	1	KOSIS
E6	Electricity consumption per capita	1	IEA	F14	Meat consumption	1	OECD
E7	Electricity generation by solar	1	IEA	F15	Food supply	1	KOSIS
E8	Electricity generation by wind	1	IEA	F16	Rail line density	1	FAOSTAT

1) SDG Sustainable Development Goal Two) MOE, Ministry of Environment of South Korea; 3) KOSIS, Korean Statistical Information Service; 4) GIMS, National Groundwater Information Management & Service Center; 5) OECD, Organization for Economic Cooperation and Development; 6) IEA, International Energy Agency; 7) KEEI, Korea Energy Economics Institute; 8) FAOSTAT, Food and Agriculture Organization Corporate Statistical Database; 9) MAFRA, Ministry of Agriculture, Food, and Rural Affairs of South Korea

3.2.2 Investigation of interactions

This study mathematically investigated the synergies and trade-offs among the WEF sectors following the methodological approach suggested by Pradhan et al. (2017), who analyzed the interactions among SDGs by analyzing the official SDG indicator data of 227 countries using Spearman's rank correlation. This approach was also used by Putra et al. (2020) and Hao et al. (2022) to investigate the interactions between different WEF security indicators. The author analyzes the correlations among the WEF security indicators as synergies (positive) and trade-offs (negative) based on Pradhan et al. (2017). All values of the indicators were re-coded consistently to advance WEF security and avoid false correlations. A positive sign was assigned to indicators that improved WEF security when the indicator value increased, whereas a negative sign was assigned to indicators that reduced WEF security when the indicator value increased. For example, a positive sign was assigned to "W3 (water use efficiency)" because an increase in the indicator improved water security; moreover, a negative sign was assigned to "F12 (non-arable land)" because an increase in the indicator decreased food security.

Spearman's rank correlation analysis, wherein the coefficient is derived using the ranks of two values instead of the actual data values (Spearman, 1904), was used to identify the correlations between paired indicator values. The correlation coefficients were calculated using the following equation:

$$r_s = 1 - \frac{6\sum d^2}{n(n^2 - 1)}$$

where r_s is Spearman's rank correlation coefficient, d is the difference in ranks between the paired items, and n is the number of pairs of observations.

Similar to Pearson's correlation coefficient, the correlation coefficient ranges from −1 to 1, with a value of 1 indicating a strong positive correlation, −1 indicating a strong negative correlation, and 0 indicating no correlation (Myers et al., 2003). However, unlike Pearson's correlation analysis, Spearman's rank correlation can identify correlations for nonlinear relationships and can be applied to discrete and ordered data if the data can be ranked (Hauke & Kossowski, 2011). In addition, Spearman's rank correlation is used as an alternative to the Pearson correlation coefficient because it is less sensitive to outliers owing to the utilization of ranks rather than actual data values in the calculation and can capture the strength of monotonic relationships (Conover, 1999).

According to previous studies (Pradhan et al., 2017; Kroll et al., 2019; Putra et al., 2020; Ronzon & Sanjuan, 2020; Hao et al., 2022), a Spearman’s rank correlation coefficient value of 0.6 or higher indicated a “synergy,” whereas a value of −0.6 or lower indicated a “trade-off.” Moreover, if the value ranged between −0.6 and 0.6, the correlation was interpreted as “unclassified” to avoid over-analysis (Hauke & Kossowski, 2011). Furthermore, only statistically significant correlations, that is, with $p < 0.05$, were considered. The open-source software Jamovi was used to perform Spearman’s rank correlation analysis (The Jamovi Project, 2021).

3.2.3 Network analysis

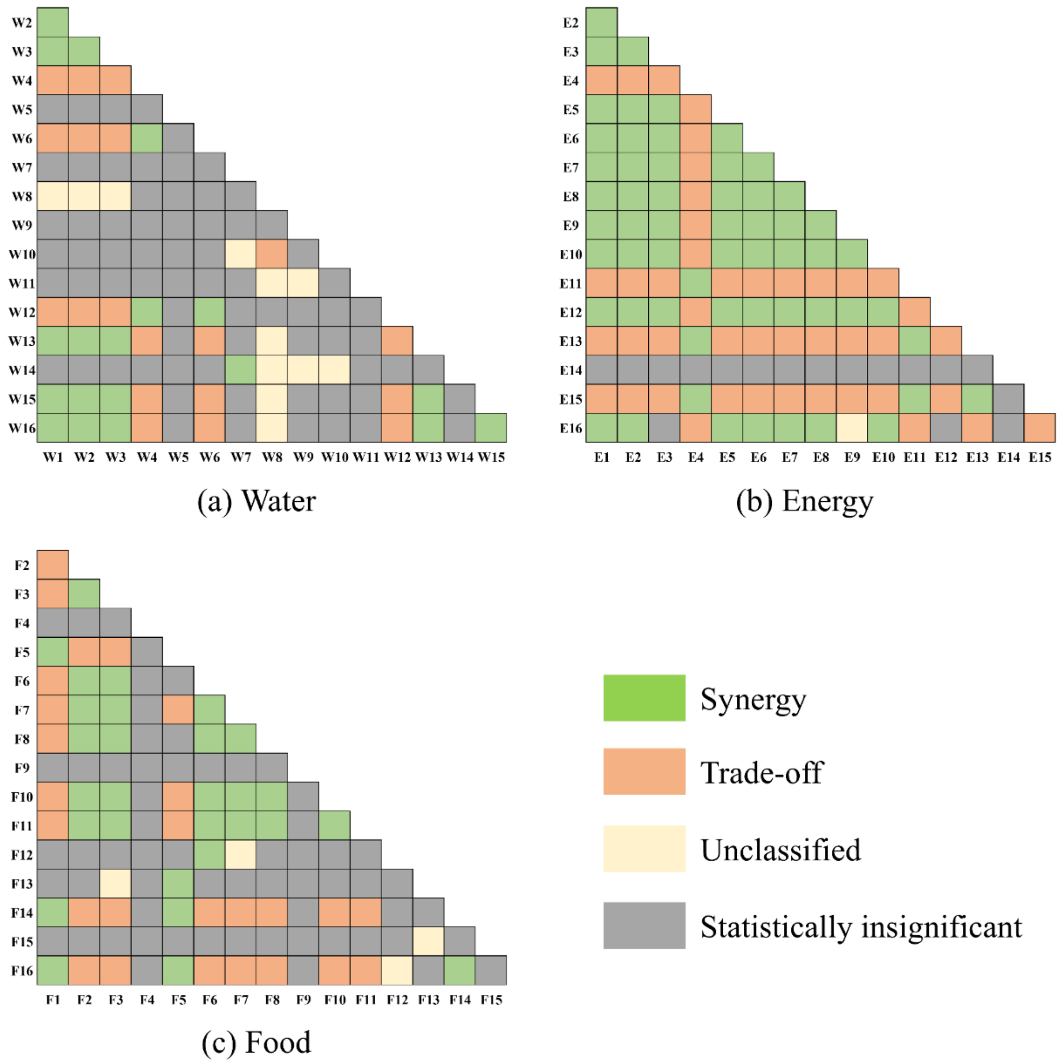
Network analysis was used to identify the most influential indicators of the WEF security nexus for South Korea, which has previously been used to analyze the most influential indicators and interactions between objects (Stein et al., 2014; Kurian et al., 2018; Weitz et al., 2018; Yeh et al., 2019; Mahjabin et al., 2020; Putra et al., 2020; An et al., 2021; Swain & Ranganathan, 2021). Network analysis is a well-developed methodology that provides various tools for analyzing the relationships between objects and patterns and interpreting such relationships (Wasserman & Faust, 1994). A network generally comprises nodes that represent objects and edges that interconnect pairs of nodes. In this chapter, the selected 48 indicators were interpreted as nodes, and the interactions between each pair of indicators, analyzed using Spearman’s rank correlation analysis, were interpreted as edges. Thus, the interactions between WEF security indicators can be visualized. The open-source software Gephi was used to visualize the network (Bastian et al., 2009).

3.3. Results

3.3.1 Interactions within WEF security indicators

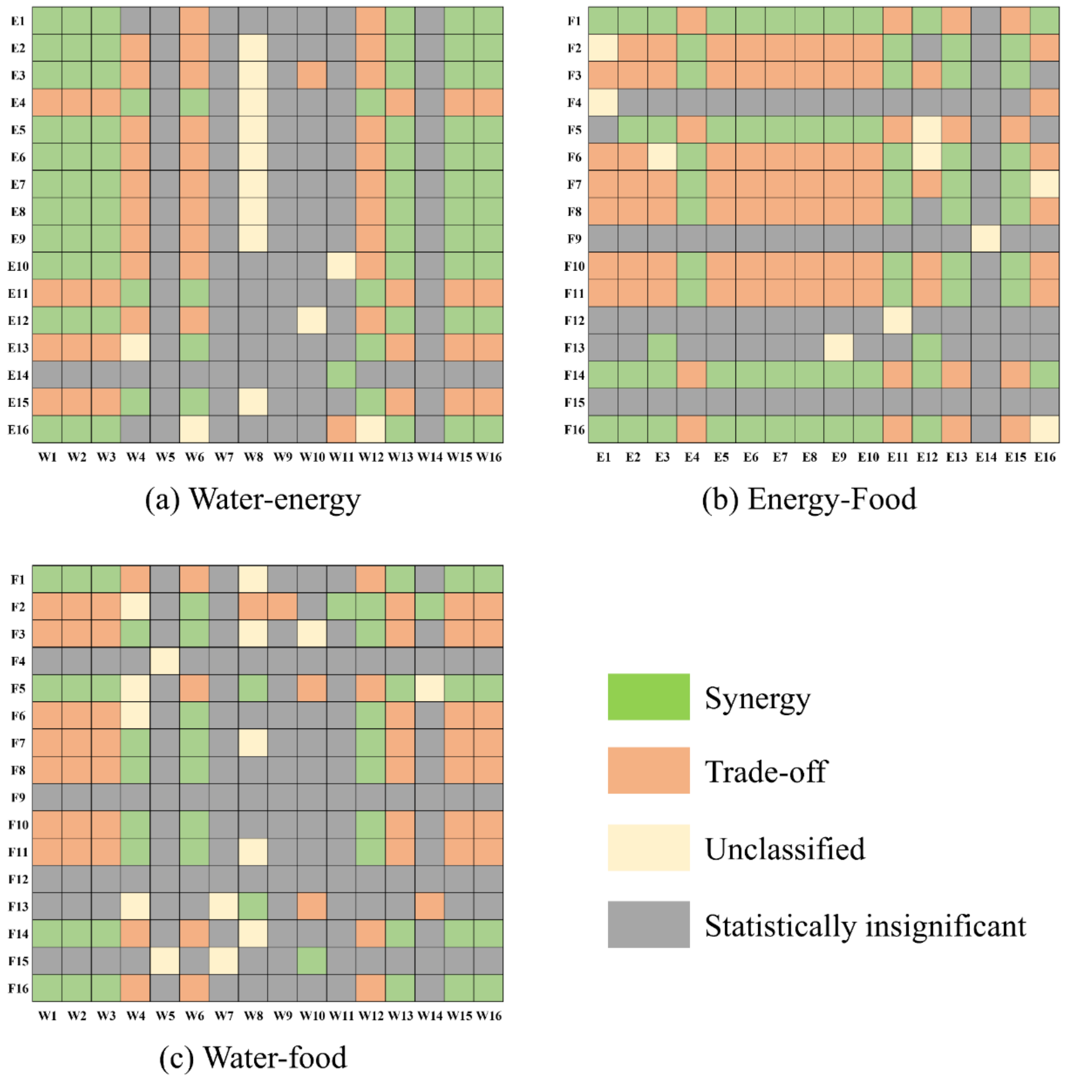
Figure 3.1-2 shows the results of analyzing the interaction with WEF security using Spearman's rank correlation analysis. Colors represent synergy (green), trade-offs (orange), and unclassified (apricot). Gray indicates statistically insignificant values with a *p*-value greater than 0.05, which were therefore excluded from the analysis. The proportions of synergies and trade-offs were the same (both 38%) within the water sector, whereas that of synergies (49–56%) was higher than that of trade-offs (43–44%) within the energy and food sectors (Figs. 3.1 and 3.3; Table 3.2). These interactions indicate that improving one indicator in each sector could improve other indicators, and vice versa. In general, as the water fee and usage increase, water stress could be aggravated, resulting in a negative impact on overall water security (Waughray, 2011; Lankford et al., 2013). Thus, water usage (W6) and fees (W12) were positively correlated with water stress (W4), whereas W4, W6, and W12 were negatively correlated with safe water (W1 and W2), water efficiency (W3), and water-supply services (W13, W15, and W16). Moreover, W1-W2-W3 and W13-W15-W16 were positively correlated. Agricultural water consumption (W7) and water withdrawal (W14) showed synergies, because South Korea uses approximately 60% of its water resources annually for agriculture (World Bank, 2021).

In the power generation field, renewable energy sources are environmentally friendly because their fuel consumption and carbon emissions are significantly lower than those of nonrenewable energy sources. Therefore, renewable energy indicators (solar: E7, wind: E8, biofuel: E9, and waste: E10) were negatively correlated with carbon emissions in the energy field (E4), and nonrenewable energy indicators (coal: E11 and natural gas: E13) were positively correlated with E4. Furthermore, because renewable energies have lower energy efficiencies than non-renewable energies, E7, E8, E9, and E10 are positively correlated with energy intensity (E3), whereas the opposite trend is observed for E11 and E13. In contrast, oil-based electricity generation (E12) showed opposite correlations with E3 and E4, unlike the other non-renewable energy indicators. This is probably because the operation of oil-fired plants has steadily decreased since 1995, accounting for only approximately 1% of the total energy mix (IEA, 2021). Energy imports (E15) are negatively correlated with budgets for low-carbon energy technologies (E16). These interactions are similar to those observed in previous studies that reported that renewable energy could enhance energy security (Valentine, 2011; Hinrichs-Rahlwes, 2013; Gökgöz & Güvercin, 2018).



W1	Safe drinking water	E1	Access to clean fuels for cooking	F1	Stunning children
W2	Safe sanitation water	E2	Renewable energy consumption	F2	Overweight children
W3	Water use efficiency	E3	Energy intensity	F3	Value-added management of agriculture
W4	Level of water stress	E4	Emission from energy sector	F4	Emission from agriculture sector
W5	Lake and river area	E5	Energy usage in agriculture	F5	Food production index
W6	Water usage per capita	E6	Electricity consumption per capita	F6	Cereal production
W7	Agricultural water consumption	E7	Electricity generation by solar	F7	Arable land
W8	Industrial water consumption	E8	Electricity generation by wind	F8	Cereal self-sufficiency rate
W9	Municipal water consumption	E9	Electricity generation by biofuels	F9	Fertilizer usage
W10	Annual precipitation	E10	Electricity generation by waste	F10	Crops and livestock products import
W11	Ground water for agriculture	E11	Electricity generation by coal	F11	Consumer food price index
W12	Water supply service fee	E12	Electricity generation by oil	F12	Non-arable land
W13	Water supply service rate	E13	Electricity generation by nature gas	F13	Agricultural productivity
W14	Water withdrawals	E14	Electricity generation by nuclear	F14	Meat consumption
W15	Wastewater treatment	E15	Energy imports	F15	Food supply
W16	Sewerage supply rate	E16	Budget for low-carbon energy technologies	F16	Rail line density

Figure 3.1 Interactions within water, energy, and food (WEF) security indicators in South Korea



W1	Safe drinking water	E1	Access to clean fuels for cooking	F1	Stunning children
W2	Safe sanitation water	E2	Renewable energy consumption	F2	Overweight children
W3	Water use efficiency	E3	Energy intensity	F3	Value-added management of agriculture
W4	Level of water stress	E4	Emission from energy sector	F4	Emission from agriculture sector
W5	Lake and river area	E5	Energy usage in agriculture	F5	Food production index
W6	Water usage per capita	E6	Electricity consumption per capita	F6	Cereal production
W7	Agricultural water consumption	E7	Electricity generation by solar	F7	Arable land
W8	Industrial water consumption	E8	Electricity generation by wind	F8	Cereal self-sufficiency rate
W9	Municipal water consumption	E9	Electricity generation by biofuels	F9	Fertilizer usage
W10	Annual precipitation	E10	Electricity generation by waste	F10	Crops and livestock products import
W11	Ground water for agriculture	E11	Electricity generation by coal	F11	Consumer food price index
W12	Water supply service fee	E12	Electricity generation by oil	F12	Non-arable land
W13	Water supply service rate	E13	Electricity generation by nature gas	F13	Agricultural productivity
W14	Water withdrawals	E14	Electricity generation by nuclear	F14	Meat consumption
W15	Wastewater treatment	E15	Energy imports	F15	Food supply
W16	Sewerage supply rate	E16	Budget for low-carbon energy technologies	F16	Rail line density

Figure 3.2 Interactions among water, energy, and food (WEF) security indicators in South Korea

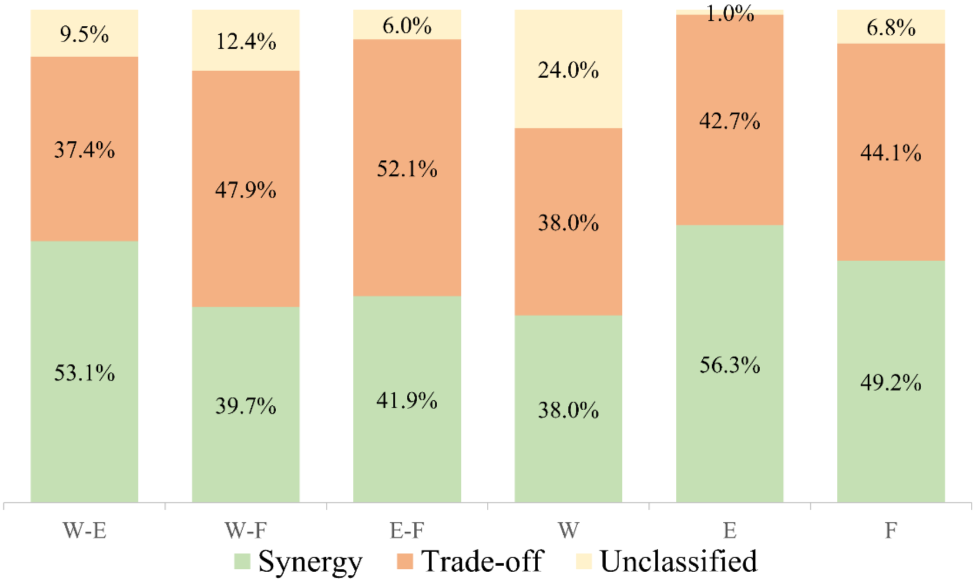


Figure 3.3 Interactions between WEF security indicators in South Korea indicated by the proportions of synergies, trade-offs, and unclassified items based on Figure 3.1-2.

Table 3.2 Number of WEF interactions in Figure 3.1-2

Type		Synergies	Trade-offs	Unclassified	Total interactions	Non-significant	Total
Within WEF security	Water	19	19	12	50	70	120
	Energy	58	44	1	103	17	120
	Food	29	26	4	59	61	120
Among WEF security	Water-Energy	78	55	14	147	109	256
	Water-Food	48	58	15	121	135	256
	Energy-Food	70	87	10	167	89	256
Total		302	289	56	647	481	1,128

Furthermore, a well-developed food supply chain can reduce food prices (Bunte, 2006; Armendariz et al., 2015). Hence, the increase in railline density (F16) and consumer food price index (F11) were negatively correlated. Additionally, a negative correlation was observed between arable land (F7) and value-added management of agriculture (F3) and between F7 and F3 and the proportion of starving children (F1). Arable land and value-added management of agriculture in South Korea are continuously decreasing (UN, 2021; World Bank, 2021); thus, improving these issues could solve hunger problems.

Because a decrease in domestic food production can be replaced by corresponding food imports (Sandström et al., 2018), the food production index (F5) and imports of crop and livestock products (F10) were negatively correlated. Moreover, F10 and F11 were positively correlated, highlighting their dependence on food imports.

3.3.2 Interactions among WEF security indicators

This study captured the interactions wherein synergies (40–53%) and trade-offs (37–52%) showed similar proportions among the WEF sectors and discovered the possibility of improving WEF security (Figs. 3.2 and 3.3; Table 3.2). Many water indicators in the water and energy fields (safe: W1 and W2; efficiency: W3; and supply service: W13, W15, and W16) showed positive correlations with renewable energy-related indicators (E2, renewable consumption; solar: E7; wind: E8; biofuel: E9; and waste: E10), and negative correlations with non-renewable energy-related indicators (E11 and E13). Furthermore, indicators related to the water stress level (W4) and water usage per capita (W6) were negatively correlated with renewable energy-related indicators (E7, E8, E9, and E10), possibly because renewable energy uses much less water than nonrenewable energy (Larsen and Drews, 2019), which uses more water for cooling (Macknick et al., 2012). The water industry is highly energy-intensive because of its strong dependence on energy (Kenway et al., 2011; Plappally and Lienhard, 2012). Thus, the water-supply service indicators (W13, W15, and W16) and emissions from the energy sector (E4) were negatively correlated.

Regarding water and food fields, as the arable land (F7) and cereal self-sufficiency rate (F8) increased, W4 and W6 increased because agriculture is water-intensive and sensitive to water stress (FAO 2017). For similar reasons, W4 and the consumer food price index (F11) were positively correlated. Moreover, annual precipitation (W10) and food supply (F15) were positively correlated because the volume of water available for food production depends on precipitation (Achite et al., 2017). The water supply service fee (W12) was positively correlated with crop and livestock product imports (F10) because as water prices increased, domestic food prices also increased, making people more dependent on cheaper imported foods (Johansson, 2000). In the livestock industry, meat has a large water footprint, which includes the amount of water consumed to obtain products, including feed (Hoekstra & Chapagain, 2011). According to Mekonnen and Hoekstra (2012), the water footprints of 1 kg of potato, beans, and rice are 900, 1800, and 4300 L, respectively, whereas for meat they are 15500, 4800, and 3900 L for 1 kg of beef, pork, and chicken, respectively. Therefore, when W4 increased, meat consumption (F14) decreased, indicating a negative correlation. Furthermore, the indicators related to water-supply services (W13, W15, and W16) were positively correlated with the food production index (F5), indicating that food production becomes more efficient when the water-supply system is well developed (Bhagwat, 2019).

In the energy and food fields, indicators related to agricultural productivity and availability (value-added management of agriculture: F3, cereal production: F6, and cereal self-sufficiency rate: F8) were negatively correlated with renewable energy indicators (E2, E7, E8, E9, and E10) and positively correlated with non-renewable energy indicators (E11 and E13). This is because the levelized cost of electricity from renewable energy sources in South Korea is higher than that from nonrenewable energy sources (Hong et al., 2019). Renewable energies are expected to achieve grid parity owing to improvements in efficiency and technological development (Breyer and Gerlach, 2013; IRENA, 2021), but such correlations could be reversed in the near future. The food industry is energy-intensive and accounts for approximately 30% of the total global energy (FAO, 2017). Accordingly, F3, F6, and F8 showed synergies with energy imports (E15), whereas crop and livestock product imports (F10) were negatively correlated with agricultural energy consumption (E5). Fluctuations in oil prices significantly affect food prices (Esmaeili and Shokoohi, 2011) because food production depends heavily on nonrenewable energy resources (Pelletier et al., 2011). Therefore, diversifying energy consumption in the food sector to renewable energy could stabilize food prices (Taghizadeh-Hesary et al., 2019).

3.3.3 Networks of interactions

Figure 3.4 shows the interaction networks within and among WEF sectors in South Korea. The diagram on the left shows synergistic interactions, whereas that on the right shows trade-off interactions. Furthermore, each node indicates one of the 48 WEF indicators, and the edges represent interactions between the two indicators, based on

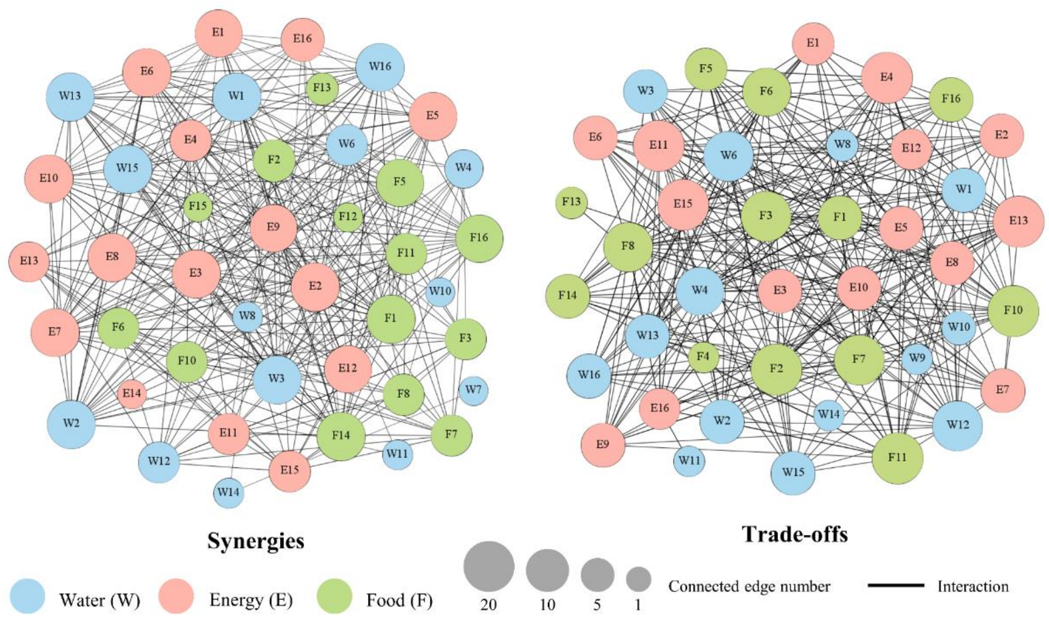
Figures 3.1 and 3.2. The higher the number of connected edges, the larger the number of nodes. Interactions are expressed in each network by distinguishing between synergies and trade-offs. Energy field indicators had the highest influence across all synergy and trade-off networks. Nonetheless, the water and food fields contributed significantly to the networks. The number of edges between nodes (interactions) ranged from 1 to 21 per indicator. Furthermore, among the top ten indicators with the largest number of connected edges, the energy field had the greatest influence (Table 3.3). Table 3.3 shows the most influential indicators with 20 or more connected edges, implying that these indicators further influenced 20 or more other indicators.

Among the energy-related indicators in the synergy networks, those related to renewable energy (E2, E7, E8, and E10) were the most influential, indicating that increasing the proportion of renewable energy can improve WEF security (Wicaksono and Kang, 2019; Putra et al., 2020) and positively influence the other 20 indicators. Energy intensity (E3) and energy consumption in agriculture (E5) have similar effects. This is because higher energy intensity corresponds to lower water consumption during energy generation and fewer food resources, and the proportion of renewable energy for power consumption in South Korea is steadily increasing (IEA, 2021). The food and energy industries are water-intensive (FAO, 2017; Bhagwat, 2019), and the indicators related to water infrastructure, safe water (W1 and W2), water efficiency (W3), and water supply services (W13, W15, and W16) in the water field had the largest impact. Water infrastructure refers to water-related facilities such as dams, reservoirs, water supply systems, and sewage facilities, including the above-mentioned water-related indicators (Monsma et al., 2019). South Korea's current water infrastructure is severely deteriorating (Kang, 2019). Thus, major improvements are required to ensure the sustainability of these indicators. As meat production has a high water footprint (Hoekstra & Chapagain, 2011), meat consumption (F14) shows many interactions with other indicators. Observations of food consumption patterns in South Korea indicate that meat consumption has increased, whereas cereal consumption has decreased since 1980 (KREI, 2019), suggesting that switching to a cereal-based diet can promote water, energy, and food security.

Energy-related indicators showed contrasting patterns in the trade-off and synergy networks. The indicators related to nonrenewable energies (electricity generation by coal and natural gas, E11 and E13; emissions from the energy sector, E4; and energy imports, E15) had the highest influence on the energy field. Emissions from the energy industry in South Korea are extremely high because the industry largely depends on thermal power for energy and imports of non-renewable energy sources (IEA, 2021; MOE, 2021). Moreover, the thermal power industry is water-intensive and can sometimes disrupt the water supply to the surrounding villages during droughts (Zhang et al., 2017). As water is an important resource for the food and energy industries, water usage per capita (W6) and water supply service fees (W12) can compromise WEF security. Interestingly, interactions with precipitation (W10), which is closely related to water availability, were few, implying that even if sufficient water is available, the impacts of W6 and W12 on water security are low, despite the inefficient management of water infrastructure and usage. Arable land (F7) and the value-added management of agriculture (F3) have the most negative impacts on WEF security because the food industry is directly and indirectly associated with the water and energy sectors (Daher and Mohtar, 2015; Vandone et al., 2018). Similarly, the nodes, namely crop and livestock product imports (F10) and the consumer food price index (F11), which are F3 elements, have the largest impact on the trade-off network (Lu and Dudensing, 2015).

3.4. Discussion

This chapter had two main findings. First, the interactions of the indicators associated with WEF security were quantified, thereby realizing the first objective of the study. These results confirm that interlinked WEF sectors interact with each other. Among all the interactions, the proportion of synergies and trade-offs was higher, whereas the proportion of unclassified correlations was lower than that observed in previous studies on South Asian (Putra et al., 2020) and Central Asian (Hao et al., 2022) countries. These findings suggest that the WEF sectors in South Korea are complexly interconnected, and that WEF security can be improved through the nexus approach (OECD, 2018). Using the approach outlined here, the author discusses different ways of maximizing synergies while minimizing trade-offs, which are especially important in countries with WEF insecurity.



W1	Safe drinking water	E1	Access to clean fuels for cooking	F1	Stunning children
W2	Safe sanitation water	E2	Renewable energy consumption	F2	Overweight children
W3	Water use efficiency	E3	Energy intensity	F3	Value-added management of agriculture
W4	Level of water stress	E4	Emission from energy sector	F4	Emission from agriculture sector
W5	Lake and river area	E5	Energy usage in agriculture	F5	Food production index
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W9	Municipal water consumption	E9	Electricity generation by biofuels	F9	Fertilizer usage
W10	Annual precipitation	E10	Electricity generation by waste	F10	Crops and livestock products import
W11	Ground water for agriculture	E11	Electricity generation by coal	F11	Consumer food price index
W12	Water supply service fee	E12	Electricity generation by oil	F12	Non-arable land
W13	Water supply service rate	E13	Electricity generation by nature gas	F13	Agricultural productivity
W14	Water withdrawals	E14	Electricity generation by nuclear	F14	Meat consumption
W15	Wastewater treatment	E15	Energy imports	F15	Food supply
W16	Sewerage supply rate	E16	Budget for low-carbon energy technologies	F16	Rail line density

Figure 3.4 Visualization of the interactions among WEF security indicators in South Korea through network analysis.

Table 3.3 Top 10 indicators with nodes having 20 or more edges in Figure 3.4

Interaction	Sector	Node (number of edges)
Synergy	Water	W1 (20), W2 (20), W3 (20), W13 (20), W15 (20), W16 (20)
	Energy	E2 (20), E3 (20), E5 (20), E6 (20), E7 (20), E8 (20), E10 (20)
	Food	F1 (20), F14 (20)
Trade-off	Water	W6 (20), W12 (20)
	Energy	E4 (21), E11 (21), E13 (21), E15 (21)
	Food	F2 (21), F10 (21), F11 (21), F3 (20), F7 (20)

Second, the most influential indicators and policy priorities for effective resource management in the WEF security nexus were analyzed, thus achieving the second and third research objectives. The corresponding results can help identify resource management policies that should be prioritized to ensure efficient WEF security (Flammini et al., 2014; Mahlknecht et al., 2020). For example, renewable and nonrenewable energy-related indicators mostly showed positive and negative influences on WEF security, respectively, in the energy sector. If the proportion of renewable energy in the energy mix increases, WEF security can be improved by maximizing synergies and minimizing trade-offs (Wicaksono & Kang, 2018; Putra et al., 2020). Improving water infrastructure and efficiency is the most effective strategy in the water sector. Currently, the water infrastructure in South Korea is rapidly deteriorating; thus, investment and repairs to maintain WEF security are necessary (Kang, 2019). Simultaneously, it is important to control water consumption and prices, which negatively influence WEF security. In the food sector, the value-added management of agriculture is the most important. Notably, meat consumption has the greatest positive influence on WEF security. South Korea relies heavily on the import of meat products, with imports increasing over time (KREI, 2019). The meat industry is both water- and energy-intensive (Mekonnen & Hoekstra, 2012), Thus, importing meat products reduces the consumption of energy and water resources, which is why the meat industry is the most influential indicator.

Overall, this analysis indicates that efforts in one area alone cannot improve WEF security. For example, even if the proportion of renewable energy and food production increases rapidly, the water supply is impaired, and WEF security will deteriorate in general. WEF security can be effectively ensured when improving the indicators in each field has the highest influence on other fields.

However, one limitation of this study is that the selected indicators covered only a part of resource security. Owing to the nature of the applied method, which requires pairs of sorted data, the availability of data significantly affects the selection of indicators. It is expected that more interactions can be analyzed in the future if more indicators related to WEF security are considered. Moreover, because linear relationships were applied to compare pairs of data points, the relationships among the three resources (WEF) could not be considered cumulatively. However, individual relationships between the two resources were analyzed by pairing them three times (W-E, W-F, and E-F). The effects of these three resources can be examined simultaneously if a simulation model, which can simultaneously explore linear and nonlinear relationships, is utilized. The results of this study provide a substantial reference for future research. Furthermore, for its active utilization, the nexus system should be combined with decision-making fields so that policies can respond to future demands for WEF resources. This can be achieved by applying various WEF food-resource scenarios.

3.5. Conclusion

In this chapter, a systematic framework is proposed to determine the interactions between WEF security in South Korea using two quantitative approaches–Spearman's rank correlation and network analysis–to better understand WEF security on a national scale. The results indicate that the WEF sectors are closely interconnected; thus, WEF security could be ensured if synergies are maximized and trade-offs are minimized regarding the interactions in WEF security. Furthermore, the interaction between energy and energy-related sectors was found to be the highest, which means that managing energy security is the most effective area for improving WEF security. Specifically, reducing the proportion of non-renewable energy sources and increasing the proportion of renewable energy sources could contribute significantly to WEF security, followed by water infrastructure management and value-added management of agriculture. An integrated approach via the WEF security nexus provides a basis for sustainable resource management, and mutual feedback enables the efficient use of each resource. In addition, sustainable and effective resource management can be achieved through policies that prioritize the most interactive indicators.

Chapter 4. Assessment of Elasticity on the Sustainable WEF nexus

This chapter builds a sustainable WEF nexus framework and analyzes the interrelationships between water consumption, electricity demand, food production, and ecological footprint, considering the Environmental Kuznets curve (EKC) hypothesis and external factors of the WEF nexus. This provides a roadmap for policymakers regarding efficient ways to improve environmental quality and WEF security.

4.1. Introduction

The demand for water, energy, and food resources, which constitute the basic needs of humans, has increased globally, and this trend is predicted to continue until 2030 (FAO et al., 2021). According to the NIC (2012), the demand for water, energy, and food will increase by 35, 40, and 50%, respectively, in 2030 compared to 2012 due to soaring population, urbanization, and an additional three billion middle-class people by 2030 (WWF and SABMiller, 2014; Ferroukhi et al., 2015). Additionally, the economic, social, and environmental impacts of the COVID-19 pandemic (Al-Saidi and Hussein, 2021; Hamid and Mir, 2021; Mofijur et al., 2021), the threat of climate change (Misra, 2014; IPCC, 2022), and geopolitical instabilities, such as the Russia–Ukraine war (Liadze et al., 2022; Shumilova et al., 2023), have aggravated these challenges (Estoque, 2022).

Further research is necessary to guarantee responsible and sustainable resource management and ensure stable access to water, energy, and food sources (Peña-Torres et al., 2022). These three resources are highly interrelated, and thus should be considered together (Daher and Mohtar, 2015; Albrecht et al., 2018; Brears, 2018). For example, water is required for drinking, agricultural irrigation, and in the food industry (FAO, 2017). Water also plays an important role in energy generation processes such as the production of hydroelectric power and biofuels, cooling of nuclear and geothermal power plants, and extraction of traditional fuels, notably in shale gas development and mining (International Energy Agency (IEA), 2020). Pumping water for food and irrigated agriculture, desalination, water purification, water distribution, wastewater treatment, long-distance water pumping, food production, and its supply chain require considerable amounts of energy (FAO, 2011; WWAP, 2014). Food production is an energy and water-intensive industry that consumes significant amounts of energy and water (Bazilian et al., 2011; Compton et al., 2018). Additionally, bio-crops can be used as renewable bioenergy sources, in addition to being a food source (IRENA, 2019).

Since the 2011 Bonn Conference on the Water, Energy, and Food Security Nexus (WEF) nexus has been used to analyze the complex interrelationship between water, energy, and food resources since the 2011 Bonn Conference on Water, Energy, and Food Security Nexus (Hoff, 2011). According to the WEF nexus framework, a choice made regarding the management of one of the three resources affects the choices made for the other two resources (Putra et al., 2020; Peña-Torres et al., 2022). This idea includes the notion that the supply and demand chains for these resources are closely intertwined (Bizikova et al., 2013; Ringler et al., 2013; Rasul, 2014). Specifically, the WEF proposes a method to maximize synergy and minimize trade-offs by analyzing complex interactions among the three resources (World Economic Forum, 2011; Mukuve and Fenner, 2015; An, 2022). A comprehensive evaluation will cover water, energy, and food as well as environmental, social, and economic drivers, which will also allow for the identification of interrelationships (synergies and trade-offs) across sectors to guide solid WEF-related management and development activities (McCarl et al., 2017).

In this context, this chapter aimed to conduct an interrelationship analysis of internal/external drivers and direct/indirect impacts on the sustainable WEF nexus in South Korea using a simultaneous equation approach. This aim is divided into three parts: (1) developing a theoretical basis for a simultaneous equation model (SEM) based on a sustainable WEF nexus framework, (2) exploring the interrelationship between WEF security and sustainability by analyzing the coefficients between factors involved in the sustainable WEF nexus, and (3) investigating sustainability in South Korea by combining the WEF nexus and the Environmental Kuznets Curve (EKC) hypothesis. The main contribution of this study is its assessment of the WEF nexus in South Korea through a systematic estimation that considers perspectives for achieving sustainable development. In particular, SEM enables the determination of the relationships between numerous variables that affect each other directly or indirectly, thereby assessing the effects of different policy interventions and evaluating hypotheses on the causal nexus among variables by systematically considering all relevant interdependencies.

4.2. Literature review

The nexus approach has drawn attention in the academic, political, and industrial fields because of its unique characteristics (Ozturk, 2015; Garcia and You, 2016; Al-Riffai et al., 2017; Weitz et al., 2017; Fayiah et al., 2020). Dynamic quantification techniques are necessary to identify the critical variables influencing the performance of the coupled nexus system and highlight the dynamics of natural processes in conjunction with various dimensions that sustain the interrelationships between nexus sectors (Zhang et al., 2018). Many earlier studies have analyzed the interactions in the WEF nexus using quantitative methods (Newell et al., 2019).

4.2.1 WEF nexus

At the national level, the nexus approach has been applied within the scope of a single country or in comparisons between several countries. Howells et al. (2013) presented an integrated assessment model called climate, land use, energy, and water strategies (CLEWs) to identify trade-offs, synergies, and co-benefits by assessing the resource system in Mauritius. Mohtar and Daher (2014) developed a scenario-based tool (WEF Nexus Tool 2.0) to analyze interactions in WEF security while considering social, environmental, and economic changes. Al-Ansari et al. (2015) considered Qatar and examined the interrelations within the WEF nexus, focusing on a food production system using a life cycle assessment. Moreover, Owen et al. (2018) calculated the consumption-based WEF of the UK and explored the critical supply chain by considering the entire lifetime of a product via an input–output analysis. Zhou et al. (2016) build a computable general equilibrium model with a tax module to study China’s nexus system. Campana et al. (2018) investigated the effects of drought on WEF resource requirements during a drought period in Sweden using a multi-objective simulation-optimization model. Putra et al. (2020) confirmed the interactions between WEF sectors in South Asian countries (Bangladesh, India, Nepal, Pakistan, and Sri Lanka) using correlation and network analyses. Wicaksono and Kang (2019) developed a computer simulation model based on a system dynamics algorithm for interconnecting WEF resources in South Korea and Indonesia. Huang et al. (2020) built China's local WEF nexus using a simultaneous equation approach involving the core, peripheral, and interactive nexuses. These studies have revealed that sustainable development can be achieved by exploring the interactions within the WEF nexus. This is because water (Goal 6: clean water and sanitation), energy (Goal 7: affordable and clean energy), and food (Goal 2: zero hunger) resources are the central elements of the Sustainable Development Goals (SDGs), and pressure on these three resources can threaten sustainable development (Bleischwitz et al., 2018; Liu et al., 2018; Simpson and Jewitt, 2019; Akinsete et al., 2022).

4.2.2 EKC hypothesis in relation to WEF nexus

The EKC hypothesis has been used to evaluate sustainability (Hartman and Kwon, 2005; Farhani et al., 2014; Sarkodie and Ozturk, 2020). Kuznets (1955) claims an inverted U-shaped relationship between economic development and environmental degradation. The inverted U-shaped curve indicates that environmental conditions deteriorate in the early stages of economic growth and improve in the later stages of economic growth. This implies that environmental degradation initially increases, and subsequently decreases as the economy grows. Ozturk (2015) conducted a sustainability assessment of the WEF nexus by utilizing dynamic panel modeling with the EKC hypothesis among BRICS countries (Brazil, the Russian Federation, India, China, and South Africa). Moreover, Zaman et al. (2017) confirmed the carbon fossil-methane EKC of sub-Saharan African (SSA) countries by analyzing the non-linear relationship between WEF resources and air pollutants. Nassani et al. (2019) used a simultaneous generalized method of moments to investigate the relationships among WEF resources, carbon fossil-GHG emissions, and growth-specific factors to verify the EKC in Pakistan. Xu et al. (2022) examine the link between economic growth and the WEF footprint by exploring the existence of the EKC in China's economic zones and regions.

4.2.3 Literature gap

Despite the increasing literature on the WEF nexus, the application of nexus frameworks to policy recommendations (Gain et al., 2015; Pahl-Wostl et al., 2018; Silalertruksa and Gheewala, 2018; Olawuyi, 2020; Lazaro et al., 2022) and the consideration of external drivers (environmental, economic, and social dimensions) in the WEF system are still limited (Räsänen et al., 2015). Systematic studies that explain the interaction between WEF security and its indirect impacts are lacking (Wicaksono and Kang, 2019). Furthermore, there is a lack of research on sustainability, even though the WEF nexus is closely related to sustainable development. Finally, most studies on the EKC hypothesis rely on atmospheric indicators, whereas literature on the EKC hypothesis that uses land, biodiversity, and freshwater indicators is erratic and sparse (Sarkodie and Strezov, 2019).

Therefore, applying SEM and considering sustainability will help establish policies for the sustainable WEF nexus by simultaneously analyzing the bi-directional interactions caused by external drivers and indirect impacts (Ozturk, 2016; Galdeano-Gómez et al., 2017; Fan et al., 2018).

4.3. Methods

4.3.1 Research area

This study was conducted at the national level in South Korea, which has experienced considerable economic and population growth with limited resources. South Korea, formally the Republic of Korea (ROK), is located in Northeast Asia, with a total land area of 97.6×10^3 km^2. In 2022, South Korea’s total population was 52 million and its gross domestic product (GDP) was 1.67 trillion USD. The country’s dependence on energy resource imports is 95% (Korea Energy Economics Institute, 2019), and its food self-sufficiency rate is only 23% (Korea Rural Economic Institute, 2019). Moreover, it has a considerably large water footprint (Hoekstra and Chapagain, 2011), which, together with the deterioration of water infrastructure (Kang, 2019), threatens water security. Therefore, the availability aspect of WEF resources are particularly vulnerable (Simpson et al., 2022).

Integrating the interactions between WEF security and the nexus approach can help achieve sustainable resource management.

4.3.2 Frameworks and variables

Various frameworks have been suggested according to the purpose and scope of the study. However, the following are the cornerstones of the WEF nexus framework: Hoff (2011) presented a WEF nexus framework centered on water supply, energy, and food security, all of which are connected to water availability. It also considers global trends, including urbanization, population, and climate change, to promote WEF security, sustainable growth, and a productive environment. The World Economic Forum (2011) offers a framework in which water and food security are connected to economic disparities and global governance failures, as well as energy security, causing chronic WEF shortages and crises. This comprehensive structure includes external drivers affecting the nexus, such as demographic, economic, and environmental factors. The Food and Agriculture Organization (FAO)'s WEF framework addresses the interrelations between human and natural systems, focusing on the biophysical and socioeconomic resources related to the WEF nexus (Flammini et al., 2014). These interactions are affected by external global drivers such as population change, urbanization, climate change, industrial development, and sectoral policies.

Based on the existing literature on the WEF, the author built a systematic framework for a sustainable WEF nexus by coupling it with sustainability at the national level (see Figure 4.1). In this framework, WEF security and sustainability, which are core and internal factors, are not only influenced by each other's security but also by external factors such as the environment, society, and economy. The criteria for the WEF security indicators considered availability, accessibility, affordability, and productivity drivers, following An (2022). Each indicator can satisfy more than one criterion and affect other internal nexus factors. For example, agricultural productivity (AP) affects not only the accessibility, affordability, and productivity of food but also water and energy security. This influence also has a ripple effect on sustainability, which is linked to WEF security. Ecological footprint was selected as an indicator of sustainability. It identifies the use of productive surface areas, which consist of cropland, grazing land, fishing grounds, built-up land, forest areas, and carbon demand and assesses the amount needed to produce various resources that humans consume and dispose of as waste (Wackernagel and Rees, 1998; Moffatt, 2000; Wackernagel et al., 2021). Therefore, it is regarded as an accounting measure of the demand and supply of natural systems.

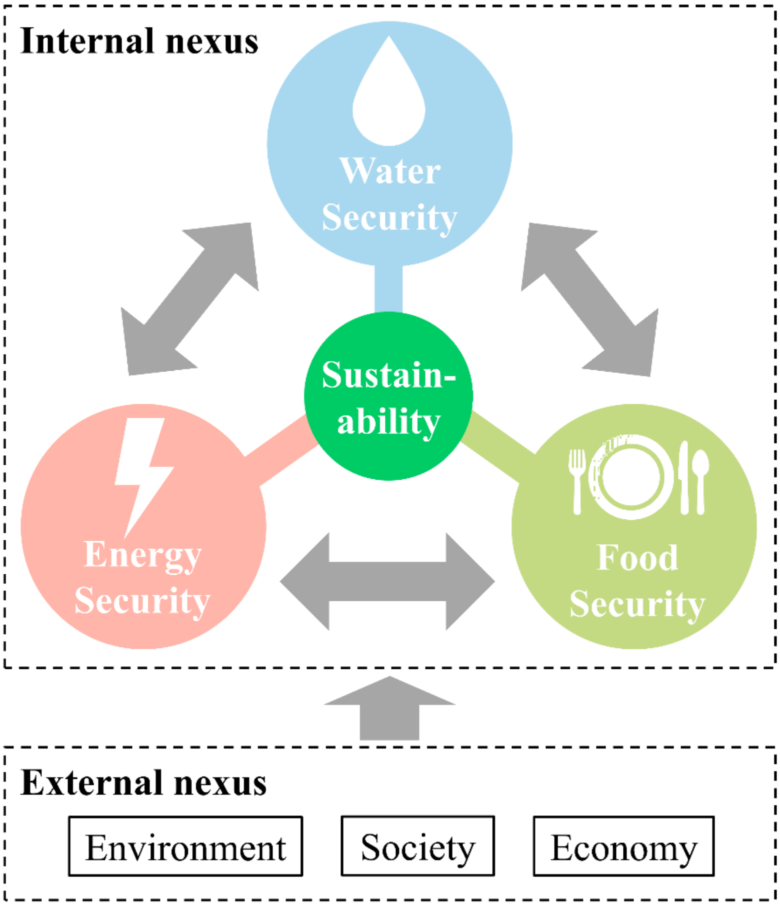


Figure 4.1 Framework of the WEF nexus at the national scale

To examine the interrelationships in the proposed framework, author collected a panel dataset covering 2005–2019 (Table 4.1). Appendix 2 presents the descriptive statistics of all the variables for the entire period. Data were obtained from the IEA, UN, Organization for Economic Cooperation and Development (OECD), Global Footprint Network (GFN), Ministry of Environment of South Korea (MOE), Korean Statistical Information Service (KOSIS), Ministry of Agriculture, Food, and Rural Affairs of South Korea (MAFRA), and the National Groundwater Information Management and Service Center (GIMS).

Table 4.1 Description of variables.

Variables (Symbol)	Specifications	Units	Sources
Water consumption (WC)	Amount of total water consumption	Million cubic meters	MOE (2022)
Electricity demand (ED)	Peak electricity demand	Ten thousand kW	KOSIS (2022)
Food production (FP)	Agricultural output of meats, vegetables, and fruits	Thousand tons	MAFRA (2021)
Ecological footprint (EF)	Annual growth rate of ecological footprint	Score	GFN (2023)
Agricultural support (AS)	Subsidy for agricultural sectors	Million Euros	OECD (2022a)
Agricultural water consumption (AWC)	Water consumption in agricultural sectors	Million cubic meters	MOE (2022)
Total groundwater usage (TG)	Total amount of total groundwater usage	Million cubic meters	GIMS (2022)
Low-carbon energy technology (LE)	(Research, Demonstration, and Development) RD&D budget for low-carbon energy technologies	USD per thousand units of GDP	IEA (2022a)
Climate disaster cost (CD)	Total amount of economic damage from natural disasters	Billion Korean Won	KOSIS (2022)
Producer protection (PP)	Proportion between the average price received by producers and the border price.	Ratio	OECD (2022a)
Public energy RD&D budget (PEB)	Total RD&D budget for public energy technologies	USD per thousand units of GDP	IEA (2022a)
Annual precipitation (AP2)	Precipitation per year	mm	KOSIS (2022)
Population growth (PG)	Population growth rate per year	Percent	OECD (2022a)
Lakes and rivers permanent water area (LRA)	Change in the extent of water-related ecosystems	Square kilometers	UN (2022)
Rice production (RP)	Amount of rice production per cultivation area	kg/ha	KOSIS (2022)
Agricultural productivity (AP)	Amount of agricultural productivity per unit area	9,917.4 Square kilometers/Tons	KOSIS (2022)
Consumer price index for energy (CPIE)	Annual growth rate of energy price index	Percent	OECD (2022a)
Consumer price index for food (CPIF)	Annual growth rate of food price index	Percent	OECD (2022a)
Low-carbon power (LCP)	Share carbon sources in power generation	Percent	IEA (2022a)

Energy efficiency RD&D budget (EEB)	RD&D budget for energy efficiency technologies	USD per thousand units of GDP	IEA (2022a)
Economic growth (EG)	Annual growth rate of GDP	Percent	KOSIS (2022)
Groundwater for agriculture (GWA)	Total amount of groundwater usage for agriculture sector	Million cubic meters	GIMS (2022)
Industrial water consumption (IWA)	Water consumption in industrial sectors	Million cubic meters	MOE (2022)
Carbon emission (CE)	Annual growth rate of carbon emission	Percent	KOSIS (2022)
CO_2 intensity of power (CI)	Emitted CO_2 to produce a kilowatt hour	Index (2000 = 100)	IEA (2022a)
Hydrogen and fuel cells budget (HFB)	RD&D budget of hydrogen and fuel cells in US dollars	USD per thousand units of GDP	IEA (2022a)

4.3.3 Model specification

SEM is a system of linear equations that includes a feedback relationship between variables, where some variables occur as explained in one equation, whereas others may appear as explanatory variables (Wooldridge, 2012). SEM variables may be connected through direct relationships, indirect ties, reciprocal interactions, feedback loops, and correlations between disturbances (Maddala, 1992; Paxton et al., 2011). The two most popular estimation methods for SEM are two-stage least squares (2SLS) and three-stage least squares (3SLS) (Kapteyn and Fiebig, 1981). 2SLS, which is a single-equation approach, implies that over-identifying restrictions in other equations are not considered when estimating the parameters in a particular equation. By contrast, 3SLS, which is a system equation approach, uses information concerning the endogenous variables in the system and considers error covariances across equations; hence, it is asymptotically efficient in the absence of specification errors (Greene, 2008). A systemic method can also help consider important indicators such as sustainability and resilience with regard to linkages across different domains, rather than just their respective components (Huntington et al., 2021). The endogeneity issue in the SEM estimation can also be resolved using the 2SLS approach. However, if the variance–covariance matrix of the disturbance is not diagonal, the estimators from the 2SLS cannot be asymptotically effective (Zellner and Theil, 1992). As a combination of 2SLS and seemingly unrelated regression (SUR), 3SLS provides consistent and efficient estimates if the disturbances are correlated contemporaneously (Henningsen and Hamann, 2008) because SUR may enhance the efficiency of parameter estimates in the presence of contemporaneous correlation of errors across equations. In addition, 3SLS is often, but not always, superior to 2SLS, especially in overidentified equations (Kennedy, 2008; Larcker and Rusticus, 2010). Therefore, in this study, 3SLS was used to examine direct and indirect relationships in the WEF nexus framework.

In this study, four equations for interrelationships in the internal and external nexuses, based on the abovementioned literature, structural concepts, and collected data, are presented in Section 4.2. Water consumption, energy demand, food production, and the ecological footprint were classified as endogenous variables, whereas the other variables were categorized as exogenous. These four endogenous variables are indicators that play key roles in each sustainable WEF nexus (Hoff, 2011; Bizikova et al., 2013). Moreover, the security of one resource is affected by the security of the other two resources because WEF security interact with each other (Ringler et al., 2013; Artioli et al., 2017; Albrecht et al., 2018; Endo et al., 2020). For example, the FAO has analyzed these indicators for sustainable water–energy, water–food, and energy–food linkages (Flammini et al., 2014). The external factors affecting WEF security and sustainability include environmental, social, and economic factors. Considering these relationships and the multicollinearity among the independent variables, the following equations were established:

Equation (1): Water consumption

$$\begin{aligned} \boldsymbol{Ln(WC)_t = a_0 + a_1 Ln(ED)_t + a_2 Ln(FP)_t + a_3 Ln(AWC)_t + a_4 Ln(CI)_t} \\ \boldsymbol{+ a_5 Ln(CPIF)_t + a_6 Ln(EEB)_t + a_7 Ln(HFB)_t + a_8 Ln(PP)_t} \\ \boldsymbol{+ a_9 Ln(RP)_t + a_{10} Ln(TG)_t + u_W} \end{aligned}$$

Equation (2): Energy demand

$$\begin{aligned} \boldsymbol{Ln(ED)_t = b_0 + b_1 Ln(FP)_t + b_2 Ln(WC)_t + b_3 Ln(AP)_t + b_4 Ln(AS)_t} \\ \boldsymbol{+ b_5 Ln(LE)_t + b_6 Ln(CD)_t + b_7 Ln(CPIE)_t + b_8 Ln(CPIF)_t} \\ \boldsymbol{+ b_9 Ln(EG)_t + b_{10} Ln(GWA)_t + b_{11} Ln(IWC)_t + u_E} \end{aligned}$$

Equation (3): Food production

$$\begin{aligned} Ln(FP)_t = c_0 + c_1 Ln(ED)_t + c_2 Ln(EF)_t + c_3 Ln(AP)_t + c_4 Ln(AWC)_t \\ + c_5 Ln(CI)_t + c_6 Ln(EG)_t + c_7 Ln(HFB)_t + c_8 Ln(LRA)_t \\ + c_9 Ln(PG)_t + c_{10} Ln(PP)_t + c_{11} Ln(TG)_t + u_F \end{aligned}$$

Equation (4): Ecological footprint

$$\begin{aligned} Ln(EF)_t = d_0 + d_1 Ln(WC)_t + d_2 Ln(AP2)_t + d_3 Ln(CE)_t + d_4 Ln(EG)_t \\ + d_5 Ln(GWA)_t + d_6 Ln(LRA)_t + d_7 Ln(PG)_t + d_8 Ln(RP)_t \\ + d_9 Ln(LCP)_t + d_{10} Ln(PEB)_t + u_{EF} \end{aligned}$$

where t is the time span from to 2005–2019, and u is the error term. Equation 4 confirms the EKC by analyzing the relationship between environmental sustainability and economic growth. Including economic growth in Equation 4 helps us explore the EKC hypothesis.

The system of equations is over-identified in most simultaneous equation models (Zellner and Theil, 1992). Every equation of the system obeyed the rank and order conditions for identifiability (identified and over-identified). Moreover, to systematically understand the analysis results of 3SLS systematically, all variables were transformed into logarithmic scales (Equations 1–4). The estimated coefficient is the elasticity obtained by adopting a logarithmic form (Auster et al., 1972). For example, if an independent variable exhibits a negative coefficient (b), a 1% increase in the value of the independent variable decreases the value of the dependent variable by b%. Using this mathematical structure, the interrelationship of the WEF nexus is evaluated in Section 4.4.

4.4. Results and discussion

4.4.1 Model verifications

Before interpreting the 3SLS results, several tests were conducted to verify the appropriateness of the proposed model. First, the Wu–Hausman test was used to detect the endogenous regressors for the four suggested equations (Hausman, 1978). Second, the validity of the over-identifying restrictions was verified by applying the Sargan–Hansen test (Sargan, 1958). Third, the Wald test, a parametric statistical measure, was conducted to confirm whether the independent variables are significant for the model (Wald, 1943). Finally, the variance inflation factor was used to detect multicollinearity (Alin, 2010). As shown in tables 4.2 and 4.3, the results of the four tests indicate that the model was appropriate.

Table 4.2 Model diagnostics

Test	Water consumption	Energy demand	Food production	Ecological footprint
Wu–Hausman	2.38 (p = 0.296)	5.28 (p = 0.148)	4.02 (p = 0.295)	4.54 (p = 0.167)
Sargan–Hansen	3.63 (p = 0.163)	3.97 (p = 0.137)	2.66 (p = 0.103)	4.28 (p = 0.118)
Wald	423***	30.6***	19.3**	10.9***

Table 4.3 Multicollinearity check

Variance inflation factor							
Water consumption		Energy demand		Food production		Ecological footprint	
AWC	2.72	WC	3.77	EF	1.99	WC	3.72
HFB	4.24	GWA	4.56	EG	5.41	EG	2.34
RP	5.57	AS	2.30	AWC	3.63	CE	6.04
PP	4.08	AP	6.95	HFB	3.71	PG	2.27
EEB	3.95	LE	5.97	AP	6.71	PEB	8.15
FP	3.58	CPIF	3.14	CI	7.56	RP	3.35
TG	2.18	FP	2.33	TG	2.32	AP2	2.89
CI	2.55	CD	2.81	PP	3.52	LRA	3.40
ED	7.54	IWC	5.58	LRA	5.04	LCP	5.38
CPIF	5.74	EG	3.23	PG	2.17	GWA	4.45
		CPIE	4.29	ED	6.68		

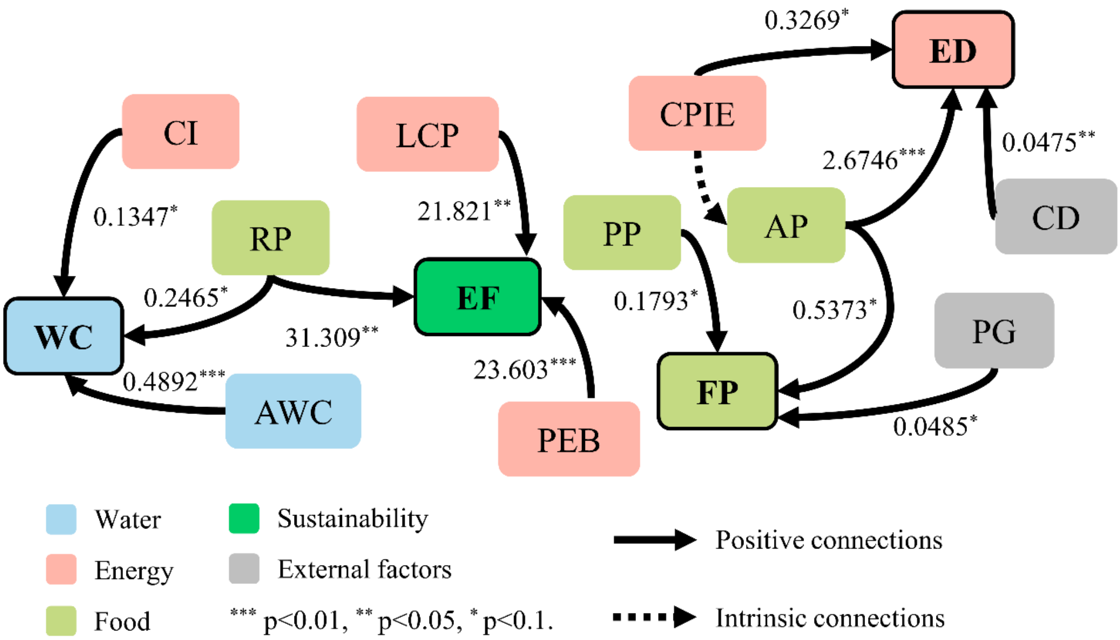
4.4.2 Empirical findings

Table 4.4 shows the estimation results for the system of simultaneous equations with water consumption, energy demand, food production, and ecological footprint as the endogenous variables. The goodness of fit, measured by the overall R-squared value of 0.9592 in all equations, shows that the explanatory variables are sufficient to explain the changes in the endogenous variables across South Korea. Figures 4.2 and 4.3, were visualized using only the statistically significant values from the results in Table 4.4. The interrelationships for each indicator consist of three parts: positive links representing synergies, negative links indicating trade-offs, and intrinsic links representing inherent connections. Intrinsic links are used according to the theoretical background because the interrelationships between the indicators are difficult to explain. This relationship can be interpreted using a nexus approach. For example, the consumer price index for energy (CPIE) cannot explain the direct effect on electricity demand (ED); however, it indirectly affects ED because it affects the AP.

Table 4.4 3SLS estimation results

Variables	Water consumption	Energy demand	Food production	Ecological footprint
	$ln(WC)$	$ln(ED)$	$ln(FP)$	$ln(EF)$
$ln(WC)$		-0.6508^{**}		-12.830
$ln(ED)$	-0.0817		-0.0364	
$ln(FP)$	0.0453	-0.7029^{**}		`
$ln(EF)$			-0.0093^{**}	
$ln(AWC)$	0.4892^{***}		-0.1037	
$ln(HFB)$	-0.0108		-0.0371	
$ln(LRA)$			-1.4900^{**}	-52.654^{*}
$ln(GWA)$		0.2036		-14.274^{**}
$ln(RP)$	0.2465^{*}			31.309^{**}
$ln(TG)$	0.0457		-0.0393	
$ln(AP)$		2.6746^{***}	0.5373^{*}	
$ln(AP2)$				1.8886
$ln(AS)$		0.2243		
$ln(CD)$		0.0475^{**}		
$ln(FID)$				
$ln(PG)$			0.0485^{*}	-3.7583^{**}
$ln(LE)$		-0.3563^{**}		
$ln(LCP)$				21.821^{**}
$ln(CPIE)$		0.3269^{*}		
$ln(CPIF)$	-0.0134	-0.1289^{*}		
$ln(IWC)$		-0.5101^{*}		
$ln(EG)$		0.0290	-0.0404^{*}	-0.1418
$ln(EEB)$	-0.0257^{*}			
$ln(CI)$	0.1347^{*}		-0.9609^{**}	
$ln(PP)$	-0.0749		0.1793^{*}	
$ln(CE)$				-0.2345
$ln(PEB)$				23.603^{***}

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

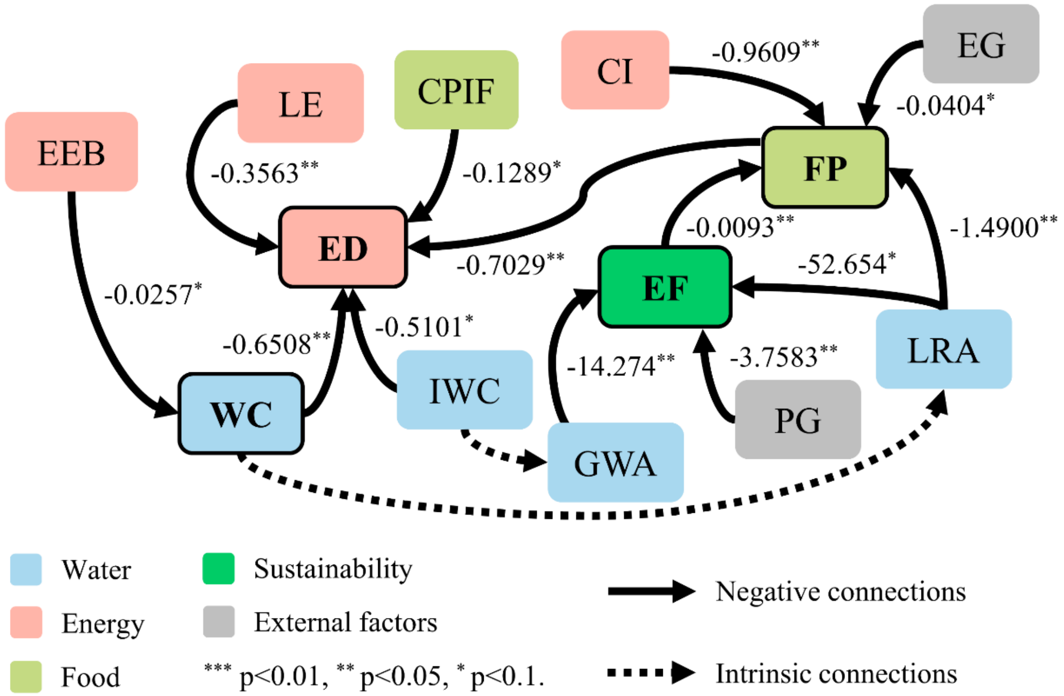


WC	Water consumption	LCP	Low-carbon power
ED	Electricity demand	PP	Producer protection
FP	Food production	CPIE	Consumer price index for energy
EF	Ecological footprint	PEB	Public energy RD&D budget
CI	CO_2 intensity of power	AP	Agricultural productivity
AWC	Agricultural water consumption	CD	Climate disaster cost
RP	Rice production	PG	Population growth

Figure 4.2 Positive feedback loops of sustainable WEF nexus

(1) Synergy context

Figure 4.2 summarizes the estimation results for the synergistic relationships, excluding values that were not statistically significant. Carbon intensity (CI) indicated a positive relationship with water consumption (WC = 0.1347). A high carbon intensity of power generation implies that the proportion of fossil energy sources such as coal, oil, and natural gas is high in the energy mix (Rahman et al., 2022). These fossil-fuel-based power plants use substantial amounts of water resources for power generation (Qin et al., 2015; Stokes-Draut et al., 2017; Lee et al., 2018), accounting for approximately 60% of South Korea's energy mix. Rice production and agricultural water consumption (AWC) increased WC by 0.2465 and 0.4892%, respectively. Although the food self-sufficiency rate was 23% in 2018, the rice self-sufficiency rate was 97%. Approximately 80% of agricultural water, which accounts for 61% of total water use, is used in paddy fields, and rice is grown on most paddy farms (MOE and K-water, 2023). Therefore, agriculture, particularly rice production, accounts for a significant portion of the country's water resources (Yoo et al., 2014). The introduction of technologies and policies that increase agricultural water use efficiency (Wallace, 2000; Howell, 2001; Hsiao et al., 2007) and the production of crops with a lower water footprint than rice (e.g., potatoes, sweet potatoes, and taro) (Mekonnen and Hoekstra, 2011) will simultaneously improve water and food security (Davis et al., 2017).



WC	Water consumption	CPIF	Consumer price index for Food
ED	Electricity demand	CI	CO_2 intensity of power
FP	Food production	LE	Low-carbon energy tech
EF	Ecological footprint	PG	Population growth
EEB	Energy efficiency RD&D budget	EG	Economic growth
IWC	Industrial water consumption	LRA	Lakes and rivers permanent water area
GWA	Ground water for agriculture		

Figure 4.3 Negative feedback loops of sustainable WEF nexus

The climate disaster cost (CD), which escalates owing to climate change (Banholzer et al., 2014), exerts a significantly positive effect on ED (0.0475). This relationship can be explained by the fact that increasing average global temperatures are associated with widespread changes in weather patterns (IPCC, 2022). Extreme temperature fluctuations increase the demands for heating and cooling, leading to an increase in electricity demand (Parkpoom et al., 2004; Franco & Sanstad, 2008; Eskeland & Mideksa, 2010; Allen et al., 2016; Auffhammer et al., 2017).

The AP was significant and positive for ED (2.7646) and food production (FD, 0.5373). Recently introduced agricultural automation helps improve food productivity by reducing labor costs, improving crop productivity, and decreasing working hours (Edan et al., 2009; Kim et al., 2020; O'Shaughnessy et al., 2021). Hence, the share of electricity in agriculture increased from 11.7% in 2001 to 40% in 2019, whereas that of oil decreased from 85.9% to 57.3% over the same period (Korea Energy Economics Institute, 2022). The average rate of increase in the use of agricultural electricity has been 7.4% per year since 2005, far exceeding the rate of increase in total electricity consumption (5.7%), which is expected to increase further in the predictable future (KOSIS, 2022). As Korea relies heavily on energy resource imports for power generation, it also relies on energy imports for food security, even though it currently increases domestic food production. This explains why the CPIE has an intrinsic connection with the AP. The use of renewable energy, a sustainable power supply, in agricultural areas can maximize agricultural productivity and minimize electricity demand, thereby overcoming the abovementioned problems (Ravi et al., 2016; Aghajanzade and Therkelsen, 2019; Gorjian et al., 2020; Gorjian et al., 2022).

The ecological footprint (EF) increased by 31.309% when the rice production increased by 1%. In Korea's food consumption pattern, per capita rice consumption continues to decrease and meat consumption increases (KOSIS, 2022). The government has provided huge subsidies for rice production through a direct payment system to support the supply of rice, which is a staple food source (OECD, 2022b). As a result, farmers have flocked to rice production because it guarantees a stable income, resulting in an oversupply of rice since the 2000s. In contrast, the self-sufficiency rates for crops other than rice, such as wheat (1.2%), corn (3.3%), beans (25.4%), and barley (32.6%) are very low (MAFRA, 2021). An oversupply of food worsens food security and environmental conditions through food waste (Messner et al., 2021). In Korea, where only an oversupply of rice has been observed, this effect is more severe. According to Xu et al. (2021), rice production in paddy fields generates the highest carbon emissions among plant-based foods. If rice oversupply subsidies can be invested in crop diversification, food security can be improved while minimizing environmental damage (Smith et al., 2008; Massawe et al., 2016; Renard and Tilman, 2019).

A 1% increase in both low-carbon power (LCP) and the public energy RD&D budget (PEB) has a positive impact on EF by 21.821 and 23.603%, respectively. This result is inconsistent with the findings of Garrone and Grilli (2010), Brouwer et al. (2016), Anadón et al. (2017), Pehl et al. (2017), Zeyringer et al. (2018), and Zhu et al. (2021), who found that a low-carbon power system and public energy RD&D investment promote a decarbonized society and contribute to sustainability by improving energy efficiency and reducing carbon intensity. Over the past decade, the Korean government has invested significantly in renewable energy, particularly solar power (IEA, 2020). Additionally, investments in low-carbon power and public energy RD&D have focused on solar photovoltaics. As a result, the renewable energy mix in 2021 represented solar, hydroelectric, wind, wave, and tidal power at 69.5, 19.8, 9.3, and 1.3%, respectively, indicating that solar power will account for most renewable energy generation (IEA, 2022a; IEA, 2022b). However, solar power may lead to land occupation and change, which can adversely affect ecosystems and biodiversity (Turney and Fthenakis, 2011; Wu et al., 2021). Korea has not yet considered these aspects of solar power deployment. The indiscriminate installation of solar power can damage farmland and forests, consequently destroying the ecosystem and offsetting the benefits of reducing carbon emissions. Therefore, solar energy that minimizes environmental burdens, such as building-integrated photovoltaics (BIPV) (Peng et al., 2011; Shukla et al., 2017), agrivoltaic farming (Adeh et al., 2019; Miskin et al., 2019), and floating solar technology (Oliveira-Pinto and Stokkermans, 2020; Hooper et al., 2021), should be actively introduced to overcome the paradoxical situation in which solar power damages sustainability.

(2) Trade-off context

Figure 4.3 shows the estimation results with trade-off relationships, except for the statistically insignificant values. Energy efficiency RD&D budget (EEB) indicates a negative relation with WC (−0.0257). An increase in the energy efficiency indicates a decrease in the energy input. Approximately 90% of South Korea's energy mix in 2021 will be non-renewable energy, such as nuclear energy, LNG, and coal (KOSIS, 2022). These nonrenewable energy sources use significant amounts of water for power generation, particularly during cooling (Spang et al., 2014; Qin et al., 2015; Lee et al., 2018; Larsen and Drews, 2019). In contrast, renewable energy (solar and wind) consumes a small amount of water for cleaning, whereas non-renewable energy uses more than 500 gal MW^{-1} h^{-1} of water for cooling (Macknick et al., 2012).

Economic growth (EG) is significantly negative for FP (−0.0404). As the economy grows, meat consumption tends to increase (Gerbens-Leenes et al., 2010; Sans and Combris, 2015). South Korea has continued economic growth, and meat consumption per capita has also increased by more than 20 kg, from 31.9 kg in 2000 to 53.9 kg in 2018 (MAFRA, 2021). Although meat productivity has improved, it has not sustained increasing meat consumption and has begun to rely on imports. The meat self-sufficiency rate has decreased by 14.6%, from 78.8% in 2018 to 64.2% in 2000 (MAFRA, 2021). Consequently, as the economy grows, it becomes dependent on food imports and domestic food production decreases. CI exerts a significant negative effect on FP (−0.9609). Agricultural water accounts for 62.3% of total water consumption (MOE, 2022). Limited water availability and increased water consumption for non-renewable energy due to the positive relationship between CI and WC negatively impacted agricultural water use. This finding is consistent with that of Wicaksono and Kang (2019), who found that securing water availability by decreasing the share of nonrenewable energy will help food security in the future. As the EF value increased and became a threat to sustainability, it had a negative impact on FP (−0.0093). Given that it entails the use of land, water, and energy and the creation of trash, food production is one of the key contributors to the ecological footprint (Noordwijk and Brussaard, 2014; Galli et al., 2017). Hence, an increasing ecological footprint implies that more resources are being used and more waste is generated, which can deteriorate the quality and availability of water and land for food production (Wackernagel and Rees, 1998; Wackernagel et al., 2021). A 1% increase in lake and river permanent water areas (LRA) will directly result in a 1.49 and 52.65% decrease in FP and EF, respectively. Agriculture is a water-intensive industry closely related to water availability (Postel, 1998; Wallace, 2000; Gordon et al., 2010). Globally, approximately 70% of surface water consists of lakes and rivers (Shiklomanov and Rodda, 2003). An increase in the area of lakes and rivers can negatively impact food production if the cost of pollution exceeds water availability. In South Korea, nonpoint pollution sources pollute water resources owing to urbanization and a steady increase in meat production, and this trend is gradually increasing (OECD, 2018a). In contrast, the ecological footprint can be reduced by increasing the area of lakes and rivers, because freshwater environments clean and store water, which is crucial for people and ecosystems (Kitzes et al., 2007; Kitzes and Wackernagel, 2009). Consequently, simultaneous management of water quality and quantity is necessary for sustainable food production and ecosystems (Kirby et al., 2003).

The negative relationship between population growth (PG) and EF does not correspond to the findings of Dietz et al. (2007) and Kitzes et al. (2008), who suggested that PG consumes more resources and adds to the environmental burden. Generally, as the population decreases, the number of resources used also decreases. However, if unsustainable consumption continues, such as overconsumption of water, overemission of carbon, use of fossil fuels, and a diet centered on meat consumption, the environmental burden will be greater than that of declining resource consumption (Spangenberg and Lorek, 2002; Jackson and Papathanasopoulou, 2008; Hoekstra and Wiedmann, 2014). Groundwater for agriculture (GWA) has a trade-off relationship with EF. Groundwater is a crucial source of water for irrigation, and accounts for more than 40% in many OECD nations and 70% of water use globally (Gruère and Shigemitsu, 2021). In 2020, South Korea's agricultural sector accounted for approximately 53% of total groundwater use (GIMS, 2022). In the agricultural sector, groundwater use is more efficient in terms of energy consumption than surface water use because of the more streamlined distribution, transportation, and supply processes (Siddiqi and Anadon, 2011; Yang et al., 2016). This can reduce the carbon footprint and thus help diminish the ecological footprint in the short-term. However, land subsidence, saltwater intrusion, and other environmental issues can result from intensive groundwater pumping for agriculture, which depletes aquifers in the long term (Hallberg, 1986; Han, 2003; Raquel et al., 2007). Groundwater is considered a finite resource because aquifer recharge rates are frequently sluggish (Merchant, 1994; Madramootoo, 2012; Richey et al., 2015). Hence, controlling the use of GWA, while considering the environmental burden and availability caused by the consumption of subsurface water, is important (Shan et al., 2009).

A 1% increase in low-carbon energy technology (LE) decreases ED by 0.3563%. High electricity prices have suppressed growth in electricity demand worldwide (IEA, 2023). South Korea's levelized cost of electricity (LCOE) is as follows (Lorenczik et al., 2020): gas, 90.19–100.43 USD/MWh; coal, 81.04 USD/MWh; nuclear, 67.16 USD/MWh; wind (offshore), 119.31 USD/MWh; solar (commercial), 121.14 USD/MWh; wind (onshore), 137.02 USD/MWh; and wind (offshore), 193.24 USD/MWh. Owing to continued investment in clean energy, the LCOE of renewable energy is declining faster than that of nonrenewable energy. For example, solar power in South Korea is expected to achieve grid parity by 2025 (Hong et al., 2020). Hence, the negative relationship between LE and ED is expected to gradually increase. Consumer price index for food (CPIF) is intrinsically linked to EG and negatively affects ED. Maintaining stable food prices is an important factor in the economic growth of Asian countries (Dawe and Timmer, 2012). This is because the ripple effect of economic and social costs resulting from price instability slows economic growth (Byerlee et al., 2006; Jayne, 2012; Verpoorten et al., 2013). For example, when food prices rise, households reduce their consumption of goods, which worsens their economic cycle. Contrary to previous studies that showed a positive relationship between food production and electricity demand (Khan and Hanjra, 2009; Ladha-Sabur et al., 2019), ED decreased by 0.7029% when FP increased by 1%. This is because energy consumption in the agricultural sector comprises 57.3% oil and 40% electricity, and agricultural productivity is continuously increasing (Korea Energy Economics Institute, 2019). In addition, power savings in the food industry, which are directly related to food production, have steadily increased since 2013 (KOSIS, 2022). However, the potential for productivity decline due to the aging rural population and the increasing share of electrification in agricultural energy use remain issues that need to be addressed (OECD, 2018b). The WC and industrial water consumption have intrinsic connections to the LRA and GWA, respectively. When water is removed from rivers and lakes for drinking, the water flow may decrease, reducing the total area of the water body (Wurtsbaugh et al., 2017). The increased evaporation rate owing to climate change will further accelerate this situation (Shenbin et al., 2006; Woolway et al., 2020). Water availability in a country is limited by factors, such as precipitation and water resource management (Chenoweth, 2008; Elliott et al., 2014). Increased water use in the industrial sector has reduced the availability of water resources for municipal and agricultural use.

(3) EKC hypothesis

As described in Table 4.4, the empirical findings of this study cannot establish the EKC hypothesis, as is evident from the EG estimates, which depict a statistically insignificant relationship with EF. This conflicts with the findings of Iwata et al. (2012), Onafowora and Owoye (2014), Onater-Isberk (2016), and Destek and Sarkodie (2019), who find that the EKC hypothesis is valid for South Korea. The rationale behind this discrepancy is that the present study considers indicators associated with WEF security that have been neglected in previous studies. The rejection of the EKC hypothesis implies that economic growth does not guarantee environmental sustainability. Therefore, additional actions are required to address these critical environmental problems (Ali et al., 2017; Gill et al., 2018; Pata et al., 2022). Moreover, focusing on the scaling up of economic and other external factors undermines the improvement of WEF security (Huang et al., 2023). According to the above discussion, the components of WEF security (LCP, RP, PEB, LRA, and GWA) affect environmental sustainability rather than economic development. Maximizing synergies and minimizing trade-offs between WEF resources improves WEF security and achieves environmental sustainability. This finding is consistent with those of Zaman et al. (2017), Zaman (2018), Nassani et al. (2019), and Xu et al. (2022) who found that environmental quality could be enhanced through the WEF nexus framework.

4.5. Conclusion

In the present study, a sustainable WEF nexus framework was introduced to explore the interrelationships between WEF security and sustainability in South Korea from 2005 to 2019 using a simultaneous equation model and the EKC hypothesis. The key findings and relevant policy implications of this study are as follows: First, rice production is a water- and energy-intensive industry with low production per unit area, which adversely affects the sustainable WEF nexus. Excessive use of agricultural water reduces water availability and quality, resulting in scarce water resources. Environmental degradation negatively affects energy production and sustainability. Korea’s rice-oriented food production structure accelerates this effect; therefore, expanding the production of alternative crops such as potatoes and sweet potatoes is important. Second, an increase in agricultural productivity caused by automation can improve food security; however, it can also threaten energy security by increasing electricity demand and energy imports. The share of renewable energy sources must increase to achieve stable food production. Compared to non-renewable energy, renewable energy consumes little water and does not emit pollutants; therefore, it can positively impact the sustainable WEF nexus. However, South Korea’s renewable energy industry focuses on solar power, and the current solar power policy is detrimental to sustainability because installations can damage nature. Solar power sources, such as agrivoltaic farming, float solar power, and BIPV, which do not adversely affect sustainability, should be actively introduced. Third, according to the EKC, environmental problems cannot be resolved through economic development. In South Korea, even if the population decreases because of unsustainable consumption patterns, sustainability is undermined. Policy established on a “wait and grow” presumption is not appropriate (Agras and Chapman, 1999), and the current generation should strive for sustainable development. Sustainable WEF security can be achieved by analyzing the synergies and trade-offs of WEF security, a key element of the SDGs, through the Nexus approach.

This study had three limitations. First, a few indicators associated with the sustainable WEF nexus were selected based on data availability and statistical characteristics of the SEM. Although this study considered more indicators than previous studies, the selected indicators do not thoroughly represent a sustainable WEF nexus. Introducing dimension-reduction methods, such as principal component analysis, allowed the author to handle larger amounts of data. Second, only the GDP growth rate is selected as a factor to analyze the EKC hypothesis. Future studies should consider various economic factors such as GDP, squared GDP, and GDP per capita for a more in-depth analysis. Finally, the analysis performed in this study and suggestions were based on historical data. In particular, there is speculation about the development of renewable energy, even though reasonable grounds for speculation are presented based on the existing literature. To handle a broader range of possible results, a procedure to verify the effectiveness of the proposed measures should be developed in future studies.

This study presents a sustainable WEF nexus framework that considers sustainability and external factors in the existing WEF nexus theory. Through SEM and the EKC hypothesis, it was determined that the optimization of synergies and trade-offs between the interconnected sustainable WEF nexus can contribute to sustainable development in South Korea.

Chapter 5. Conclusions and Recommendations

This section summarizes the main findings of this dissertation. It proposes policy recommendations for improving WEF security and sustainable development under the nexus perspective for better development in the future. Moreover, it suggests the contributions, limitations, and future directions of this research.

5.1. Summary of the research findings

This dissertation explored the interactions in WEF security to achieve sustainable development through a nexus approach using quantitative methods, suggesting the importance of maximizing synergies and minimizing trade-offs within the WFE nexus framework. The conclusions of this dissertation offer a valuable framework for conducting similar investigations in the future. However, previous studies on the interactions among the WEF sectors are scarce at the national scale. In particular, the application of nexus frameworks to policy recommendations for external drivers is still lacking. In addition, there is a dearth of studies on sustainability, even though the WEF is closely associated with sustainable development. The major objective of this dissertation is to address the WEF nexus in the national context and evaluate the interactions of selected national-scale indicators in WEF security by applying a conceptual and quantitative analysis framework and considering sustainability aspects together with external factors. To achieve this objective and overcome the limitations of the aforementioned studies, the following chapters are formulated:

In Chapter 2, an extended literature review reveals that the WEF nexus is a field that must be approached comprehensively and that a quantitative methodology helps analyze the interactions in the WEF nexus. Moreover, the drivers handled by the nexus framework expanded beyond WEF security.

In Chapter 3, an interaction analysis proved that South Korea's interactive relationships with the WEF nexus are stronger than those of other countries and that national resource security can be improved through the nexus approach. The results indicated that the interaction between energy and energy-related sectors was the highest, indicating that managing energy security is the most effective area for improving WEF security.

In Chapter 4, a sustainable WEF nexus framework is established to consider sustainability and external factors, and an assessment of elasticity is conducted to estimate specific interactions using SEM and the EKC hypothesis. Based on these investigations, it was determined that establishing synergies and reducing trade-offs in WEF security through the nexus approach can improve overall resource security and achieve sustainable development. In particular, the indicators related to WEF security influence sustainability rather than economic development. These results indicate that WEF security and sustainability can be improved simultaneously by maximizing synergies and minimizing trade-offs within a sustainable WEF nexus.

5.2. Policy recommendations

The results of this dissertation show that WEF security interactions can be efficiently managed in South Korea if the following policies are introduced from a nexus approach point of view.

First, the interaction between energy and energy-related sectors was the highest because of the country's heavy reliance on energy resources. Specifically, increasing the proportion of renewable energy utilization improved WEF security. By reducing the proportion of nonrenewable energy that consumes a large amount of water in the energy mix, the availability of water, which can be used as a resource for food production, can be increased. However, focusing on a small number of renewable energy sources has the potential to increase environmental burden and worsen resource security. To prevent this, it is necessary to introduce various renewable energy sources. The Korean government has invested heavily in renewable energy, particularly solar power. Moreover, investments in low-carbon power and energy RD&D have focused on solar energy, indicating that solar power accounts for most renewable energy generation. In particular, Korea's land area is very small, and most (63%) consists of forests. Solar power can lead to land development and change, negatively affecting ecosystems, biodiversity, and food production. Korea has not scrutinized the above-mentioned aspects of solar power installation. The indiscriminate deployment of solar power can damage farmland and forests, consequently destroying the ecosystem and offsetting the benefits of reducing carbon emissions. Therefore, solar energy that minimizes environmental burdens, such as BIPV, agrivoltaic farming, and floating solar technology, should be vigorously introduced to overcome the ironic situation in which solar power deteriorates sustainability. Furthermore, it is necessary to diversify renewable energy sources such as marine energy, offshore wind power, hydrogen energy, geothermal heat, bioenergy, and hydrothermal energy.

Second, rice production causes the excessive use of agricultural water, thereby deteriorating water availability and quality. This leads to scarce water resources and environmental degradation, which adversely affect energy production and sustainability. Rice production accounts for a significant proportion of South Korea’s water resources. The introduction of technologies and policies that increase agricultural water use efficiency and the production of crops with lower water consumption than rice, such as potatoes, sweet potatoes, and taro, will simultaneously promote water and food security. Therefore, it is crucial to expand the production of alternative crops, such as less water- and energy-intensive crops, and encourage people to change their diet to these crops. To achieve this goal, government-level rice subsidies must be distributed across various crops. Currently, Korean farmers have flocked to rice production because it guarantees a stable income through a direct payment system, resulting in rice since the 2000s. An oversupply of food worsens food security and environmental conditions through food waste. Rice production in paddy fields generates the highest carbon emissions of all plant-based foods. If subsidies for rice oversupply can be invested into crop diversification, food security can be improved while minimizing environmental damage. Furthermore, although increased agricultural productivity through automation improves food security, it can also pose a threat to energy security by increasing electricity demand and energy imports. Because Korea relies heavily on imported energy resources for power generation, it also relies on energy imports for food security. The use of renewable energy as a sustainable power supply in agricultural areas can maximize agricultural productivity and minimize electricity demand.

Thirdly, economic growth does not guarantee environmental sustainability. However, the indicators related to WEF security influence environmental sustainability rather than economic development. Hence, additional actions are required to address these critical environmental problems. These results indicate that WEF security and sustainability can be improved simultaneously by maximizing synergies and minimizing trade-offs within a sustainable WEF nexus. To achieve the “killing two birds with one stone”, resource management policies that take into account the nexus approach should be implemented at national level.

5.3. Contributions and future research

The dissertation presented in this dissertation makes referential, conceptual, and practical contributions to literature. At the reference level, South Korea, the study area, is a resource-poor country that has recently joined the ranks of developed countries. Hence, this research can serve as a reference for developed and developing countries whose resource security is threatened. At a conceptual level, it has been proven that WEF security is closely related. Moreover, the existing WEF nexus system was expanded into a ‘sustainable WEF nexus’ that takes into account external factors and sustainability, and it was revealed that sustainable development can be achieved through resource management through the nexus approach. At the practical level, the two manuscripts (Chapter 3-4) offer detailed practical insights. Spearman’s rank correlation and network analyses demonstrated that resource security is an interconnected rather than an independent system, and that WEF security improves efficiently when indicators are preferentially upgraded with many interactions, providing important guidelines for prioritizing policies to implement sustainable resource management systems (Chapter 3). An assessment of the national WEF nexus via a systematic estimation that considers perspectives for achieving sustainable development using the 3SLS and EKC hypotheses. In particular, SEM enables the determination of the relationships between numerous variables that affect each other directly or indirectly, thereby assessing the effects of different policy interventions and evaluating hypotheses on the causal nexus among variables by systematically considering all relevant interdependencies. (Chapter 4).

This dissertation has some limitations. First, the selection of indicators was significantly affected by the availability of data, owing to the nature of the applied method, which necessitates pairs of sorted data. If other WEF security-related indicators are considered, additional interactions will be examined in the future. Second, the analysis and recommendations of this study are based on historical data. In particular, there is a conjecture on the advancement of renewable energy, despite the fact that plausible justifications for this conjecture are provided by the body of current studies. To accommodate a wider variety of potential outcomes, future studies should establish protocols to confirm the efficacy of suggested interventions. The nexus system should also be integrated with decision-making domains so that policies can address future WEF resource demands for full utilization. Third, the quantitative method used in this dissertation is based on linear analysis. Using a simulation model that can simultaneously examine linear and non-linear interactions, the effects of the three resources can be investigated simultaneously. Moreover, applying multiple WEF food resource scenarios would help to overcome this limitation.

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Appendices

Appendix 1. Descriptive analysis (1)

	Mean	Standard deviation	Minimum	Maximum
W1	97.93	0.71680	97.003	98.98
W2	90.00	5.91608	81.000	99.00
W3	41.13	7.79843	29.930	53.81
W4	-85.21	0.00915	-85.220	-85.20
W5	418.03	8.06601	399.686	428.12
W6	-279.40	6.74854	-295.000	-270.00
W7	-11089.20	1248.29010	-13555.300	-9377.70
W8	2442.79	221.70680	2182.800	2765.90
W9	7615.73	123.88498	7406.200	7779.60
W10	1284.72	206.84099	949.000	1622.60
W11	-1.85e−9	1.96e+8	-2112696161	-1484648381
W12	-337.85	110.30714	-559.200	-202.90
W13	94.86	2.55525	90.100	98.40
W14	-22824.12	3002.34450	-29163.000	-18665.00
W15	89.71	3.79629	81.400	93.55
W16	89.75	3.84650	81.400	93.90
E1	97.13	1.16879	96.570	100.00
E2	1.75	0.85335	0.770	3.18
E3	-6.00	0.28513	-6.590	-5.47
E4	-555.21	61.26132	-632.400	-460.30
E5	32534.53	11341.98160	17593	50078
E6	9.55	1.20763	7.400	11.10
E7	2219.53	2864.82053	10	9208
E8	964.27	718.66329	47	2465
E9	1901.40	2363.56056	163	7335
E10	127.93	41.09652	69	196
E11	-209190.67	38699.06691	-258286	-142263
E12	-19350.13	5223.04208	-29480	-11795
E13	-104414.27	30898.85897	-155542	-59399
E14	-148362.33	9361.71215	-164762	-130715
E15	-264813.07	29048.67373	-307557	-215772
E16	683.47	88.56948	492	793
F1	-53.70	6.48757	-69.000	-44.70
F2	-173.80	9.07689	-185.200	-162.00
F3	2.19	0.31270	1.750	2.96
F4	-21.16	0.39785	-22.100	-20.60
F5	95.84	3.45354	90.050	102.00
F6	4.99e+6	418013.60992	4397532	5669209

F7	1.52e+6	86119.57523	1374000	1653000
F8	25.65	2.50624	21.800	29.60
F9	319.40	45.19572	270.900	430.70
F10	-3.27e−7	3.88e+6	-38272378	-27038517
F11	-88.49	14.45860	-108.718	-67.77
F12	-2.72	0.52536	-3.800	-2.10
F13	4.65	0.21321	4.330	4.93
F14	2990.81	538.60043	2117.999	3866.98
F15	2981.07	71.13917	2844	3112
F16	3.67	0.29921	3.400	4.20

Appendix 2. Descriptive analysis (2)

	Mean	Standard deviation	Minimum	Maximum
WC	9.95	0.066	9.85	10.1
FP	9.83	0.0449	9.76	9.9
ED	10.7	0.0942	10.6	10.8
EF	0.98	2.2	−3.88	4.15
BL	6.54	0.124	6.2	6.68
AP	1.54	0.0461	1.47	1.6
AP2	7.13	0.164	6.86	7.39
TG	8.22	0.11	7.98	8.32
LCP	3.37	0.0989	3.19	3.54
CI	4.65	0.0437	4.58	4.72
PEB	6.71	0.147	6.3	6.88
HFB	4.08	0.287	3.71	4.75
PP	0.547	0.0757	0.445	0.703
AS	10.1	0.0662	9.96	10.2
GWA	7.51	0.114	7.3	7.66
AWC	9.3	0.111	9.15	9.51
IWC	7.8	0.0875	7.69	7.93
LRA	6.04	0.0206	5.99	6.07
RP	8.82	0.0439	8.74	8.89
CE	0.346	2.55	−5.26	4.55
EG	1.15	0.498	−0.223	1.92
CD	5.75	1.12	3.55	7.8
CPIF	0.586	0.67	−0.96	1.54
CPIE	4.59	0.114	4.4	4.76
PG	−0.76	0.342	−1.55	−0.263
EEB	5	0.281	4.15	5.32