Ph.D. Dissertation of City Planning

Essays on the Impact of Expanding Renewable Energy on Carbon Emissions and the Regional Economy

재생에너지 확대가 탄소배출 및 지역경제에 미치는 영향 연구

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Abstract

The energy sector is the largest contributor to climate change. Drastically reducing carbon emissions from energy use is imperative to ensure a sustainable future. Renewable energy sources, such as wind and solar photovoltaic (PV) emerged as leading clean energy alternatives, However, the transition implicates significant changes due to their major distinctions from the conventional energy system.

Renewable energy encompasses a broad range of value chain, particularly requiring flexibility resources due to its intermittency. Consequently, it is essential to evaluate carbon emissions over the complete lifecycle, from development to decommissioning. Moreover, as a distributed energy source, renewable energy is often located close to residential areas raising both public concerns and interest in regional job creation. The recent rise in green protectionism has further amplified the focus on enhancing the national competitiveness of renewable energy industries.

The thesis aims to analyze the impact of renewable energy expansion on carbon emissions and regional economy. It considers the inherent characteristics of the renewable energy system, such as the 1) lifecycle value chain, 2) capacity building, 3) regional characteristics such as natural resources, and industry structure. By doing so, it seeks to propose sustainable development strategies related to carbon emission reduction. The study consists of three essays, each exploring different aspects of renewable energy characteristics in the impact assessment. The research employs various analytical methods, including input-output analysis, lifecycle assessment, and cost analysis.

The first essay assesses the lifecycle carbon emissions resulting from the expansion of 211MW onshore wind power in Jeju. It utilizes the Economic Input-Output Life-cycle Assessment (EIO-LCA) based on cost analysis and Environmentally Extended Input-Output (EEIO) analysis. The study identifies primary sources of emissions, providing recommendations to mitigate carbon emission. Battery manufacturing of Energy Storage System (ESS) emerges as the

single largest source of carbon emission, followed by manufacturing of turbine elements. The results highlight the significance of carbon emission of flexibility resources and the importance of employing various mitigation efforts such as reusing batteries from electric vehicles and other flexible resources such as DR and V2G that require relatively little additional infrastructure. In addition, sensitivity analysis reveals that increasing both the capacity factor and operational period of onshore wind farms could further enhance carbon emission reduction potential. The most notable carbon emission contributing industries are identified as 1) 'Electricity, gas and steam' supply, 2) 'Primary metal products' (Steel production) 3) 'Non-metallic mineral products' (Cement production). Ultimately, it is crucial not only to increase the share of renewable energy in the electricity generation sector but also to actively transform unsustainable industrial processes.

The second essay evaluates the impact of onshore wind power expansion on Jeju's regional economy based on cost analysis and Interregional Input-Output (IRIO) analysis considering various levels of capacity building in the form of local content (%). The study accentuates the extensive value chain activities of renewable energy, generating value-added and employment opportunities across various sectors. The induced value added by onshore wind Operation& Maintenance (O&M) is comparable to that of Jeju's construction, restaurant and hotel, and agriculture and fisheries industries. Moreover, renewable energy system creates jobs across various sectors, even beyond those directly related to onshore wind energy, distinguishing it from conventional power plants. This also implicates that finding personnel with diverse skill sets and talents will be a significant challenge in the future. Furthermore, the results indicate that an increase in regional local content has a minimal effect on the total number of jobs created in the country, while an increase in national manufacturing leads to a rise in regional jobs. Hence, regional local content can effectively address local acceptance issues associated with renewable energy.

Building upon preceding studies, the third essay analyzes the relationship

between carbon emissions and economic impacts, focusing on onshore wind and solar PV expansion in Korea utilizing IRIO and multi-regional EIO-LCA. By studying the installation of 19GW of renewable energy, the essay highlights that incorporating flexibility options and increasing local content rate substantially increases employment opportunities but can also lead to higher carbon emissions, indicating a trade-off. The case of Jeju Island is examined from a consumption-based emission perspective to analyze the regional distribution of carbon emissions and job creation during the operation of onshore wind and solar PV. It is discovered that there are regional variations in carbon emissions and job creation depending on the ESS production region. Interestingly, the region with the highest carbon emissions does not necessarily create the most jobs. Therefore, aligning renewable energy expansion with sustainable supply chain strategies can ensure job creation while minimizing carbon emissions. This approach could provide incentives for corporations to adopt sustainable practices.

In conclusion, this study emphasizes the integration of renewable energy expansion with sustainable industrial activities. The findings have implications for countries facing similar challenges in managing intermittent renewable energy and energy-intensive industries. While renewable energy presents advantages, it also entails complexities due to intermittency and distributed nature. Flexibility resources play a crucial role but can have significant environmental and economic impacts. However, aligning clean energy production with clean industry practices allows for the minimization of carbon emissions impact while ensuring national competitiveness and revitalizing the regional economy. This paves the way for a sustainable future for generations to come.

Keyword: Renewable Energy, Carbon Emission, Regional Economy, Wind Energy, Solar PV, Flexibility Resources, Input-Output Analysis, Life-cycle Assessment

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List of Abbreviations

BOK	Bank of Korea
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CFI	Carbon Free Island
CGE	Computable General Equilibrium
DER	Distributed Energy Resources
DR	Demand Response
DRI	Direct Reduced Iron
EEIO	Environmentally Extended Input-Output
EF	Employment Factor
EIO-LCA	Economic Input-Output Life-cycle Assessment
ESS	Energy Storage System
FTE	Full Time Equivalent
GHG	Greenhouse Gas
GRDP	Gross Regional Domestic Product
GW	Gigawatt
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IO	Input-Output
IRA	Inflation Reduction Act
IRIO	Inter-Regional Input-Output
KSIC	Korean Standard Industrial Classification
LCA	Life-cycle Assessment
LCR	Local Content Requirement
LNG	Liquified Natural Gas
LUC	Land Use Change
MCI	Manufacturing, Construction, Installation
MREEIO	Multi-Regional EEIO
NDC	Nationally Determined Contribution
NZIA	Net Zero Industry Act
O&M	Operation and Maintenance
OPEX	Operating Expenditure
P2G	Power-to-Gas
P2H	Power-to-Heat
P2L	Power-to-Liquid
PV	Photovoltaic
RE100	100% Renewable Energy
RES	Renewable Energy System
SAIDI	System Average Interruption Duration Index
UBESS	Used Battery Energy Storage System

V2G	Vehicle-to-Grid
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
WTO	World Trade Organization

Chapter 1. Introduction

1.1. Motivation

Energy is a bedrock of survival and growth of all living things. For this, we endlessly strive to procure and utilize energy. If the unsustainable energy utilization as well as the industry structure that upholds this do not undergo a drastic change, humanity will face irreversible threats in the form of climate change, air pollution and destruction of biodiversity. Our actions today will impact future generations.

The Korean economy is established on the reliance on imported fossil fuels. Korea imported 98% of its energy which is consumed in energy transition (electricity and heat production), industry, building and transportation sectors. And the industry sector consumed 60% (including electricity and heat) of total primary energy as feedstock and fuel in the production in 2020 (KEEI, 2021; EIA, 2023). Energy-intensive manufacturing industries[1], responsible for 70% of the total industrial emission in 2020 (EG-TIPS, 2022), produced on average 34% of the total national manufacturing profit in the past 5 years (ISTAN, 2023). Although these activities improved living standards of the country, they have contributed to Korea becoming the 13th largest greenhouse gas producer globally in 2020 (Climate Watch, 2023).

Environmental problems are transboundary in nature that requires global effort. Global efforts to combat climate change has led Korea to pledge to reduce net greenhouse gas emission to 40% of 2018 level by 2030 and to zero by 2050 which requires emission reduction in all sectors. Hence, the importance of expanding clean energy sources is emphasized more than ever. Renewable energy sources such as solar PV and wind, are very prominent clean energy solutions with high market potential in Korea. They operate without fuel, discharge lowest CO_2

[1] Steel, Refining and Petrochemical, Cement, Display and Semiconductor industries

emissions during the entire lifecycle, are cheaper to build (Schlömer, et al., 2014, pp. 1333,1335), create jobs (Hong, 2023; Hong, et al., 2019; Jacobson, et al., 2019; Lehr, Lutz, & Edler, 2012), take shorter amount of time to plan, build and replace fossil fuel system than new nuclear programs, saving more carbon per year (Schenider & Froggatt, 2019, p. 253).

The framework for a sustainable energy transition requires that energy systems not only deliver energy services, but also do so in a way that is consistent with and achieves global and national policy goals (Polack, 2021). Therefore, it is important to assess the environmental impact of the new energy system to ensure that the expansion of renewable energy is aligned with sustainable development goals. To do so, the carbon emissions from the entire lifecycle of renewable energy system, including manufacturing, installation, and flexibility resources must be evaluated to identify solutions for improvement.

Meanwhile, global decarbonization efforts under current geo-political circumstances have posed a new transboundary challenge – trade regulations and initiatives such as Carbon Border Adjustment Mechanism (CBAM), 100% Renewable Energy (RE100) initiative, Net Zero Industry Act (NZIA) and Inflation Reduction Act (IRA). First two measures are mainly involved with removing carbon dioxide in the production but the latter two interfere with where the production takes place. The COVID-19 pandemic and the Ukrainian war have brought supply chain complexities in the world which have led the U.S and EU reduce external trade dependencies particularly from China in the form of green goods subsidy race. Hence, national capacity building is increasingly becoming a popular policy tool despite the prohibition from World Trade Organization (WTO). It is believed that domestic manufacturing will create socio-economic impacts such as innovation and jobs (Hong, 2023) which can in turn garner political support for renewable energy (Lewis, 2014), and carbon neutrality goals.

Renewable energy sources are inherently different from centralized conventional energy sources such as coal, oil, gas, and nuclear power plants.

Renewable energy resources are generally spatially dispersed, often located within close vicinity of the local community and livelihood often causing acceptance issues (Im, Yun, Yoon, & Kim, 2021). Naturally, there is a high level of social interest in the impact of expanding renewable energy on local communities. Under this context, capacity building of renewable energy intended to create local jobs and garner social acceptance is also becoming a regional concept. This is especially noticeable in places where the environmental justifications for the adoption of renewable energy may be insufficient and is desperate for economic revitalization.

To thoroughly understand the impact of expanding renewable energy on carbon emissions as well as the regional economy, it is necessary to examine the entire value chain comprehensively. Renewable energy consists of a wide range of value chain activities (Hong, 2023, p. 316). For example, wind energy system can include finance, planning, design and manufacturing of turbines, control system, electronics, blades, towers, foundation works, assembly, transformers and operation and maintenance where each of these components has its own supply chain. Moreover, due to intermittency[2], as penetration of renewable energy (%) increases, flexible options such as energy storage and extensive grid connections are required for stable operation. This is increasingly posing challenge in Korea in the form of curtailment as the country's electricity grid is completely isolated, requiring more resilient energy storage systems, sector coupling technologies, demand-side management (decentralize power demand) – to match with excess or shortage of power (Lee T. , 2020). The level of capacity to provide required products and services, as well as the type of flexibility options required, may also vary depending on the regional industry structure. Increased demand for such products or services also have an impact on the level of other industries associated with that industry. Especially, given such an extensive value chain, it is necessary

[2] The power output is variable depending on the local climate which may lead to frequent voltage fluctuations.

to examine the influence of each value chain industry by considering the interdependence of all related industries and to closely examine how renewable energy expansion affects the regional economy.

Transition to renewable energy-based power system poses many benefits as well as challenges and must be meticulously planned. By analyzing both carbon emission and economic impacts of renewable energy expansion at a regional level, it will be possible to generate effective sustainable development strategies that minimize carbon emission yet ensure economic competitiveness. This will be valuable for regional policymaking especially now that municipality is increasingly becoming more accountable in reducing regional carbon emission, hence renewable energy adoption. [3]

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[3] Climate budget system is a priority budgeting that is functioning as municipality legislation in Seoul, Gyeonggi-do, Gyeongsangnam-do and Daejeon (Daedeok-gu).

1.2. Research Objectives

The study aims to analyze the impact of renewable energy expansion on carbon emissions and the regional economy, taking into account the inherent characteristics of the renewable energy system such as the 1) lifecycle value chain, 2) capacity building, 3) regional characteristics such as natural resources, and industrial structure. The research objectives are designed to explore various facets of these characteristics to assess the impact of renewable energy expansion effectively.

First, the study aims to assess the lifecycle carbon emissions resulting from renewable energy expansion coupled with flexibility options. By doing so, the study aims to identify primary sources of emissions, providing recommendations to enhance the emission reduction potential. The study also provides carbon emission reduction potential compared to conventional power sources.

Second, the study focuses on analyzing the regional economic impact of renewable energy expansion, considering different levels of national and regional capacity building in the form of local content (%). It ultimately seeks to understand how regional industries are affected by renewable energy operations and devise meaningful implications. Additionally, the study aims to analyze how much jobs and value added are preserved in the region of installation.

Third, the study aims to analyze the impact of renewable energy expansion across Korea to provide national implications under multi-regional setting. Specifically, the focus is on understanding the relationship between carbon emissions and economic impacts.

In summary, the study intends to contribute to a deeper understanding of the impact of renewable energy expansion on carbon emissions and the regional economy and suggest sustainable development strategies, by recognizing the inherent characteristics of the renewable energy system.

1.3. Scope and Methodology

The research scope of the thesis encompasses the following areas.

The renewable energy system being investigated in this study involves the utilization of wind and solar PV technologies. While other renewable energy sources like hydroelectric power, geothermal energy, and biomass have their own advantages and applications, wind and solar PV technologies are more geographically flexible and adaptable to diverse settings. Additionally, the cost of implementing solar PV and wind power systems has been decreasing, making them increasingly competitive with conventional energy sources such as coal and natural gas. As of 2021, solar PV and wind energy accounted for over 10% of global electricity generation, and it is projected to contribute nearly 20% of global power generation by 2027 according to the International Energy Agency (IEA, 2023). Due to resource limitations, Korea is also focusing on renewable energy policies centered around wind and solar PV. The market potential for renewable energy in Korea, as of the year 2020, indicates that solar PV has a capacity of 369 GW, and wind power has a capacity of 65 GW, exceeding the necessary potential for achieving the nation's carbon neutrality goals (KNREC, 2020).

The study specifically focuses on onshore wind energy instead of offshore wind due to the availability of reliable cost information gathered from ten years of operation in Korea. Additionally, the study emphasizes the role of renewable energy as Distributed Energy Resources (DER), considering the special law on distributed energy that limits the capacity of distributed energy sources to below 40 MW. Offshore wind energy tends to have larger scale installations in the gigawatt (GW) range, which exceeds the capacity defined by the law. However, future studies may expand the analysis to include offshore wind, both bottom-fixed and floating systems. The study bases onshore wind installation capacity in Jeju to the CFI 2030 plan. It is the only available provincial plan that estimates onshore wind energy installation potential by 2030.

The study investigates flexibility options within the renewable energy system, with a specific focus on lithium-based ESS and their role in supporting the integration of renewable energy. Other infrastructures such as High-Voltage Direct Current (HVDC), heat pumps, Power-to-Gas (P2G) or Power-to-Liquid (P2L) technologies (involving hydrogen, methane, or ammonia), and pumped hydro-storage are not considered in the present study due to their lack of commercial viability in the foreseeable future in Korea and reliable cost information.

The main methodologies employed in this research include cost analysis and Input-Output (IO) analysis. The IO methodology is extended to cover multiple regions and includes environmental assessments. By combining these methodologies, the study aims to provide a comprehensive analysis of the renewable energy system, including the evaluation of greenhouse gas emissions (carbon emissions), value-added analysis, and employment effects. Although, there are many indicators for environmental impact assessment; Greenhouse gas (GHG) emission, air pollution, land occupation, water use, material resources, ionizing radiation, and human toxicity, reducing GHG emission and preventing climate change is considered to be most urgent and has even led to the establishment of an international environmental treaty[4]. Hence the study will focus on estimating the carbon emission (in CO_2eq).

The regional boundary for the research is defined as the administrative districts, chosen for the sake of research convenience. The research encompasses the 17 Metropolitan cities and Provinces of Korea in general, with a particular regional focus on Jeju in Chapters 4, 5 and partly in Chapter 6.

The research overview is shown in Figure 1.1 below.

[4] In 1992, in Rio de Janeiro, 154 states signed the United Nations Framework Convention on Climate Change (UNFCCC).

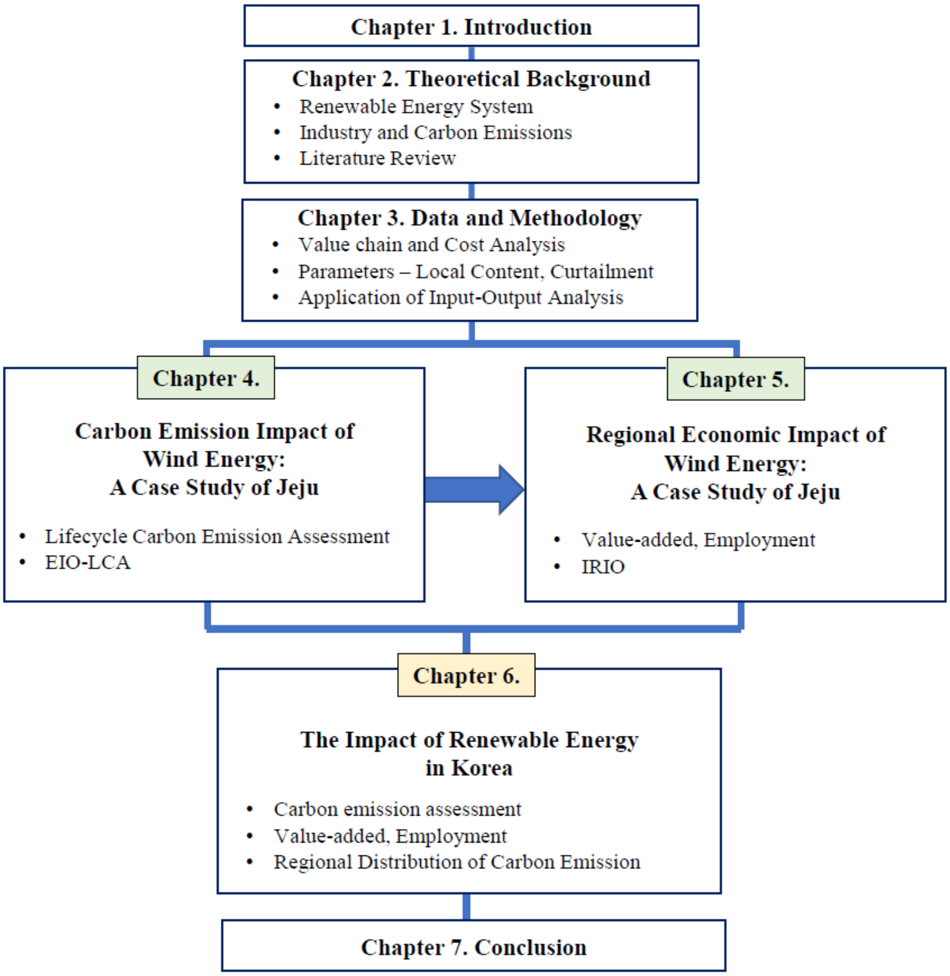

Figure 1.1 Research overview

This study is composed of 7 chapters in total. Chapter 2 introduces the theoretical background and explores previous studies relevant to the research. It first examines the crucial factors for assessing the impact of renewable energy expansion within the context of sustainable development. Additionally, it delves into the existing literature on IO-based impact assessment studies, with a specific focus on carbon emissions and regional economy.

Chapter 3 provides an overview of the methodologies and parameters utilized in this study to facilitate quantitative analysis. It explains the development of onshore wind, solar PV, and ESS value chains, along with cost data, local content scenarios, and the construction of various IO tables. Furthermore, this chapter compares the IO-based approaches employed in the following chapters.

In Chapter 4, the analysis centers on the use of Economic Input-Output Life-cycle Assessment (EIO-LCA), employing cost analysis and the national Environmentally Extended Input-Output (EEIO) model to investigate the lifecycle carbon emissions (CO_2eq) resulting from the expansion of onshore wind energy in Jeju. The main objective is to identify the primary sources of carbon emissions and propose effective mitigation solutions. Based on the Carbon Free Island (CFI) 2030 plan, the study assumes a deployment of 211 MW by 2030. Additionally, the study includes the integration of flexibility options, such as ESS.

Chapter 5 also analyzes the deployment of 211 MW of onshore wind, but with the utilization of a 2x2 Inter-Regional Input-Output (IRIO) model encompassing Jeju and the rest of Korea. The aim is to examine how renewable energy operations impact the regional economy. The analysis focuses on assessing value-added effects and job creation both within and outside the region under various local content scenarios. The study strives to understand the dynamics within Jeju and the overall interaction between Jeju and the rest of Korea.

Building upon the previous chapters, Chapter 6 investigates the impact of rooftop solar PV and onshore wind expansion on a national scale, reaching a total of 19 GW throughout Korea. The objective is to identify the relationship between carbon emissions and economic impacts resulting from the expansion of renewable energy. The first part of the chapter utilizes a combination of IO models to incorporate local content scenarios. In the second part, a 17x17 multi-regional EEIO and IRIO model is employed to analyze the regional distribution impact based on a consumption-based approach, focusing on renewable energy O&M in Jeju.

Chapter 7 provides a summary of the three studies and presents policy implications focused on sustainable development strategies regarding renewable energy system. This chapter also offers suggestions for Jeju's energy transition policy based on the research findings. Additionally, the chapter highlights the research's contribution, limitations, and explores potential research directions.

Chapter 2. Theoretical Background

In this chapter, various facets of the renewable energy system within the context of sustainable development are explored. Additionally, the impact assessment studies of renewable energy are examined. By investigating relevant theories and research, a solid theoretical background is established for the subsequent chapters.

2.1. Clean Energy Transition

The pursuit of economic growth has been achieved at the cost of environmental degradation. Natural resources have been exploited in an environmentally inefficient and reckless manner, leading to perilous consequences like climate change that pose a threat to humanity. Sustainable development is a carefully planned strategy to embrace growth while using resources more efficiently, with utmost consideration of immediate and long-term benefits for our planet and the humans who live on it (Emerald Built Environments, 2022).

Sustainable development has become the international community's most urgent priority, and the core aim of the post-2015 development agenda.

2.1.1. Sustainable Development and Renewable Energy System

Most widely accepted definition of sustainable development was described by the 1987 Bruntland Commission Report (WCED, 1987)[5] also known as <Our Common Future.

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

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[5] World Commission on Environment and Development (WCED) submitted the report to the General Assembly of the United Nations for its consideration during its 42nd Session in the fall of 1987.

Since the Brundtland Report, the concept of sustainable development has undergone a shift, with an increasing emphasis on the **economic development, social development and environmental protection** for future generations, often known as three pillars of Sustainable development (Purvis, Mao, & Robinson, 2019).

A significant proportion of a society's environmental impact is linked to the utilization of energy resources. Dincer & Rosen (1999) suggests two important implications of energy in relation to sustainable development; 1) Discovering sustainable energy resources and 2) Increasing the energy efficiencies.

The first implication relates to the supply side of energy resources. A sustainable development within a society requires a supply of energy resources that are available in the long term and sustainably at reasonable costs and can be used for all necessary tasks without having negative social impacts. Supplies of fossil fuels (coal, oil, and natural gas) and uranium are generally considered finite. Other sources of energy, such as sunlight, wind, and falling water, are generally considered to be renewable and therefore sustainable in the relatively long term (Dincer & Rosen, 1999). Recent research has also discovered that renewable energy sources such as wind and solar energy discharge the lowest CO_2 emissions during the entire lifecycle, are cheaper to build (Schlömer, et al., 2014, pp. 1333, 1335), and create more jobs (Hong, 2023; Hong, et al., 2019; Jacobson, et al., 2019; Lehr, Lutz, & Edler, 2012). Renewable options also take shorter amount of time to plan, build and replace fossil fuel system than new nuclear programs saving more carbon per year (Schenider & Froggatt, 2019, p. 253).

The second implication is related to the consumption side of the energy resource. Sustainable development demands the efficient use of energy resources, allowing society to maximize benefits and minimize negative effects. By optimizing energy consumption, the required capacity for energy harvesting systems and devices is reduced, leading to decreased environmental consequences. This also necessitates energy saving.

Yun (2002) also proposes that energy policy in the 21st century must practice sustainability and equity while maximizing economic efficiency, under the notion that energy is closely related not only to economic aspects but also to social, political, and environmental aspects. This means promoting energy saving, improving energy efficiency, and expanding renewable energies at minimal cost. Thus, sustainable development demands a sustainable consumption and production of energy resources.

From an energy supply perspective, the energy transition means a shift in primary energy sources from an energy system that has historically been dominated by the fossil fuels of coal, oil, and gas to the rapidly growing renewable energy sources of solar, wind, hydro and geothermal energy (Polack, 2021).

Energy systems are complex, interconnected supply chains that encompass the production, conversion, delivery, and use of energy, as well as the underlying business and financial models (Polack, 2021). A supply chain can be examined as a system of production processes that may span across different geographical regions. Each process can be described as a system that generates output streams based on input streams (Albino, Izzo, & Kühtz, 2002). The following Figure 2.1 displays the physical components of a typical energy system supplying fuels and electricity to end-users. In case of wind energy supply, wind energy is converted to mechanical energy through the blade rotor and shaft which is then converted to electricity via generator. The produced electricity is then delivered to the substation which is either stored or sent to electricity grid via transmission cables leading to final energy demand such as buildings, industries, agriculture, and transport.

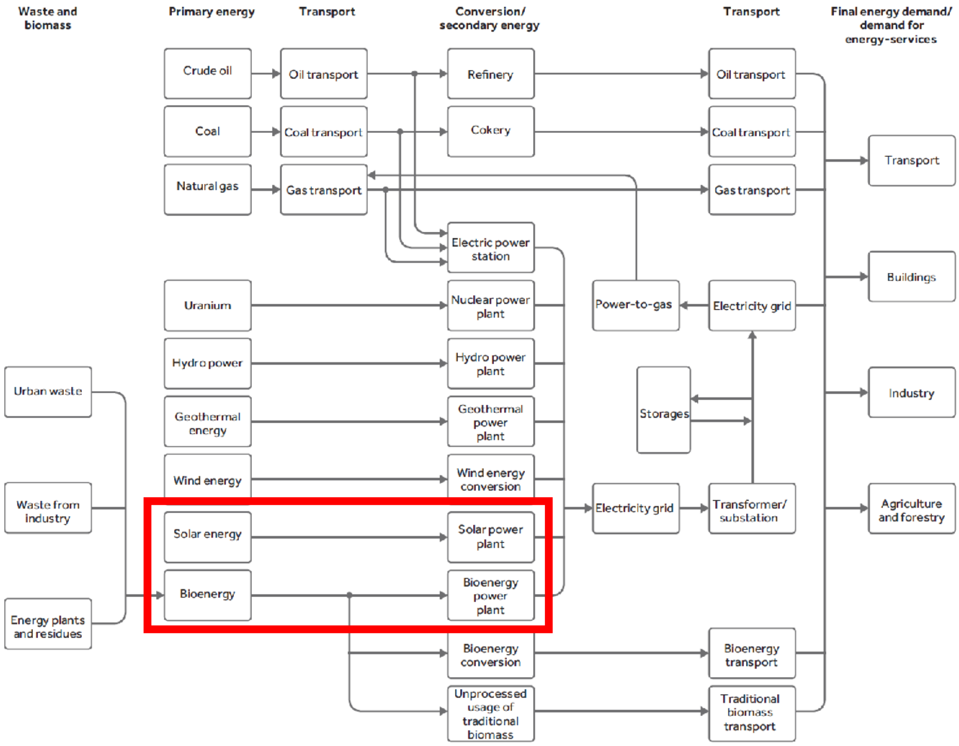

Figure 2.1 Physical components of an energy system

*Reference: Polack (2021)

The renewable energy system being investigated in this study involves the utilization of wind and solar PV technologies outlined in red in Figure 2.1. While other renewable energy sources like hydroelectric power, geothermal energy, and biomass have their own advantages and applications, wind and solar PV technologies are more geographically flexible and adaptable to diverse settings. Additionally, the cost of implementing solar PV and wind power systems has been decreasing, making them increasingly competitive with conventional energy sources such as coal and natural gas.

As of 2021, solar PV and wind energy accounted for over 10% of global electricity generation, and it is projected to contribute nearly 20% of global power generation by 2027 according to the International Energy Agency. Due to resource limitations, Korea is also focusing on renewable energy policies centered around wind and solar power. The market potential for renewable energy in Korea, as of the year 2020, indicates that solar PV has a capacity of 369 GW, and wind power has a capacity of 65 GW, exceeding the necessary potential for achieving the nation's carbon neutrality goals (KNREC, 2020).

The study specifically focuses on onshore wind energy instead of offshore wind due to the availability of reliable cost information gathered from ten years of operation in Korea. Additionally, the study emphasizes the role of renewable energy as DER, considering the special law on distributed energy that limits the capacity of distributed energy sources to below 40 MW. Offshore wind energy tends to have larger scale installations in the gigawatt (GW) range, which exceeds the capacity defined by the law. However, it is hoped that future studies expand the analysis to include offshore wind, both bottom-fixed and floating systems. The study investigates flexibility options within the renewable energy system, with a specific focus on lithium-based ESS and their role in supporting the integration of renewable energy. Other infrastructures such as HVDC, heat pumps, P2G or P2L technologies (involving hydrogen, methane, or ammonia), and pumped hydro-storage are not considered in the present study due to their lack of commercial viability in the foreseeable future and reliable cost information. Economic feasibility of flexible options is not included in the study as it is beyond the research scope. It is also worth noting that the current energy policy in Korea does not revolve around energy transition, as nuclear power is determined independently, coal is being phased out, and gas power generation predominantly serves as a replacement (MOTIE, 2023). Therefore, the research scope will consider “solar PV” and “wind power” amongst renewable energy sources and ESS amongst flexibility resources.

The framework for a sustainable energy transition requires that energy systems not only deliver energy services, but also do so in a way that is consistent with and achieves global and national policy goals (Polack, 2021). Therefore, it is also important to assess the overall environmental impact of the new energy system to ensure that the expansion of renewable energy is aligned with sustainable development goals.

2.1.2. Stability of Variable Renewable Energy

The power output from variable renewable energy such as solar and wind is variable depending on the local climate which may lead to frequent voltage fluctuations. As penetration of variable renewable energy (%) increases, flexible options such as energy storage or more extensive grid is required for stable operation. This is posing a huge challenge in Korea in the form of curtailment as the country's electricity grid is completely isolated, requiring even more resilient energy storage systems, sector coupling technologies, demand-side management (decentralize power demand) – to match with excess or shortage of power (Lee T. , 2020).

Germany was one of the first countries to devise ambitious national goals for the energy transition. Problems encountered by Germany and other pioneering countries can be a very useful lesson for Korea. In addition, Germany, much like Korea, is also a heavily industrialized country based on manufacturing industry as shown below in Figure 2.2. Both countries have similar characteristics of primary energy supply where fossil fuel resources are entirely imported. Since implementing Energiewende for two decades in Germany, wind, and solar PV combined produce more electricity than nuclear, coal or natural gas. It was possible for Germany to have supply security with a quarter of power supplied by renewables given ample reserves and well-developed interconnections with neighboring grids (Sopher, 2015). This is proven by high value of System Average Interruption Duration Index (SAIDI)[6].

[6] The World Bank (https://govdata360.worldbank.org/indicators/h2d96dbda?country=DNK&indicator=42570&countries=ITA,FRA&viz=line_chart&years=2014,2019)

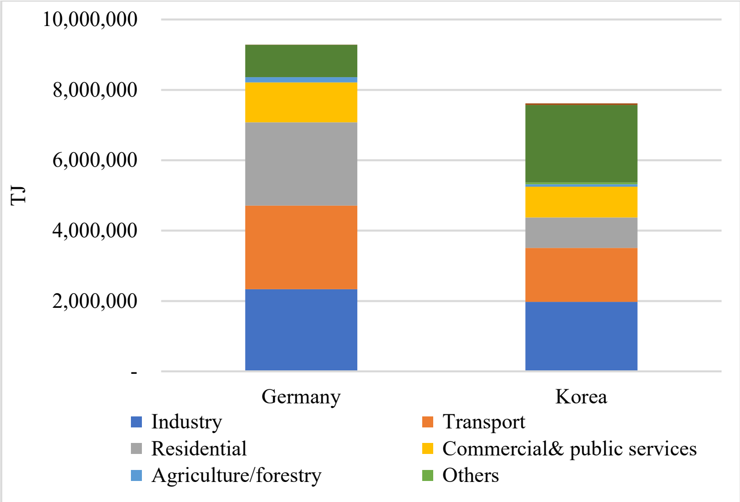

Figure 2.2 Total final energy consumption by sector in 2019

*Reference: IEA (2020a, 2020b)

However, Germany's biggest obstacle in further expanding solar and wind also lies in installing more transmission and distribution. Insufficient grid to deliver electricity produced from wind turbines in the north of the country to the west and south, where electricity consumption is concentrated, has created bottlenecks in Germany and loop flows in neighboring countries. The construction of four major north-south transmission lines met public opposition, eventually forcing more costly underground construction of interconnectors and delays that caused significant congestion management costs (IEA, 2020a). It is important to note that while underground cables are expensive, they can introduce minor delays from regional resistance. In addition, intermittency requires backup capabilities and flexibility mechanisms such as DR, smart grid, and energy storage to increase grid reliability.

Korea[7] is a peninsula surrounded by sea on three sides, and the country is currently at war with North Korea[8]. This technically makes the country an island with north side of the country that leads to the continent completely blocked. Hence the country is unable to exchange electricity or import oil and gas via pipelines with neighboring countries and relies solely on tanker shipments of LNG, coal, and crude oil to produce electricity (EIA, 2023). This is very different from the circumstances in Europe where countries benefit from international grid. Hence, variability of solar and wind energy sources will become even more problematic to Korea and the country will need well-networked transmission, distribution, and storage systems within the country. Without them, the increasing use of renewable energy will lead to high congestion and losses for renewable energy providers. Table 2.1 below summarizes procs and cons of viable flexibility options to encounter curtailment issues in Korea.

[7] Officially the Republic of Korea or South Korea
[8] Officially the Democratic People's Republic of Korea

Table 2.1 Various flexibility options

Flexibility Options	Pros	Cons
HVDC	- Two-way transmission and distribution - Play a crucial role in ensuring stable power grid operation	- High Investment Costs - Site selection issues - Land connection requires central government permission
P2G	- Enables long-term, high-capacity, high-density energy storage - Can be linked to CCS for thermal power generation - Synergistic expansion of renewable energy and decarbonization by utilizing fuel for transportation and power generation s	- Promising technology, but no commercial operations - Economic feasibility is key
Heat Pump	- Relatively low cost and high technical maturity - Allows for planned load balancing	- No power generation, only heating and cooling power loads - Energy losses, Limited as a long-term storage device
ESS	- Stabilizing the grid by mitigating volatility - Verified by demonstration and commercial operation - Costs are trending downward	- Short lifespan of 10 years - Long-term, high-capacity storage is limited

*Reference: based on Jeju & KEEI (2019)

Due to Korea's geographic conditions, certain technologies such as pumped storage power are not feasible. On the other hand, lithium-ion batteries-ESS, heat pumps, electric vehicles and the storage of green hydrogen generated from excess renewable energy utilized by fuel cell are considered more commercially viable. The battery-ESS serves as short-term storage of daily or weekly units and hydrogen as long-term storage beyond the season (GESI et al., 2022). However, transporting and storing gaseous or liquified hydrogen is not only technically challenging but also has safety concerns especially in residential areas, hence there is increasing R&D efforts taking place in developing a safe and cost-effective hydrogen storage and distribution system (StartUs Insights, 2023; Shaposhnikov, 2023).

It is suggested that one of Germany's challenges in meeting its short-term greenhouse gas emissions targets primarily lies in the difficulties of decarbonizing the transport and heating sectors (Pflugmann, Ritzenhofen, Stockhausen, & Vahlenkamp, 2019; IEA, 2020a). To address these challenges, the concept of sector coupling has emerged as a potential solution. According to IEA, sector coupling involves integrating different energy sectors, such as electricity, hydrogen, gas, and heat, through the application of technologies, policies, and market mechanisms. Another perspective defines sector coupling as the integration of energy end-use and energy supply sectors (Van Nuffel, Gorenstein Dedecca, Smit, & Rademaekers, 2018). The overall objective of sector coupling is to maximize energy efficiency and improve the overall flexibility and stability of the energy system. This integration will ultimately lead to an increased share of renewable energy sources and reduced carbon emission. For instance, the electrification of heating, cooking, transportation, and industry will allow for the usage of electricity generated from renewable sources via national grid or stored in energy storage systems (ESS) or usage of green hydrogen[9] via fuel cells.

This concept is depicted in Figure 2.3 below. However, Germany's experience reveals that potential obstacles exist in the form of high electricity costs and the availability of cheap fossil fuels, which may hinder the electrification of the heating and transportation sectors.

[9] Green hydrogen is defined as hydrogen produced from renewable energy sources via electrolysis.

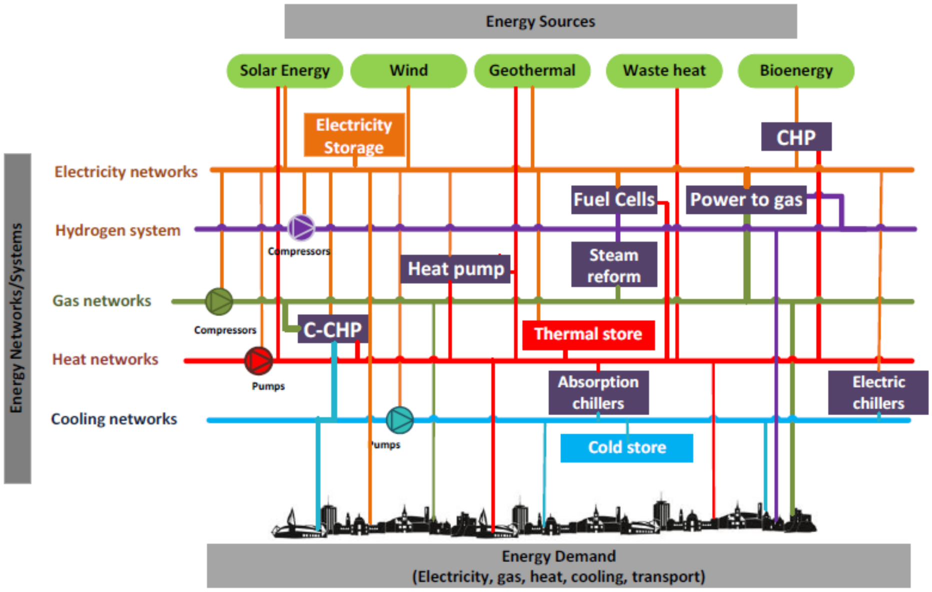

Figure 2.3 Sector coupling technology

*Reference: Abeysekera, Wu, & Jenkins (2016, p. 3)

Therefore, Korea needs to broaden the scope of energy and climate policies beyond the focus on the power sector. Without having flexible and electrified demand infrastructure for the indirect use of renewable energies, increased increasing the renewable energy share of electricity alone will not achieve the goal of carbon neutrality.

Although there are numerous technology options mentioned above to enhance the operation and utilization of renewable energy, the study is limited in its scope and focuses on as lithium-based ESS. ESS is the most commercially viable flexibility options that can also be domestically manufactured.

2.1.3. Regional Perspective

Regions are a key spatial scale for examining the nature and impacts of political, economic, social, and environmental change and innovation[10].

Productive resources are unevenly distributed in space. Hence, quantitative, and qualitative imbalances in the geographical distribution of resources and economic activities result in unequal levels of prosperity and well-being (Capello, 2015). The need for general economics to include the concept of geographical imbalance was later developed into a discipline of regional science, a broader study of regional economics. Nourse (1968, p. 1) defined it as a study of the spatial organization of the economy and further with the geographical allocation of rare geographical resources. From this perspective, regional economics intents to find the optimal space or region for production and consumption activities (Jeong, 2017, p. 3).

Understanding renewable energy system such as wind or solar PV power plants requires even deeper understanding from a regional perspective due to two distinct features: variability and spatially dispersed nature. Renewable energy sources are variable and intermittent. The uncertainty can pose new challenges for national and local utilities and system operators (NREL, 2013). One of the measures is extending a local transmission grid to a wider area and constructing inter-regional systems to smooth out power generated by wind and solar and manage volatile local voltage (Nakano, Arai, & Washizu, 2018). However, extending high voltage transmission lines often faces challenges due to low local acceptability, a regional problem.

Renewable energy sources are concentrated in the southern regions of Korea, namely Jeolla-do and Gyeongsang-do. On the other hand, electricity demand is concentrated in the northern regions, particularly in Metropolitan area. This implies

[10] Regional Studies (https://www.regionalstudies.org/)

that whatever is additionally produced by renewables in the southern region will be transmitted northbound. And with currently saturated transmission lines, more high voltage lines must be installed. This issue has recently led to the implementation of 'Distributed Energy Enablement Special Act'[11] which will impose varying tariff depending on the region and also allow distributed energy providers to directly supply electricity to users within the region. The Act is expected to reduce social cost incurred with transmission lines and towers and promote the expansion of renewable energy.

Different regions have differing level of natural conditions, hence differing levels of wind and solar power potentials. This implies that more RES will be built in regions with higher wind or solar generation capacity leading to decentralized and spatially dispersed nature (Jenniches, 2018). Also, new infrastructure in a region may stimulate differing levels of spill-over effects from one located in another region due to unique regional inter-industrial linkages. Consequently, the generation capacity and economic and environmental impact would strongly depend on the regional context.

Renewable energy resources are generally spatially dispersed, often located within close vicinity of the local community and livelihood often causing acceptance issues. Naturally, there is a high level of social interest in the impact of expanding renewable energy on local communities. Local officers' priority is to seek increase in local income and employment by analyzing the region's economic structure and identifying key industries that will drive regional growth (Jeong, 2017). Under this context, capacity building of renewable energy intended to create local jobs and garner social acceptance is also becoming a regional concept. This is especially noticeable in places where the environmental justifications for the adoption of renewable energy may be insufficient and is desperate for economic revitalization. Thus, initiating renewable energy system projects and using these

[11] Legislation (https://www.law.go.kr/lsInfoP.do?lsiSeq=251685&viewCls=lsRvsDocInfoR#)

sources effectively requires a deep understanding of regional and inter-regional considerations to avoid conflicts between developers and residents and plan regional energy management systems as local consumption is essential for efficient usage (Nakano, Arai, & Washizu, 2018).

Hence, an impact assessment at regional than national level will be essential to decision makers, especially in circumstances where RES developments are critically observed. So, there is a need for a thorough study of how an installation of renewable energy facility creates value and jobs throughout its lifespan and how these jobs affect livelihood of the region in question.

IO analysis, amongst many theories allows capturing direct and indirect impact. This method was first devised by Wassily Leontief who developed IO model to analyze the Structure of American Economy in 1951. Walter Isard, principal founder of the discipline of regional science-location theory, helped Leontief adapt input-output model to a local economy. Historically, regional impact studies have been mainly focused on traditional sectors such as tourism and primary metal industry (Miller R. E., 1957). Renewable energy is relatively a new subject in regional economic impact assessment and has a lot to offer to the society.

2.2. Industry and Carbon Emissions

The Korean economy is established on the reliance on imported fossil fuels. Korea imported 98% of its energy which is consumed in energy transition (electricity and heat production), industry, building and transportation sectors. And the industry sector consumed 60% (including electricity and heat) of total primary energy as feedstock and fuel in the production in 2020 (KEEI, 2021; EIA, 2023). Energy-intensive manufacturing industries[12], responsible for 70% of the total industrial emission in 2020 (EG-TIPS, 2022), produced on average 34% of the total national manufacturing profit in the past 5 years (ISTAN, 2023). Although these activities improved living standards of the country, they have contributed to Korea becoming the 13th largest greenhouse gas producer globally in 2020 (Climate Watch, 2023). Korea's primary energy supply from 1981 to 2020 is illustrated as Figure 2.4 below. Korea's renewable energy share in primary energy supply and electricity generation was respectively 3.2% and 7.15% in 2021, being the lowest amongst IEA and OCED member countries.

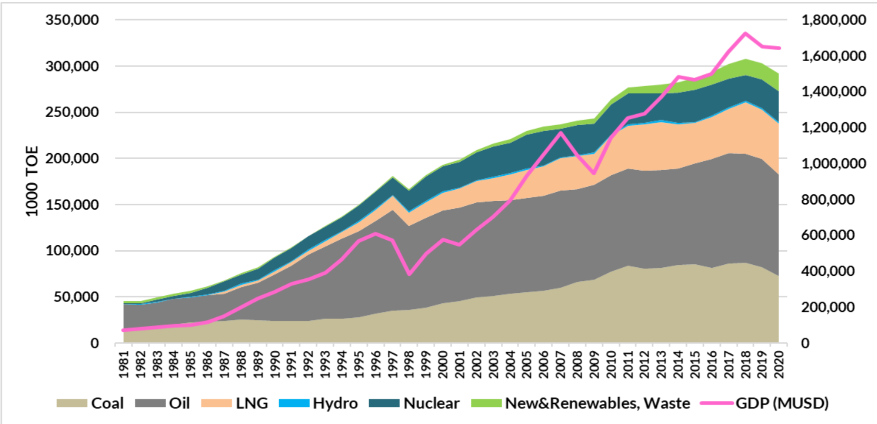

Figure 2.4 Korea's primary energy supply[13]

*Reference: based on KEEI (2021), World Bank (2023)

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12 Steel, Refining and Petrochemical, Cement, Display and Semiconductor industries

13 New& Renewable energy includes hydrogen, fuel cell, liquified/gasified coal and gasified vacuum

In terms of energy demand, industrial energy consumption % is the highest among IEA countries. As shown in the Figure 2.5 below, the industry sector is responsible for 56% of total national carbon emission when including scope 2 which is electricity and heat supplied by the grid.

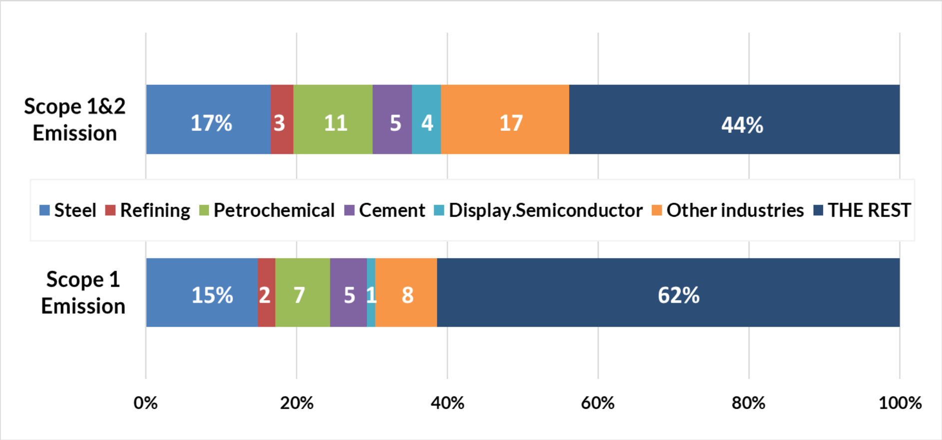

Figure 2.5 Industry sector emission in 2020

*Reference: based on KEEI (2021), GIR (2022)

This implies that 18% of total national emission occurs from industry indirectly consuming electricity and heat. Hence, a strong correlation exists between industry sector's electricity consumption, Korea's electricity generation, and the resulting carbon emissions.

Meanwhile, global decarbonization efforts posed trade regulations and initiatives such as CBAM, RE100, NZIA and IRA. First two measures are mainly involved with removing carbon dioxide emission in the production lifecycle and the latter two interfere with where the production takes place.

The significance of the industry and carbon emissions has the following underlying meaning. Developed economies like the EU and the US consider green products and technology to be a highly promising industry in the future, especially

residue

in the era of carbon neutrality. To maintain their leadership status in the international market, both economies are striving to achieve this by implementing barriers to filter out high-polluting products from abroad and by granting preferential rights to domestically produced green goods and technology. This is particularly important when relatively inexpensive products from China flood their markets.

This section will introduce theories related to value chains, carbon emission, and local capacity building under lifecycle perspective with respect to renewable energy system.

2.2.1. Value chain Perspective

When introducing renewable energy to the energy system in a particular region, one needs to consider from a lifecycle perspective to fully understand the process and the impact it has on the energy system, society, and the environment. This is because each stage on the lifecycle have different territorial nature and stability over time and requires different amount of labor as well as specialization or local content (Kim & Kim, 2021). This underlines how important it is to consider temporal as well as regional perspective when introducing an infrastructure in a region.

A value chain encompasses the complete lifecycle of a product or process, consisting of material sourcing, production, consumption, and disposal/recycling activities required to bring a product from its conception to the final consumer. Value chain and supply chain are commonly used to describe the flow of the entire production process. Although value chain and supply chain are sometimes used interchangeably, value chain focuses more on value creation and distribution from the perspective of a specific industry, while supply chain merely deals with the overall flow of goods and services from a logistics perspective (WBCSD, 2011, pp. 3, 5; Mccormick & Schmitz, 2002). In previous studies related to input-output analysis, the ripple effects of the expansion of the renewable energy industry have been analyzed in the context of the interaction between the "value chain" of the renewable energy sector and the "supply chain" of the region. Hence it is more appropriate to use the term value chain when analyzing renewable energy industry.

Although each technology has inherent characteristics, they all have a common value chain consisting of the following stages: (1) Research and design (2) Development and manufacture (3) Construction and installation (4) Operation and maintenance (5) Updating and/or dismantling (Llera Sastresa, Usón, Bribián, & Scarpellini, 2010). The level of local investment and job creation depends on the region's available industrial structure. For example, if certain research experts or production facilities required for the local project are not available in one region, they must be outsourced from other regions or countries. Therefore, the longevity as well as the direct employment or economic impact will depend on the type of work (lifecycle stage) created in the region. This is summarized as Table 2.2 below.

Table 2.2 Stages, volume, and quality of employment

Phase	Volume of generation	Location	Temporary nature	Level of specialization
Technological development	Medium	From foreign to local	Stable	Very high
Installation/ uninstallation	High	From local to foreign	Temporary	High
Operation and maintenance	Low	Local	Stable	Medium

*Reference: Llera Sastresa, Usón, Bribián, & Scarpellini (2010)

Renewable energy consists of a wide range of value chain activities. To thoroughly understand the impact of expanding renewable energy the carbon emissions as well as the regional economy the entire value chain must be comprehensively examined and included in the analysis.

Value chain of wind energy system can include financing, planning, design and manufacturing of turbines, control system, electronics, blades, towers, foundation works, assembly, transformers and operation and maintenance as shown in Figure

2.6 below. These components have its own supply chain – flow of goods and services to deliver the component.

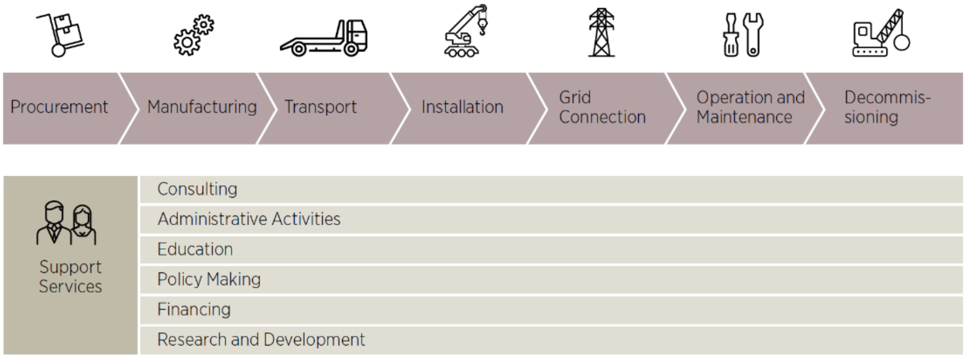

Figure 2.6 Onshore wind energy value chain

*Reference: IRENA (2017)

Changes in demand also have an impact on the level of other industries associated with that industry. Especially, given such an extensive value chain, it is necessary to examine the influence of each value chain industry by considering the interdependence of all related industries and to closely examine how and to what extent renewable energy expansion affect the regional economy. Hence, it is also important to look beyond the "direct effect" from the value chain.

Figure 2.7 illustrates how the increasing demand for wind power within the region leads to employment opportunities in the local area through various pathways. For example, a new "installation activity" in a region itself requires inputs from other industries such as services and construction. This concept is referred to "indirect effect" as it is triggered by the supply chain effect (linkage effect) from direct effect. "Induced effect" corresponds to a contribution from the overall increased income spent in service sectors such as restaurants and shopping. Indirect and induced effects are often referred as ripple effect or spill-over effect. Accounting for these effects in planning stage can help maximize benefits strategically (Faturay, Vunnava, Lenzen, & Singh, 2020).

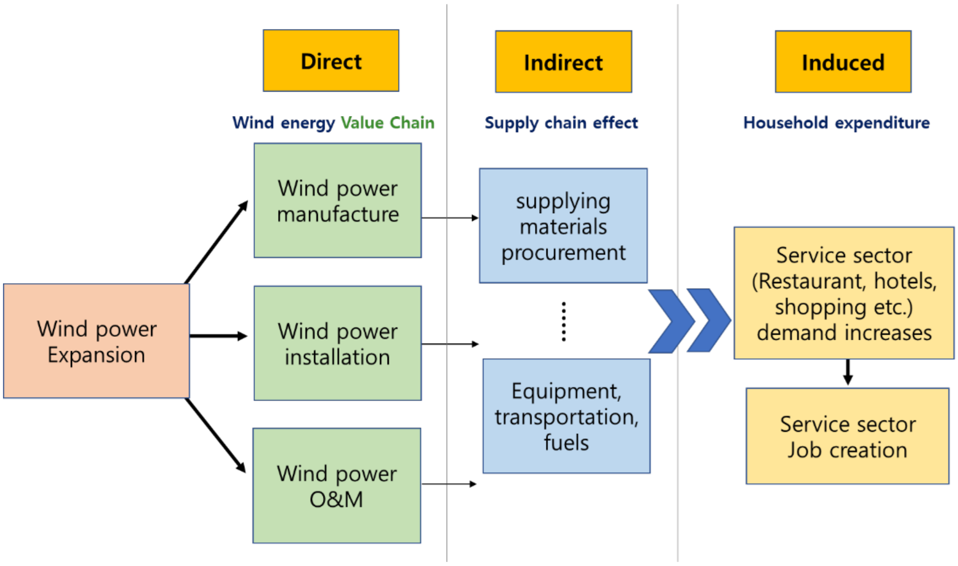

Figure 2.7 Pathway of economic spill-over effects

*Reference: adapted from Breitschopf , Nathani, & Resch (2011)

Formal definition of the three effects are described below.

• Direct effects: primary effects that arise directly from a certain renewable energy project

• Indirect effects: secondary effects created in related input sectors

• Induced effects: economy-wide effects, or jobs created in sectors that are not directly related to renewable energies but created through services or goods provided to people affected by direct or indirect effects

The magnitude of three impacts differs based on the economic composition of the region. For example, sectors that create numerous linkages may yield greater indirect effects. Conversely, the labor-intensity of sectors, particularly services, significantly influences the induced effect. (Schallenberg-Rodriguez & Inchausti-Sintes, 2021).

2.2.2. Lifecycle Perspective

Reducing greenhouse gas emission and preventing climate change is considered to be most urgent and has even led to the establishment of an international environmental treaty. Solar and Wind energy is a clean energy source that do not emit carbon dioxide during the power generation process and can significantly reduce carbon emissions when replacing fossil fuels.

To reduce carbon emissions further responsibly, it is important to consider the emissions from the entire lifecycle of renewable energy, including manufacturing, installation, and flexible resources, and propose measures to maximize the carbon reduction effect. No matter how much carbon emission an energy system can abate during operation, the emission along the value chain cannot be justified if significant harm is done to the environment. Therefore, it is important to analyze the carbon emission (in CO_2eq) over the entire lifecycle of renewable energy and identify solutions for improvement.

The impact assessment framework described in the previous section will impose accountability of the value chain or industry in producing carbon emission. Hence, the scope of carbon emission can also be divided under direct, indirect, and induced emissions.

• Direct emission: Primary emission that arise directly from a certain demand

• Indirect emission: Secondary emission triggered by the linkage effect from direct effect.

EIO-LCA allows these emissions specific to the responsible value chain and industries as shown in the Figure 2.8 below.

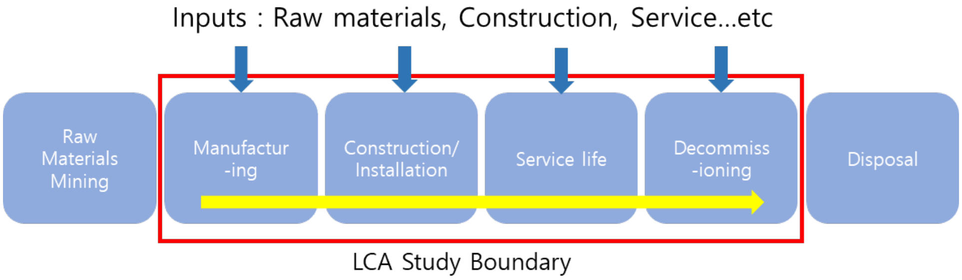

Figure 2.8 EIO-LCA boundary

2.2.3. Local Capacity Building

Given the current geopolitical circumstances, global decarbonization efforts have introduced legislation such as the NZIA and the IRA, which interfere with the location of production. The COVID-19 pandemic and the Ukrainian war have brought supply chain complexities in the world which have led the U.S and EU reduce external trade dependencies particularly from China in the form of green goods subsidy race. Hence, national capacity building is increasingly becoming a popular policy tool despite the prohibition from WTO. It is believed that domestic manufacturing will create socio-economic impacts such as innovation and jobs (Hong, 2023) which can in turn garner political support for renewable energy (Lewis, 2014), and carbon neutrality goals.

Above section explained the concept of value chain and lifecycle of a technology or infrastructure. It was then explained that each phase of the lifecycle triggers a direct impact on the economy and employment, the extent of which depends on the productive resource and industrial structure of the region. This section analyzes employment level under each stage of renewable energy value chain in Korea.

‘National New& Renewable Energy Industry Statistics (KNREC, 2022a, 2022b)’ reports number of firms, jobs, sales, and investment created in each year. The notion of "New & Renewable Energy," a concept unique to Korea, has been a subject of concern (SFOC, 2020). According to the law, "New energy," including fuel cells and integrated gasification combined cycle (IGCC), is acknowledged as a clean and promising energy source, alongside what is traditionally known as "Renewable energy," as indicated in Table 2.3 below. Furthermore, even "waste energy," which does not meet the International Energy Agency (IEA) standards for renewable energy, is also classified under the category of "New & Renewable Energy." However, it's worth noting that as of October 2019, "waste energy from non-renewable waste" has been excluded from being categorized as renewable energy under the waste energy classification (refer to Table A.1 in Appendix-1).

Table 2.3 Scope of new& renewable energy industry

New Energy	Renewable Energy
Hydrogen Energy Fuel Cell Liquified or gasified coal and gasified vacuum residue Other new energy	**Solar - PV**, thermal **Wind** Hydropower Marine energy Geothermal energy Bioenergy Waste energy Other renewables

*Reference: modified from Statistics Korea (2021)

Previously, the statistics only included manufacturing industry resulting highly underestimated economic potential of the industry[14]. However, the statistics now recognizes beyond just manufacturing since the 2020 report (KNREC, 2022a) by including upstream and downstream[15] activities of construction, power generation and heat supply and professional services in the ‘New& Renewable Energy Act’.

[14] Previous statistics reported total employment of 12,599 in 2019 and 13,885 in 2018.
[15] Upstream activities are operations that occur near the extraction or utilization of natural resources, producing primary commodities or virgin materials as their output (Van Beukering, van den Bergh, Janssen, & Verbruggen, 2000). Downstream activities enhance the value of products through manufacturing or customization, resulting in the creation of final commodities (Singer & Donoso, 2008).

KNREC (2022b) reported total sales of KRW 28.8 trillion, total employment of 140,953 and total investment of KRW 6.4 trillion of national new& renewable energy industry in 2021.

As shown in the Table 2.4 below, total number of employments has risen by 19% despite new capacity deployment has decreased compared to the previous year. This shows that the employment from O&M phase and downstream services can be substantial.

Table 2.4 National new& renewable energy statistics

Criteria	**Employment (persons)**		
	2020	**2021**	**Changes**
New Installation Capacity GW	**5.5**	**4.5**	**-18%**
Accumulated Capacity GW	**138**	**143**	**4%**
Industry Total	**118,098**	**140,953**	**19%**
Manufacturing	12,353	11,864	-4%
Construction	17,617	14,937	-15%
Power and Heat Supply	82,810	108,462	31%
Service	5,318	5,690	7%

*Reference: based on KNREC (2022a, 2022b)

Figure 2.9 below indicates specific activities/sectors in the value chain of solar PV and wind power industry.

Upstream		Downstream	
Manufacturing of equipment	**Construction and installation of power generation facility**	**Power generation**	**Services on** Engineering R&D, Science, Technology Operation and Maintenance Rent and Sales Finance, Education, Associations

Figure 2.9 Scope of value chain for solar PV and wind industry

*Reference: modified from Statistics Korea (2021)

Table 2.5 below lists the sales, investment, number of firms and employment of wind and solar PV industry in 2020 under manufacturing (M), construction (C), and power generation (G) sub-sectors/activities.

Table 2.5 National solar and wind industry statistics in 2020

Activities/ sectors		No. of Firms	No. of Workers	Sales				Investment
				Total	Domestic	Export	Overseas	
SOLAR	M	216	7,761	61,242	21,856	17,695	21,691	2,352
	C	2,028	16,058	57,653	57,653	-		930
	G	77,737	78,734	32,479	31,558	921		58,625
	Sum	**79,981**	**102,553**	**151,374**	**111,067**	**18,616**	**21,691**	**61,907**
WIND	M	25	1,555	19,202	3,435	5,583	10,184	240
	C	7	158	3,275	3,275	-		25
	G	93	375	5,152	4,191	961		4,096
	Sum	**125**	**2,088**	**27,629**	**10,901**	**6,544**	**10,184**	**4,361**
TOTAL		**80,106**	**104,641**	**179,003**	**121,968**	**25,160**	**31,875**	**66,268**

Unit:100 million KRW for sales and investment

*Reference: based on KNREC (2022a, 2022b)

However, the values for service sector of solar and wind was not available as only an aggregated value for the entire new& renewable energy was provided. Hence, it is difficult to comprehend the specific values for the wind and solar PV industry.

Even without considering the service sector, values of solar PV take up majority of the entire new& renewable energy industry. Sales and investment of solar PV was around KRW 15.1 and 6.2 trillion, making up of 59% and 81% of total new& renewable energy industry values. No. of firms and employment was 79,981 and 102,553, which was 98% and 87% of the corresponding values for the entire new& renewable energy industry. Wind industry was relative insignificant as sales and investment values were only 11% and 5.7%, and no. of firms and employment were 0.15% and 1.8% of the corresponding values for new& renewable energy industry. This corresponds to the accumulated installation capacity of 11.77GW for solar PV and 1.49GW for wind energy in 2019. The newly added capacity was 3.79 GW and 0.19 GW. Although the current renewable industry is concentrated on solar PV, this will change as more wind is invested in the future as was proposed by the government. Solar PV and wind energy generated 12,996 GWh and 2,679 GWh of which accounted for only 3% of domestic electricity consumption[16] in 2019 (KEA, 2021a).

On the other hand, nuclear energy industry survey (MSIT, 2021) for year 2019 reported sales value of KRW 20.7 trillion, investment of KRW 9.5 trillion and no. of employment of 35,469. Considering that nuclear power accounts for more than 28% of domestic electricity generation, this suggests that the direct economic impact of the solar PV and wind energy industry is significantly higher. The overall impact will be even larger if indirect and induced impact triggered from solar and wind investment are considered. Although solar PV and wind power are very promising industries, increasing the % of local content is a main challenge required

[16] 520498.7 GWh was consumed in Korea in 2019

to increase domestic impact (Allan, Comerford, Connolly, McGregor, & Ross, 2020).

While renewable energy expansion and industrial development are actively pursued worldwide, there are challenges in Korea, mainly due to issues of acceptance. The limited land area in the country has led to intensified conflicts with local residents, fisheries, agriculture, and the military. For local governments, one of the key concerns in resolving acceptance issues is assessing how renewable energy can provide jobs in the region. Consequently, institutional mechanisms are being established to connect the proliferation of renewable energy with the revitalization of the local economy. The wind power competitive bidding system, introduced last year, evaluates domestic supply chain contributions and local acceptance through non-price indicators. The government assesses wind power project developers and awards contracts based on their bidding scores, which include a 60% weight on price and a 40% weight on non-price indicators. Projects are selected in the order of highest scores, up to the announced capacity. The "Ordinance on Wind Power Generation Licensing and Zone Designation"[17] in Jeju Island requires a certain proportion of local residents to be employed in wind power projects. Similarly, the "Ordinance on the Promotion of Renewable Energy Industries and Citizen Participation"[18] in Jeollanam-do encourages the use of locally produced goods by regional companies.

Gathering from above, there are two types of local capacity building measures – national and regional. National capacity building is more concerned with promoting national competitiveness usually focused on manufacturing industries and export items, while regional capacity building is more related to job creation and local acceptance of renewable energy. These regulations, in the form of local content requirement (LCR), will directly impact the national and regional economy.

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[17] Jeju ordinance (https://www.law.go.kr/LSW/ordinInfoP.do?ordinSeq=1280538)
[18] Jeollanam-do ordinance (https://www.law.go.kr/LSW/ordinInfoP.do?ordinSeq=1485035&gubun=ELIS)

In turn, it will consequently affect the level of carbon emission produced along the entire value chain as carbon intensity differs depending on the production location.

Hence this research employed two levels of capacity building in analyzing its impact on carbon emission and regional and national economic impact. It is difficult to find exact local content value for each region. Previous studies have applied either no local content, assuming 100% contribution from the region, or a single assumed value or a varying scenario of local content. Byeon & Jeong (2011) did not apply any local content scenario. Connolly (2020) has applied single value of local content of 17.06% for Capital Expenditure (CAPEX) and 38% for Operating Expenditure (OPEX). Schallenberg-Rodriguez & Inchausti-Sintes (2021) has applied different regional content (%) for each task under CAPEX (39%~19%), OPEX (40%~35%) and decommissioning phases under two scenarios (High and Low Regional content), where regional content for decommissioning is 100% in both scenarios and OPEX being higher than CAPEX. The local content rate devised for the study was based on extensive literature review and consultation with industry professionals. More will be explained in the methodology section.

2.3. Literature Review

The literature review was conducted to summarize the papers related to the three studies carried out in this thesis. First, a review was conducted on national and international studies that analyzed the lifecycle environmental assessment, specifically focusing on carbon emissions of renewable energy. Second, the summary included studies that analyzed the regional economic effects of renewable energy expansion. Finally, the distinctive features of this study in comparison to the existing literature were also summarized.

2.3.1. Carbon Emission Assessment of Renewable Energy

2.3.1.1. Methodologies for Environmental Impact Assessment

Three primary methodologies are used to assess the environmental impact of renewable energy sources. The first is LCA, which is a bottom-up approach involving the exclusion of activities that are not expected to contribute significantly, leading to potential errors. The second method is Environmentally Extended Input-Output (EEIO) analysis, a top-down approach that quantifies inventories using monetary data at the economic sector level. While it does not require cut-offs, its high aggregation level may result in a coarse sector resolution. (Oliveira Henriques & Sousa, 2023).

LCA only allows for the assessment of greenhouse gas emissions resulting from direct energy use. However, environmental input-output analysis, similar to input-output analysis, enables the analysis of direct and indirect ripple effects. As a result, it has the advantage of being able to track emissions pathways resulting from indirectly used energy upstream, in addition to the energy consciously used and consumed by economic agents.

Last, a hybrid approach combines process-LCA to model crucial operations with EEIO to include operations that might otherwise be excluded. This hybrid method, known as EIO-LCA, provides both detailed information at the process level and nearly complete coverage of the entire product system.

2.3.1.2. Studies on Carbon Emission Assessment of Renewable Energy

A comprehensive review of literature on the environmental assessment of renewable energy reveals important findings. Noori, Kucukvar, & Tatari (2015) conducted an economic input-output-based sustainability analysis of onshore and offshore wind energy systems, demonstrating that increasing the lifetime of wind turbines significantly reduces their environmental footprint. Similarly, Vélez-Henao & Vivanco (2021) conducted a hybrid lifecycle assessment of an onshore wind farm and found that carbon emissions were dependent on capacity factors, lifespan, and percentage losses. Kumar, Tyner, & Sinha (2016) used an economic input-output lifecycle assessment to analyze greenhouse gas emissions across the entire lifecycle of utility-scale wind energy, accounting for manufacturing, installation, operation, and maintenance stages. Arvesen & Hertwich (2012a) investigated the potential environmental impacts of large-scale wind power adoption, while Li, Li, & Wu (2020) assessed the carbon intensity and emission reduction potential of wind power projects. Oebels & Pacca (2013) highlighted the advantage of wind farms in regions with a high proportion of renewable energy in the electricity mix. Martínez, Sanz, Pellegrini, Jiménez, & Blanco (2009) analyzed the entire lifecycle of wind power systems and found that the environmental effects were recovered in less than one year. Chipindula, Botlaguduru, Du, Kommalapati, & Huque (2018) performed a lifecycle analysis of onshore and offshore wind farms in Texas, quantifying greenhouse gas emissions and comparing different locations. The study conducted by Lee, Ryu, & Yang (2010) focused on the lifecycle CO_2 emissions of renewable energy systems equipment components only. Furthermore, Nugent & Sovacool (2014) conducted a meta-survey of lifecycle assessment studies on wind energy, emphasizing the cultivation and fabrication stages as major contributors to greenhouse gas emissions. Finally, Arvesen & Hertwich (2012b) reviewed the lifecycle environmental impacts of wind power systems, identifying the wind turbine as the most important component in terms of energy use and emissions. Hybrid lifecycle analysis and environmentally extended input-output assessments were suggested for more accurate and comprehensive evaluations.

Key findings include the significant reduction of environmental impacts with increased wind turbine lifetime, improved manufacturing and recycling processes, choice of location, capacity factors, and electricity sourcing can influence the environmental performance of wind power systems. Overall, these studies contribute valuable insights into the environmental implications of renewable energy, highlighting the importance of sustainable practices and continuous improvement in the wind power industry.

However, there has not been a study that analyzed the carbon emission impact of wind energy expansion in conjunction with flexibility options using EIO-LCA. Studies rarely identified primary sources in upstream responsible for the carbon emissions beyond the wind energy value chain. Moreover, although EIO-LCA models have been utilized to assess the effects of renewable energy promotion on a national scale, the application of these models to subnational scale evidently lacks. To better inform local energy policy, further research is required at the sub-national level (Oliveira Henriques & Sousa, 2023).

2.3.1.3. Studies on Building EEIO Table

In the literature review, various methods of creating EEIO tables are examined. Kim Y. (2006), Choi & Lee (2006), Park (2009), Byeon (2009), Noori, Kucukvar, & Tatari (2015), Kumar, Tyner, & Sinha (2016), Park Y. (2020), and Yang, Park, Smith, Kim, & Park (2022) employed different approaches and data sources to develop their EEIO tables. Kim Y. (2006) utilized Korean trade and energy input tables, while Choi & Lee (2006) employed a mixed input-output model and inserted a row of consumption energy data limited to four primary energy sources.

Park Y. (2009) established the fuel sector in the existing IO tables while leaving out emission produced from energy consumption as feedstock. Byeon (2009) referenced Kim Y. (2006) and added energy statistics to improve accuracy. Noori et al. (2015) developed a United States EEIO table for not just greenhouse gas emission but also toxic emissions, energy, and water consumption. Kumar et al. (2016) aligned GHG emissions inventory with United States IO tables. Park Y. (2020) and Yang et al. (2022) calculated industry-specific emissions based on Korean energy balance data and classified them into sectors. However, there are challenges related to accuracy in industry classification. Despite these variations, the engineering-based approach, as exemplified by Kumar et al. (2016), Park Y. (2020), and Yang et al. (2022), demonstrates a better consideration of energy and emissions in the creation of EEIO tables. On the other hand, the economic trade-based approach employed by the rest of the studies does not accurately account for specific combustion rates or the conversion from monetary value to quantity energy consumption.

2.3.1.4. Emission Responsibility

Consumption-based and production-based emission accounting utilizes EEIO in a multi-regional setting to provide insights into developing strategies for sustainable manufacturing and consumption patterns. Numerous studies, particularly abroad, have analyzed consumption-based and production-based emissions. These studies primarily focus on emissions arising from international trade involving adjacent countries and assess impacts such as carbon emissions and air pollution (PM10, PM2.5). The objective is to identify key sectors and regions accountable and responsible for emissions.

In Korea, An, Son, & Kim (2012), Kim & Moon (2019), and Jiang & Kim (2022) have published journals on interregional analysis within Korea. An et al. (2012) focused on carbon emissions and formulated a dataset, but it applied national sector carbon emission intensity (CO_2eq/KRW) to all 16 regions, which is a significant generalization. Studies involving interregional relationships at the international level include Choi T. (2016), Kim & Moon (2022), and Mangır & Şahin (2022).

However, few studies have assessed changes in the power sector and their impact. Apart from Yuan, Rodrigues, Tukker, & Behrens (2018) and Wiebe (2016), there is a lack of research on how the environmental impact of renewable energy expansion spreads across regions within a country or internationally. Furthermore, no research has assessed renewable energy deployment under the concept of emission responsibilities in conjunction with flexibility options and curtailment.

2.3.2. Regional Economic Impact Assessment of Renewable Energy

2.3.2.1. Methodologies for Economic Impact Assessment

Four fundamental methodologies for economic impact assessment in the literature are employment factor analysis, supply chain analysis, IO modelling, and Computational General Equilibrium (CGE) analysis.

Employment Factor (EF) analysis, although simple, may not consider different levels of regional productivity. Studies like Wei, Patadia, & Kammen (2010) and Climate Analytics, & SFOC (2021) have used employment factors to estimate job creation in renewable energy industries, showing that non-fossil fuel-based technologies create more unit jobs.

Supply chain analysis provides an accurate view of the regional renewable energy sector but lacks quantification of indirect effects. Kim, Yun, Im, & Yun (2021) utilized supply chain analysis to examine the economic impacts of solar PV and wind farm projects.

IO modelling captures indirect and induced economic effects by considering interactions within the economy. It provides a fairly accurate view of the regional economy, but it may overlook factors like economies of scale, price changes, technological advances, and productivity changes. IO modelling is widely used in assessing renewable energy's economic impact on a regional level.

CGE analysis, although considering demand and interindustry competition, has seen limited application in regional-level studies compared to EF and IO analysis. Data constraints often make it challenging to create finely disaggregated economic models on a small regional scale.

Overall, IO modelling is the most predominant methodology for assessing the economic impact of renewable energy at a regional level. Table 2.6 provides a summary of the IO modelling studies of renewable energies reviewed in the chapter.

2.3.2.2. Two Approaches in Accounting for a New Industry in IO Table

The use of IO models for studying clean energy impacts has a disadvantage in that renewable energy and energy efficiency industries are not accounted for in national accounts (Garrett-Peltier, 2017). There are two main approaches in IO analysis: the "final demand approach" and "complete inclusion in the technical coefficient matrix" (Miller & Blair, 2009).

The final demand approach treats the intermediate inputs used by the new industry as an external change reflected in the final demand. This method has been extensively employed to estimate the economic impact of renewable energy, assuming that its development does not affect the inputs used by other sectors. This approach allows flexibility in analyzing various value chain activities and is suitable for regional studies.

The complete inclusion approach integrates the new industry into the technical coefficient matrix mostly used in single-region models, mainly at the national level, where industry information is readily available. However, this approach requires detailed data and reaggregation of IO tables, which can be time-consuming and challenging, especially for emerging industries like clean energy.

Overall, both approaches have their pros and cons, but the final demand approach is more commonly used for assessing the economic impact of renewable energy at a regional level.

2.3.2.3 Literature review for IO-based economic impact assessment

The literature review revealed that there is a relatively limited number of studies examining the regional impact of renewable energies compared to the extensive literature on national-level impact assessment (Lehr, Lutz, & Edler, 2012; Connolly, 2020; Kim & Kim, 2021; Lim, Park, & Yoo, 2014; Kang, Lee, & Park, 2017; Kim & Yoo, 2021; Lee C.-Y. , 2021; Kim & Seo, 2019; Kwon, 2018). Regional IO analysis is challenging due to the scarcity and less frequent updating of input-output tables at the province or city level.

Some studies focused on specific regions or countries. Nakano, et al. (2018) developed IRIO tables for renewable energy sectors in 9 regions in Japan. Faturay et al. (2020) assessed the economic impact of wind farms in US states. Vasconcellos & Caiado Couto (2021) studied the economic effects of renewable energy in two regions of Brazil. Schallenberg-Rodriguez & Inchausti-Sintes (2021) analyzed the economic impact of an offshore wind farm in the Canary Islands. Byeon & Jeong (2011) examined the IO effects of solar PV investment in the 16 Metropolitan cities and Provinces of Korea, focusing on the manufacturing and construction phases. Kim, Y. & Kim, B. (2023) and Kim, Yun, Im, Kim, & Lim (2022) have analyzed the regional economic impact of wind farms in Gangwon province and Honam province, respectively.

Other studies explored the impact of renewable energy on specific regions within a larger context. Kahouli & Martin (2017) analyzed the impact of offshore wind energy in Brittany, France. Varela-Vázquez & Sánchez-Carreira (2015) assessed the economic impact of wind energy in Galicia, Spain. Kim & Im (2014) investigated the growth of the renewable energy industry in Jeju Island, Korea.

Several studies have examined the economic and environmental impacts of wind power development, but few have considered both aspects together. It is crucial to present the environmental effects alongside economic benefits and make integrated decisions. Jenniches, Worrell, & Fumagalli (2019) analyzed the regional economic effects and monetized positive impacts of avoided emissions in Germany's Aachen district. Allan et al. (2020) explored the economic and emissions impact of the offshore wind sector in the UK, emphasizing local content. These studies demonstrate the importance of considering both economic and environmental factors in wind power assessments.

However, several limitations were identified in the reviewed literature. These include lack of specific technical coefficients for renewable energy sources thereby aggregating solar and wind energy as one industry, and a lack of detailed value chain analysis.

Also, except for Vasconcellos & Caiado Couto (2021), no other studies have identified specific industry sectors that are affected from renewable energy development. Moreover, quantitative discussions on the regional economic impact of energy system integration, also known as sector coupling, are scarce.

Overall, the literature review highlights the need for more comprehensive and detailed analyses of the regional impacts of renewable energy, including a deeper understanding of the value chains and sector-specific characteristics.

Table 2.6 Literature review of economic impact studies of renewable energies using IO analysis

Reference	Regional Boundary	No. of regions	Source	Value Chain	Method*	Main features
(Kim, Y. & Kim, B., 2023)	Gangwon	1	Onshore wind	MCI, O&M, D	Sub-sector assigned to closest sector in the IO model	Induced effect calculated (Endogenization of households)
(Kim, Yun, Im, Kim, & Lim, 2022)	Honam	1	Offshore wind	MCI, O&M	Sub-sector assigned to closest sector in the IO model	Employment calculated based on IRENA's employment factor
(Vasconcellos & Caiado Couto, 2021)	North- West region, Rest of Brazil	2	Wind	MCI, O&M	Sub-sector assigned to closest sector in the IO model	Induced effect calculated (Endogenization of households)
(Faturay, Vunnava, Lenzen, & Singh, 2020)	US	52	Wind	MCI	Created new regional table, Sub-sector assigned to closest sector in the IO model	Direct, Indirect
(Nakano, Arai, & Washizu, 2018)	Japan	9	hydro, solar PV, wind, biomass geothermal, waste	Not Specified	Created new regional table for 2005 and 2030	2005, 2030
(Byeon & Jeong, 2011)	S. Korea	16	Solar PV	MCI	Sub-sector assigned to closest sector in the IO model	The only multi-regional IO study in Korea
(Schallenberg-Rodriguez & Inchausti-Sintes, 2021)	Canary island & Spain	2	Floating offshore wind	MCI, O&M, D	Sub-sector assigned to closest sector in the IO model	Induced effect calculated First study for floating wind Decommissioning included Two local content scenarios
(Kahouli & Martin, 2017)	Brittany & France	2	Offshore wind	MCI, O&M	Created new regional table, Sub-sector assigned to closest sector in the IO model	Induced effect calculated O&M calculated with employment factor analysis
(Lehr, Lutz, & Edler, 2012)	Germany	1	Renewable energy	Not Specified	Used econometric input–output model PANTA RHEI to analyse labour market implications	Applied various scenarios
(Connolly, 2020)	Scotland, UK	1	Offshore wind	MCI, O&M	Sub-sector assigned to closest sector in the IO model	Induced effect calculated Temporal aspect included Used both IO and CGE model

(Varela-Vázquez & Sánchez-Carreira, 2015)	Galicia, Spain	1	Onshore wind	MCI, O&M	Sub-sector assigned to closest sector in the IO model	Temporal aspect included Updated IO table with RAS technique (2000~2010)
(Kim & Kim, 2021)	S. Korea	1	LNG, mega/ small solar PV, onshore, offshore wind	MCI, O&M	Complete inclusion in the technical coefficient matrix	Lagrangian multiplier method Used Technical coefficient and share of intermediate inputs and value-added of PV and wind from a Japanese study
(Kim & Im, 2014)	Jeju, S. Korea	1	Solar and wind		Complete inclusion in the technical coefficient matrix	Forecasted economic impact in 2012 and 2022
(Lee C.-Y. , 2021)	S. Korea	1	Solar, wind, hydro, fuel cell	M	Sub-sector assigned to closest sector in the IO model	Forecasted total economic impact by 2034 according to 9th electricity basic plan
(Kim & Seo, 2019)	S. Korea	1	Solar, Wind	M, CI, G	Complete inclusion in the technical coefficient matrix	Updated IO table with RAS for 2020, 2030
(Kwon, 2018)	S. Korea	1	Solar	M, G	Complete inclusion in the technical coefficient matrix	Used industrial statistics and electricity market statistics
(Cho, 2013)	S. Korea	1	Wind	MCI	Complete inclusion in the technical coefficient matrix	Used technical coefficient by combining various literature
(Kim Y. , 2012)	S. Korea	1	Solar	M	Complete inclusion in the technical coefficient matrix	Used technical coefficient from a Japanese study
(Kim & Yoo, 2021)	S. Korea	1	Nuclear, New& Renewable**	G	Rearranging IOT sector	Exogenous specification
(Kang, Lee, & Park, 2017)	S. Korea	1	Thermal, New& Renewable**	G	Rearranging IOT sector	Exogenous specification
(Lim, Park, & Yoo, 2014)	S. Korea	1	New& Renewable**	G	Rearranging IOT sector	Exogenous specification

2.3.3. Distinction from Previous Studies

Based on the review of previous studies, this research distinguishes itself from existing research in several ways. First, there is a lack of studies that analyze the emission impact of renewable energy expansion considering curtailment and flexibility options. By utilizing EIO-LCA, this study quantifies carbon emissions across the entire value chain and identifies critical enablers or bottlenecks associated with the carbon emission impact of renewable energy expansion.

Second, this study extends to the consumption-based emission accounting and analyses the regional emission distribution caused by expansion of renewable energy in conjunction with flexibility resources. It aims to comprehend the regional distribution of carbon emissions, jobs, and the associated trade-offs, leading to the development of effective strategies for sustainable practices in both production and consumption with renewable energy systems.

Third, while it is recognized that renewable energy creates job opportunities across various sectors, there is a limited presence of quantitative discussions on the regional economic impact of integrating renewable energy systems in the existing literature. This study aims to fill this gap by providing a quantitative foundation for understanding the industrial diversification resulting from the expansion of renewable energy.

Last, within the Korean context, only a few studies have analyzed the potential economic impacts of adopting renewable energy sources at a regional level. This study stands as the first in Korea to utilize IRIO analysis, encompassing an extensive value chain to assess the impact of onshore wind expansion on the regional and national economy. Additionally, it is one of the first studies in Korea to assess both the environmental (carbon emissions) and economic impacts of a renewable energy system. While An et al. (2012) formulated a Multi-Regional EEIO (MREEIO) for all municipalities in Korea, it applied a national sector carbon emission intensity (CO_2eq/KRW) to all 16 regions, resulting in a generalized approach. This study contributes by establishing an EEIO table in a multi-regional setting for carbon emissions, using regional carbon emission coefficients, thus providing a more accurate dataset.

2.4. Summary

The first part of this chapter delved into various facets of the renewable energy system within the sustainable development concept. It connected relevant theories to the present state and highlighted three distinct factors crucial for assessing the impact of expanding the renewable energy system. First, regional characteristics inherent to the renewable energy system, such as available natural resources and regional industry structure, play a vital role. As a distributed energy resource influenced by regional climate, the impact of renewable energy expansion relies heavily on the installed region. Additionally, the choice of supply chain has varying implications across regions due to interregional dynamics. Second, renewable energy encompasses a wide value chain, particularly requiring flexibility options to address intermittency. This necessitates impact assessments from a lifecycle perspective, spanning from development to decommissioning. Last, considering the global and national context and challenges surrounding renewable energy, the level of local capacity building in the value chain becomes a critical factor determining the scale of impact. This is quantified through national and regional local content. To conduct a realistic impact assessment and formulate meaningful implications, these factors must be taken into account.

The second part of the chapter examined previous literature on the IO-based impact assessment studies of renewable energy on carbon emissions and regional economy. It revealed room for improvement by incorporating the above-mentioned factors into the impact assessment of the renewable energy system.

In the following chapter, these three factors are translated into parameters of analytical models to facilitate quantitative analysis. This approach allows for a more in-depth examination and discussion of their impact on the renewable energy system, enabling the development of effective strategies to reduce carbon emissions.

Chapter 3. Data and Methodology

This chapter aims to explain methodologies and parameters employed in the study to facilitate quantitative analysis.

3.1. Value chain and Cost Analysis

A value chain refers to the complete lifecycle of a product or process as explained in Chapter 2. Value chain items and corresponding cost component of onshore wind, solar PV and ESS system was developed from extensive literature review, market survey and consultation with industry professionals.

3.1.1. Onshore Wind

Value chain of wind energy system can include financing, planning, design and manufacturing of turbines, control system, electronics, blades, towers, foundation works, assembly, transformers and operation and maintenance. These components have its own supply chain – flow of goods and services to deliver the component in the value chain.

Information of wind turbines costs are rarely openly available in Korea. The cost information of wind power projects, provided by Lee & Lim (2021) is based on only two projects, hence cannot be regarded as a representative value for Korea.

The cost breakdown has a base on Kim, Y. & Kim, B. (2023), which was developed through consultation with professionals from the wind power industry and incorporates cost components from various case studies provided by NREL (2020)'s JEDI Wind Energy Models, Stehly & Duffy (2022), EIA (2020), and Lee & Lim (2021), as shown in Table 3.1. Demolition cost was assigned by referring to Okkonen & Lehtonen (2016)'s research on onshore wind development and calculated as 1.31% of total CAPEX. This study did not consider cost and benefit incurred from recycling of end of use onshore wind farms. Unit cost for value chain items for each phase (MCI, O&M, Decommissioning) are shown in Table 3.1 below. All costs are adjusted to standard year of 2020.

Table 3.1 Onshore wind cost component

CAPEX Cost Distribution (1,000KRW/kW)			
#1	Turbine equipment	Tower, shaft, nacelle housing, rotor blade	560.8
		Gearbox, rotor bearings	173.3
		Generator, transformer, power converter	203.9
		Yaw drive, pitch system	81.6
#2	Construction (road, site, foundation, equipment)		224.0
#3	Erection/Installation		351.0
#4	Electrical infrastructure		99.3
#5	Management/supervision/monitoring		90.1
#6	Legal services (insurance, bonding etc.)		22.6
#7	Certificate, permits, assessments		33.8
#8	Electrical interconnection		501.8
#9	Engineering (Design)		163.5
#10	Finance, contingency, miscellaneous		90.2
CAPEX Total			2,596.0
OPEX Cost Distribution (1,000KRW/kW/yr)			
#1	Field Salaries (i.e., onsite wind technicians, etc.), Site maintenance		6.1
#2	Administrative and management		3.5
#3	Vehicles		1.1
#4	Fees, Permits, Licenses, Insurance		8.6
#5	Utilities		0.9
#6	Replacement parts/consumables/tools		27.7
#7	Fuel		0.4
#8	Land Cost		5.8
OPEX Total			54.3
Decommissioning Distribution (1,000KRW/kW)			
#1	Demolition		34.1

*Reference: based on Kim, Y. & Kim, B. (2023, p. 9)

The professionals also advised that the CAPEX (excluding compensation fee for residents) for onshore wind has not fallen in the past 10 years due to various internal and external reasons. Internal reasons are 1) unlike other countries, onshore wind turbines are built mostly in mountainous areas as flat open plains are not available. This implies that large-scale development which may bring down cost from economies of scale is difficult. 2) delivering construction materials to mountainous areas is becoming more difficult with time due to legal restrictions in road entry and resulted construction delay. External reasons are 1) Korea has a small market for onshore wind, hence the country's buying power is weak. This makes it very difficult to negotiate price with foreign manufacturers. 2) The material cost has increased since 2019 and transportation cost has also risen since the outbreak of COVID 19.

3.1.2. Solar PV

Value chain of solar PV system can include financing, planning, design and manufacturing of solar panel, control system electrical infrastructure, foundation works, assembly and operation and maintenance.

For the roof-top solar PV, cost distribution information was obtained from Lee & Lim (2021) for roof-top/building solar PV costs, EIA (2020), Lee C.-Y. (2021), and NREL (2016)'s I-JEDI model. The reliability of the average cost values provided by Lee & Lim (2021) for roof-top solar PV in 2021 was confirmed, and the cost structure was organized into categories based on NREL (2016), EIA (2020), and Lee C.-Y. (2021) to facilitate industrial IO analysis. The final cost structure was verified through consultation with industry experts from Hanbit ENS and Eco Network of Korea. The demolition cost was derived from Kim, Kang, Park, Jang, & Hong (2019). The referenced cost of 718 KRW/kg was based on consultation with an end-of-use panel recycling firm. Since the cost structure in this study is calculated per installed capacity (KW), unit conversion is necessary. The weight of solar PV per installed KW, which was found to be 61kg, was obtained from a market survey conducted on Hanwha Q CELLS modules. The calculated value of 43.90 thousand KRW/kW is derived from the equation: (718 KRW/kg x 61 kg/kW)/1000. However, this study did not consider the cost and benefit of recycling end-of-use solar PV panels, as commercial-level recycling has only recently begun and there is no officially available cost information or demolition cost for reference in this study. Various company surveys will be conducted in the future to obtain accurate cost data. Unit cost for value chain items for each phase (MCI, O&M, Decommissioning) of roof-top solar PV are shown in Table 3.2 below. All costs are adjusted to standard year of 2020.

Table 3.2 Solar PV cost component

CAPEX Cost Distribution (1,000KRW/kW)		
#1	Cell	106.32
#2	Wafer	155.39
#3	Module	139.03
#4	Inverter	81.47
#5	Electrical infrastructure	191.81
#6	Management	51.49
#7	Construction	220.35
#8	Supervision	9.66
#9	Legal services	58.63
#10	Engineering (Design)	87.50
#11	Finance	2.09
#12	Insurance	0.66
#13	Electrical interconnection	10.10
CAPEX total		1,114.50
OPEX Cost Distribution (1,000KRW/kW/yr)		
#1	Insurance	4.638
#2	Operation and Maintenance	12.039
#3	Inverter replacement	5.566
OPEX total		22.243
Decommissioning Distribution (1,000KRW/kW)		
#1	Demolition	43.80

3.1.3. Energy Storage System

The cost breakdown of commercial building-scale battery system, also called as ESS, was based on NREL tool[19] as shown in Table 3.3 below. Operation period was assumed as 12.5 years. And Yearly OPEX was assumed to be 2.5% of CAPEX. The IO alignment was based on literature review.

According to Kong, Kim, Kang, & Jung (2019), the optimal capacity ratio

[19] National Renewable Energy Laboratory (https://atb.nrel.gov/electricity/2022/commercial_battery_storage)

between wind turbine and ESS battery was determined as 1:3 (kW:kWh) and, the optimal capacity ratio between solar PV and ESS battery was determined as 1:3.3 (kW:kWh).

Table 3.3 ESS cost components

CAPEX Cost Distribution (1,000KRW/kWh)		
#1	Battery manufacturing	283
#2	Electrical works (local)	60
#3	Installation, Construction	67
#4	Development	120
#5	Legal works	4.1
OPEX Cost Distribution (1,000KRW/kWh/yr)		
#1	Operation and Maintenance	6.68
#2	Battery replacement	6.68

Battery from EV are reused ESS as Used Battery Energy Storage System (UBESS) as shown in Figure 3.1 below. It was assumed that UBESS will not require any investment in Battery manufacturing in CAPEX nor replacement of battery in OPEX.

Figure 3.1 Reused Battery from EV as ESS in EUREF Campus Berlin

*Reference: photo taken by author

The value chain items are largely categorized into three phases: Manufacturing, Construction, and Installation (MCI), Operation& Maintenance (O&M), Decommissioning. ESS is generally utilized in the O&M phase. The scope of the value chain considered also forms a parameter.

3.2. Variable Parameters

This section introduces variable parameters used in the study.

3.2.1. Local Content

It is important to note that not all the investment will go towards the region in question. Local content (%) - the proportion of the investment that regional companies can meet - needs to be considered for a realistic impact assessment as it determines the economic impact induced in the region.

As mentioned in the Chapter 2 section 2.2.3, institutional mechanisms are being established to connect the proliferation of renewable energy with the revitalization of the local economy. And there are two types of local capacity building measures – national and regional. National capacity building is more concerned with promoting national competitiveness usually focused on manufacturing industries and export items. Regional capacity building is more related to job creation and local acceptance of renewable energy. These regulations, in the form of Local Content Requirement (LCR), will directly impact the national and regional economy. In turn, it will consequently affect the level of carbon emission produced along the entire value chain as carbon intensity differs depending on the production location.

Hence this research employed two levels of capacity building in analyzing its impact on carbon emission and regional and national economic impact as shown in Figure 3.2 below. The local content rate was based on extensive literature review and consultation with industry professionals. The contents of local content rate for onshore wind was enhanced from Kim, Y. & Kim, B. (2023, p. 20).

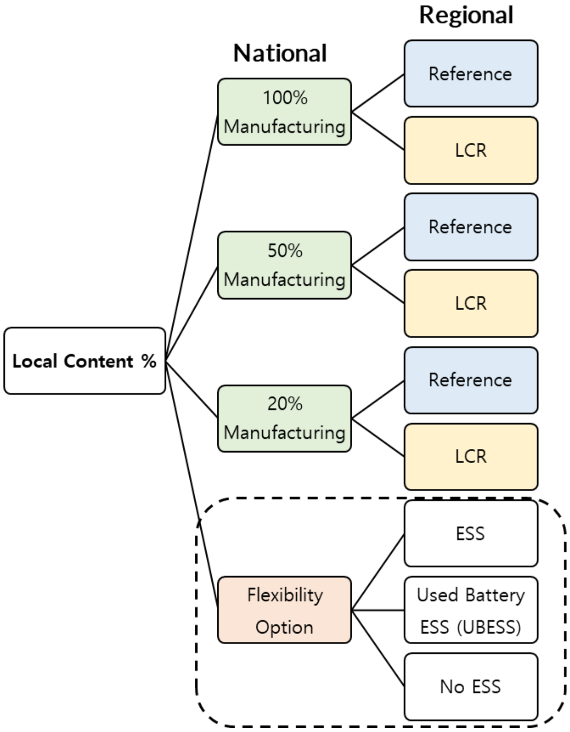

Figure 3.2 Local content scenario

3.2.1.1. Onshore Wind

Local content (%) of each cost component from onshore wind value chain for 6 regions is summarized in Table 3.4.

(1) National Local content – 100%, 50%, 20%

- Any turbine equipment (#1) in CAPEX or turbine equipment replacement produced (#6) in OPEX under national local content, is supplied from Gyeongsangnam-do (GN).

(2) Regional Local content – Reference

- Erection and assembly of onshore wind turbine (#3), management (#5), certificate/permits/assessment (#7) and engineering (#9) are almost entirely provided by developers and EPC company located elsewhere.

- Electrical infrastructure (#4) and electrical interconnection (#8) is either entirely or mostly supplied from companies in Gyeongsangbuk-do (GB).
- Legal services (#6) and finance (#10) for onshore wind development was assumed to be supplied equally from local companies and rest from metropolitan regions

(3) Regional Local content – LCR

- Jeju Island's 'Ordinance on Wind Power Project Permit and District Designation' requires that at least a certain percentage of the project's workforce be hired from local residents. This measure is applied to regions with onshore wind installation under this scenario.
- Hence, the local content rate for items (#3) through (#10) of the CAPEX cost is set as a condition for further enhancement.

(4) Constant

- Although construction of road, site and foundation (#2) is provided locally.
- Demolition (#1), at the end of operation cycle in the decommissioning phase, is done entirely by local construction companies.
- Local contents for OPEX items are relatively simple. Except for replacement parts/consumables/tools (#6) of which 45% is provided locally and the rest provided from Gyeongsangnam-do (GN) under the national local content scenario, all the other OPEX times are provided and served locally.

Table 3.4 Local content scenario for onshore wind

Local content (%)													
National		100% manufacturing				50% manufacturing				20% manufacturing			
Regional		Reference		LCR		Reference		LCR		Reference		LCR	
CAPEX		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Tower, shaft, nacelle housing, rotor blade	0	100	0	100	0	50	0	50	0	30	0	30
	gearbox. Rotor bearing	0	100	0	100	0	50	0	50	0	10	0	10
	Generator, transformer, power converter	0	100	0	100	0	50	0	50	0	10	0	10
	Yaw drive, pitch system	0	100	0	100	0	50	0	50	0	10	0	10
#2	Construction (road, site, foundation, equipment)	100	0	100	0	100	0	100	0	100	0	100	0
#3	Erection/Installation	0	100	50	50	0	100	50	50	0	100	50	50
#4	Electrical infrastructure	0	100	50	50	0	100	50	50	0	100	50	50
#5	Management/supervision/monitoring	10	90	50	50	10	90	50	50	10	90	50	50
#6	Legal services (insurance, bonding etc.)	50	50	70	30	50	50	70	30	50	50	70	30
#7	Certificate, permits, assessments	10	90	50	50	10	90	50	50	10	90	50	50
#8	Electrical interconnection	20	80	40	60	20	80	40	60	20	80	40	60
#9	Engineering (Design)	0	100	40	60	0	100	40	60	0	100	40	60
#10	Finance, contingency, miscellaneous	50	50	70	30	50	50	70	30	50	50	70	30
Regional		Reference		LCR		Reference		LCR		Reference		LCR	
OPEX		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Field Salaries (i.e., onsite wind technicians, etc.), Site maintenance	100	0	100	0	100	0	100	0	100	0	100	0
#2	Administrative and management	100	0	100	0	100	0	100	0	100	0	100	0
#3	Vehicles	100	0	100	0	100	0	100	0	100	0	100	0
#4	Fees, Permits, Licenses, Insurance	100	0	100	0	100	0	100	0	100	0	100	0
#5	Utilities	100	0	100	0	100	0	100	0	100	0	100	0
#6	Replacement parts/ consumables/tools	45	55	45	55	45	30	45	30	45	10	45	10
#7	Fuel	100	0	100	0	100	0	100	0	100	0	100	0
#8	Land cost	100	0	100	0	100	0	100	0	100	0	100	0
Decommissioning		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Demolition	100	0	100	0	100	0	100	0	100	0	100	0

3.2.1.2. Solar PV

Local content (%) of each cost component from solar PV value chain for 17 regions is summarized in Table 3.5.

(1) National Local content – 100%, 50%, 20%

- Module (#3) industry, Inverter (#4) and electrical infrastructure (#5) is assumed to be entirely manufactured in Chungcheongbuk-do (CB) under national local content.

(2) Regional Local content – Reference

- Inverter replacement cost (#3) in OPEX item is also assumed as 100% in CB region and 30% elsewhere very small electrical devices can be supplied within the region.
- Main electrical interconnection (#13) manufacturers are found in Gyeongsangbuk-do (GB) and Chungcheongnam-do (CN) hence is assigned 100% in these regions and 20% elsewhere, again as small electrical devices can be supplied within the region.
- Only half the project development and installation activities such as finance, design and construction are supplied from the region as the region cannot meet the entire solar PV demand.

(3) Regional Local content – LCR

- Inverter replacement cost (#3) in OPEX item is also assumed as 100% in CB region and 50% elsewhere.
- In this scenario larger fraction of electrical devices in the operation phase was assumed to be supplied within the region.
- Main electrical interconnection (#13) manufacturers are found in Gyeongsangbuk-do (GB) and Chungcheongnam-do (CN) hence was assigned

100% in these regions and 40% elsewhere. larger fraction of electrical devices in the operation phase was assumed to be supplied within the region.

- All the installation activities from finance, design to construction are supplied from the region as the supposed LCR rule mandates.

(4) Constant

- A Cell (#1) and wafer (#2) is assumed 0% local content as they are almost entirely imported from China.
- Demolition (#1), at the end of operation cycle in the decommissioning phase, is done entirely by local construction companies.
- Local contents for OPEX items are constant except for inverter replacement.

Table 3.5 Local content scenario for solar PV

Local content (%)													
National		100% manufacturing				50% manufacturing				20% manufacturing			
Regional		Reference		LCR		Reference		LCR		Reference		LCR	
CAPEX		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Cell	0	100	0	100	0	50	0	50	0	20	0	20
#2	Wafer	0	100	0	100	0	50	0	50	0	20	0	20
#3	Module	0	100	0	100	0	50	0	50	0	20	0	20
#4	Inverter	0	100	0	100	0	50	0	50	0	20	0	20
#5	Electrical infrastructure	100	0	100	0	100	0	100	0	100	0	100	0
#6	Management	50	50	100	0	50	50	100	0	50	50	100	0
#7	Construction	50	50	100	0	50	50	100	0	50	50	100	0
#8	Supervision	50	50	100	0	50	50	100	0	50	50	100	0
#9	Legal services	50	50	100	0	50	50	100	0	50	50	100	0
#10	Engineering (Design)	50	50	100	0	50	50	100	0	50	50	100	0
#11	Finance	50	50	100	0	50	50	100	0	50	50	100	0
#12	Insurance	50	50	100	0	50	50	100	0	50	50	100	0
#13	Electrical interconnection	20	80	40	60	20	80	40	60	20	80	40	60
Regional		Reference		LCR		Reference		LCR		Reference		LCR	
OPEX		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Insurance	100	0	100	0	100	0	100	0	100	0	100	0
#2	Operation and Maintenace	100	0	100	0	100	0	100	0	100	0	100	0
#3	Inverter replacement	30	70	50	50	30	70	50	50	30	70	50	50
Decommissioning		A	RoK	A	RoK	A	RoK	A	RoK	A	RoK	A	RoK
#1	Demolition	100	0	100	0	100	0	100	0	100	0	100	0

3.2.1.3. ESS

The local content for ESS is constant throughout the scenario. This is because ESS manufacturing or management is limited to only three corporates with manufacturing facility located in three different regions: CN, CB, and US. Hence regions other them will be assigned as region A. Local content (%) of each cost component is summarized in Table 3.6 below.

Table 3.6 Local content for ESS

Flexibility Option		ESS		UBESS	
CAPEX items		A	Rest of Korea	A	Rest of Korea
#1	Battery manufacturing	0%	65%	0%	0%
#2	Electrical works (local)	20%	80%	20%	80%
#3	Installation, Construction	50%	50%	50%	50%
#4	Development	10%	90%	10%	90%
#5	Legal works	100%	0%	100%	0%
OPEX items		A	Rest of Korea	A	Rest of Korea
#1	Operation and Maintenance	100%	0%	100%	0%
#2	Battery replacement	0%	65%	0%	0%

Only 65% is produced of (#1) is manufactured within the country. This is because current localization of battery component is on average 65% according to MOTIE (2021) as shown below in Table 3.7.

Table 3.7 Battery cost component

Battery cost component	Localization
Cathode	53%
Anode	19%
Separator	31%
Electrolyte	34%
depreciation	100%
other materials	50%
direct labour	100%
energy utilities	100%
R&D	100%
Sales& Admin	100%
Warranty	100%

*Reference: based on MOTIE (2021)

3.2.2. Operating Conditions

According to 10th national electricity supply and demand plan (2022~2036) (MOTIE, 2023), wind power in Jeju suffered from 64 events of curtailment in 2021. The plan also estimates around 19% curtailment rate by 2030 for renewable energy and 24~25% between 2031 to 2036 when renewable energy installation according to CFI plan is completed. The yearly curtailment rate in Jeju used in this study was based on the plan which is suggested as Table 3.8 below.

Table 3.8 Curtailment scenario

Year	Curtailment Rate	Year	Curtailment Rate	Year	Curtailment Rate
2021	0	2032	25.06%	2044	24.57%
2022	0	2033	24.99%	2045	24.57%
2023	1.08%	2034	24.83%	2046	24.57%
2024	0	2035	24.65%	2047	24.57%
2025	0.07%	2036	24.57%	2048	24.57%
2026	0.77%	2037	24.57%	2049	24.57%
2027	2.20%	2039	24.57%	2050	25.40%
2028	4.42%	2040	24.57%	2051	25.40%
2029	8.12%	2041	24.57%	2052	25.40%
2030	18.98%	2042	24.57%	2053	25.40%
2031	25.54%	2043	24.57%	2054	25.40%

The electricity production from a particular onshore wind farm depends on various factors such as capacity factor, nameplate capacity, duration of operation and curtailment.

The capacity factor refers to the ratio of the average consumption, output, or throughput of a specific technology or infrastructure over a given time period, divided by what it would have produced or consumed if it had operated at its maximum capacity during that same time period.

3.3. Input-Output Analysis

3.3.1. Input-Output Table and Multipliers

Input-output analysis is a useful and productive method to analyze a region's industrial structure and economic impact. For IRIO[20] analysis, 2015 IO table and IRIO tables are collected from the Bank of Korea (BOK). Input output model was first devised by Wassily Leontief to analyze the Structure of American Economy in 1951. Walter Isard, principal founder of the discipline of regional science-location theory, helped Leontief adapt input-output model to a local economy.

The input–output model is constructed from observed economic data in the form of an inter-industry transactions table. The rows of such table describe the distribution of the output produced by an industry throughout the economy. The columns describe the composition of inputs that a given industry needs to produce its output. These exchanges of goods and services between industries forms the shaded portion as shown below in Figure 3.3 (Miller & Blair, 2009).

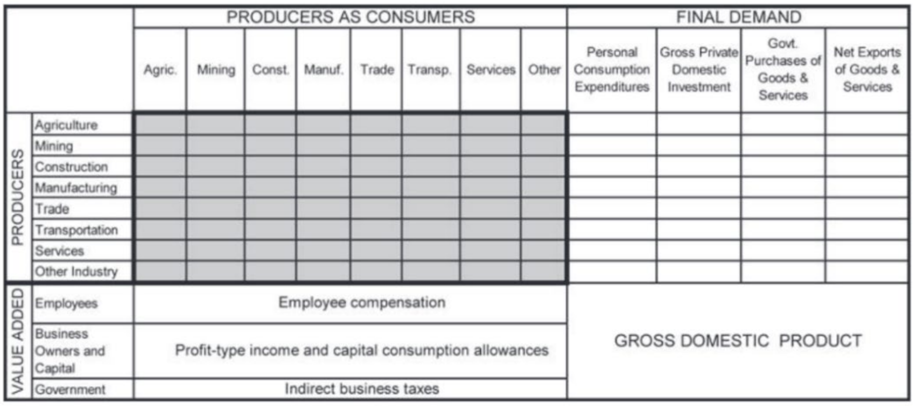

Figure 3.3 Input-Output transactions table

*Reference: Miller & Blair (2009)

[20] R. Miller (1957) was the pioneer who analyzed the introduction of aluminum in different states.

The IO analysis (Miller & Blair, 2009) is based on the following assumptions. Production technology follows a fixed proportion of inputs to produce output, known as the Leontief production function. Technical coefficients remain constant throughout the analysis. Returns to scale are also assumed constant. Each sector produces only one type of good, with no secondary production. The matrix representing the number of products and activities is symmetric. Prices does not change over time, represented by real GVA (Gross Value Added). Production is considered endogenous, while final demand is treated as exogenous.

There are inherent limitations in this analysis that should be acknowledged in terms of methodology. This study's analysis is limited by the use of fixed IO tables, which does not account for changes in the power mix. Hence, caution is needed when interpreting the economic impact using this approach. It is important to distinguish between operational effects and impacts during operation. The study's use of fixed IO neglects considerations of labor or price substitution. Moreover, it does not account for the substitution of conventional energy sources with renewables, limiting the accuracy of industry growth assessment.

There are two variations of the IO model that differ in the treatment of households' incomes and expenditure: Type I and Type II. The Type I model, also known as 'Open Leontief Model', captures the direct and indirect changes resulting from changes in final demand. And Type II model also includes the induced effect.

The basic framework of an IO table represents flows of products or money between agents in a circular flow economy by n number of sectors as shown in Figure 3.4.

		Buying Sector				
		1	⋯	j	⋯	n
Selling Sector	1	z_{11}	⋯	z_{1j}	⋯	z_{1n}
	⋮	⋮		⋮		⋮
	i	z_{i1}	⋯	z_{ij}	⋯	z_{in}
	⋮	⋮		⋮		⋮
	n	z_{n1}	⋯	z_{nj}	⋯	z_{nn}

Figure 3.4 Input-Output of interindustry flow of goods

*Reference: Miller & Blair (2009)

Industry sectors play dual roles as both producers and consumers, serving intermediate demand for goods and services (Z). The outputs (X) encompass either the value added as perceived by consumers or the final demands (Y) as perceived by producers. (Miller & Blair, 2009). IO models are based on a set of simultaneous equations that record the sectoral links of an economy in an IO table from which a Leontief inverse can be constructed (Connolly, 2020). Assuming that the economy is categorized into n sectors, sector i distributes its product through sales to other sectors and to final demand:

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + y_i$$

Where x_i denotes total output (production) of sector i, z_{ij} represents interindustry sales by sector i to all sectors j (including itself when j=i) and y_i denotes total final demand for sector i's product

In matrix notation, this can be represented by the following equation.

$$\boldsymbol{X} = \boldsymbol{Z} + \boldsymbol{Y}$$

The technical coefficient (A) for each industry sector transaction is obtained by dividing each element of the interindustry flows (Z) by the corresponding industry sector outputs (X). The technical coefficient represents the technology of production and embodies the economic relationship among the sectors.

$$\frac{\boldsymbol{Z}}{\boldsymbol{X}} = \boldsymbol{A}$$

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y}$$

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{Y}$$

$\mathbf{I}$ is an identify matrix (1 in the diagonal elements and 0 in the off-diagonal elements), with $(\mathbf{I} - \mathbf{A})^{-1}$ known as the lentief inverse matrix representing the sectoral interdependencies within the economy and refers to the total of all outputs from each domestic industry required to satisfy a unit increase in final use (The Scottish Government, 2021).

$$\boldsymbol{B} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$$

$\boldsymbol{B}$ is known as production coefficient which is defined as the total of all outputs from each domestic industry required to satisfy a unit increase in final demand (Y).

3.3.1.1. Mathematical Description of Open Leontief Model – Type I

Demand driven IO can be used to measure the effect of an increase in demand on different economic variables- in particular **output, value-added and employment.**

- Impact on output

By knowing the final demand of the project, $\boldsymbol{Y}^*$, the sum of direct and indirect impacts on the economic production is calculated as follows:

$$\boldsymbol{X}^{dir+indi} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{Y}^{*} = \boldsymbol{B}\boldsymbol{Y}^{*}$$

- Impact on value-added

By knowing $\hat{\boldsymbol{v}}$ the n-vector of value added per unit of production, the direct and indirect impact on added value is calculated as the following:

$$\boldsymbol{V}^{dir+indi} = \hat{\boldsymbol{v}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{Y}^{*} = \hat{\boldsymbol{v}}\boldsymbol{B}\boldsymbol{Y}^{*}$$

$\hat{\boldsymbol{v}}(\boldsymbol{I} - \boldsymbol{A})^{-1}$ represents the total changes in value added throughout the national economy arising from a unit increase in final use.

- Impact on employment effect

Likewise, by knowing $\hat{\boldsymbol{l}}$ the n-vector of labour intensity corresponding to the quantity of labour required to produce one monetary unit of production, the direct and indirect impact on employment is calculated as the following:

$$\boldsymbol{L}^{dir+indi} = \hat{\boldsymbol{l}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{Y}^{*} = \hat{\boldsymbol{l}}\boldsymbol{B}\boldsymbol{Y}^{*}$$

$\hat{\boldsymbol{l}}(\boldsymbol{I} - \boldsymbol{A})^{-1}$ represents the total change in employment throughout the national economy arising from a unit increase in final use.

3.3.1.2. Mathematical Description of Closed Leontief Model – Type II

There are two variations of the IO model that differ in the treatment of households' incomes and expenditure: Type I and Type II. The Type I model, also known as 'Open Leontief Model', captures the direct and indirect changes resulting from changes in final demand. Type II model includes the additional term, the "induced effect", which corresponds to an additional impact generated from the increased income in the household, therefore increased spending for services and consumer goods. It is possible to calculate induced impact by closing the IO model through endogenization of households (Miller & Blair, 2009).

Knowing the extent of induced effect from RES installation is particularly important in regions that may not benefit from extensive industrial linkage effects due to unindustrialized regional character.

		Buying Sector					
		1	...	j	...	n	*Households (Consumers)*
Selling Sector	1	z_{11}	...	z_{1j}	...	z_{1n}	$z_{1,n+1}$
	⋮	⋮		⋮		⋮	⋮
	i	z_{i1}	...	z_{ij}	...	z_{in}	$z_{i,n+1}$
	⋮	⋮		⋮		⋮	⋮
	n	z_{n1}	...	z_{nj}	...	z_{nn}	$z_{n,n+1}$
	Households (Labor)	$z_{n+1,1}$	...	$z_{n+1,j}$	...	$z_{n+1,n}$	$z_{n+1,n+1}$

Figure 3.5 Input-Output table of interindustry flows with household

*Reference: Miller & Blair (2009)

The induced effect is calculated by extending the IO model with a new row and column representing the incomes(row) and expenditures(column) of the economy as shown in Figure 3.5.

- row: household labor payment input or ‘compensation of employees’
- column: final consumption of households or ‘household expenditure’

Households are considered a sector from which all other industries acquire their workforce, and wages are regarded as part of the intermediate consumption of these industries. When calculating household expenditure coefficients, there are two approaches in determining the denominator.

① Miller & Blair (2009) = employee compensation sum (Vasconcellos & Caiado Couto, 2021)

② Batey I = Gross disposable household income[21] (GDHI) (The Scottish Government, 2021)

Total household income from all sources is used as the denominator and not the total household final consumption expenditure figure from the IxI Table. This is because not all household expenditure results from 'Income from employment' paid to households (other sources are pensions, social benefits etc.)

- Leontief inverse/output

Similar to the Open Leontief Model, the sum of direct, indirect and induced impacts for output is equal to the following:

$$\boldsymbol{X}^{dir+indi+indu} = (\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}\,\boldsymbol{Y}^{*} = \boldsymbol{B}\boldsymbol{Y}^{*}$$

- Value added

By knowing $\hat{\boldsymbol{v}}$ the n-vector of value added per unit of production, the sum of direct, indirect and induced impacts on value added is calculated as follows:

$$\boldsymbol{V}^{dir+indi+indu} = \hat{\boldsymbol{v}}(\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}\,\boldsymbol{Y}^{*} = \hat{\boldsymbol{v}}\boldsymbol{B}\boldsymbol{Y}^{*}$$

[21] Household disposable income refers to the income that households can use for consumption and saving. National income includes not only household income but also the income earned by businesses, financial institutions, and the government. (https://kosis.kr/statHtml/statHtml.do?orgId=301&tblId=DT_200Y001&vw_cd=MT_ZTITLE&list_id=Q_301009_001_001&scrId=&seqNo=&lang_mode=ko&obj_var_id=&itm_id=&conn_path=MT_ZTITLE&path=%252FstatisticsList%252FstatisticsListIndex.do)

- Employment

Likewise, by knowing $\hat{\boldsymbol{l}}$ the n-vector of labour intensity, the sum of direct, indirect and induced impacts on labour is calculated as follows:

$$\boldsymbol{L}^{dir+indi+indu} = \hat{\boldsymbol{l}}(\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}\,\boldsymbol{Y}^{*} = \hat{\boldsymbol{l}}\boldsymbol{B}\boldsymbol{Y}^{*}$$

- Induced effect using Open and Closed Leontief Model

Induced impacts can therefore be deduced as the difference between the sum of all impacts and the sum of direct and indirect impacts:

$$\boldsymbol{X}^{indu} = \boldsymbol{X}^{dir+indi+indu} - \boldsymbol{X}^{dir+indi}$$
$$\boldsymbol{V}^{indu} = \boldsymbol{V}^{dir+indi+indu} - \boldsymbol{V}^{dir+indi}$$
$$\boldsymbol{L}^{indu} = \boldsymbol{L}^{dir+indi+indu} - \boldsymbol{L}^{dir+indi}$$

3.3.2. Demand Vector Creation

The standard IO table does not have solar PV or wind power as independent industries. Table 3.9 below is a segment of sector classification for IO and IRIO table provided by the Bank of Korea displaying classification for “Electricity, gas and steam” industry referred as code ‘D’. IRIO table provided by the bank of Korea is even less segregated than the national IO table. The sector that comes closest to renewable energy is Code 450 Electricity, New & Renewable Energy. However even this does not encompass all the value chain activities.

Table 3.9 Sector classification example

<table>
<tr><th colspan="2">Basic (381)</th><th colspan="2">Small (165)</th><th colspan="2">Medium (83)</th><th colspan="2">Large (33)</th></tr>
<tr><th>Code</th><th>Sector</th><th>Co de</th><th>Sector</th><th>Co de</th><th>Sector</th><th>Co de</th><th>Sector</th></tr>
<tr><td>4501</td><td>Hydro power</td><td rowspan="5">450</td><td rowspan="5">Electricity, New& Renewable Energy</td><td rowspan="5">45</td><td rowspan="5">Electricity, New& Renewable energy</td><td rowspan="7">D</td><td rowspan="7">Electricit y, Gas, Steam</td></tr>
<tr><td>4502</td><td>Thermal power</td></tr>
<tr><td>4503</td><td>Nuclear power</td></tr>
<tr><td>4504</td><td>Self-generation</td></tr>
<tr><td>4505</td><td>New& Renewable energy</td></tr>
<tr><td>4610</td><td>Town Gas</td><td>461</td><td>Town Gas</td><td rowspan="2">46</td><td rowspan="2">Gas, Steam, Hot water</td></tr>
<tr><td>4620</td><td>Steam, Hot water</td><td>462</td><td>Steam, Hot water</td></tr>
</table>

*Reference: based on Input-Output Table Industry Classification

In most countries, renewable energy sources such as solar and wind energy are not categorized as separate industries in their respective IO tables. Various IO approaches exist in evaluating impact of an uncategorized industry. After comparing different types of IO approaches, the most appropriate approach for the study was found to be assigning the value chain analysis result to its closer sector in the given table in order to conduct impact analysis.

Cost of each value chain items have been assigned to corresponding IO industry, hence the relevant coefficients as exemplified in Figure 3.6.

For the assignment, the recently revised classification system of new& renewable energy industry from the ‘Report on the establishment of a special classification of the renewable energy industry’ (Statistics Korea, 2021) was utilized where each industry in the system was assigned a Korean Standard Industrial Classification (KSIC) number. Then, the KSIC number was appointed to the product/industry number from the IO table via KSIC-IO product comparison table provided by the Bank of Korea. The assignment was supplemented by previous research papers such as Lee C.-Y. (2021) to enforce credibility.

The IRIO table is segregated to 'small' classification, whereas the IRIO employment table is only segregated to 'medium' classification. To standardize the sector, the cost components in the value chain analysis is assigned to the industries in the 'medium' classification of the IRIO table.

The methodology will follow a combination of Byeon & Jeong (2011), Schallenberg-Rodriguez & Inchausti-Sintes (2021) and Connolly (2020) etc. from which value chain analysis result will be assigned to its closer sector in the given table in order to conduct impact analysis. The IO alignment was based on literature review and is found in the Appendix-4.

Demand vector (Yi) is required to be multiplied with corresponding environmental and economic multipliers found in section 3.3.1~3.3.2 in order to calculate final impact.

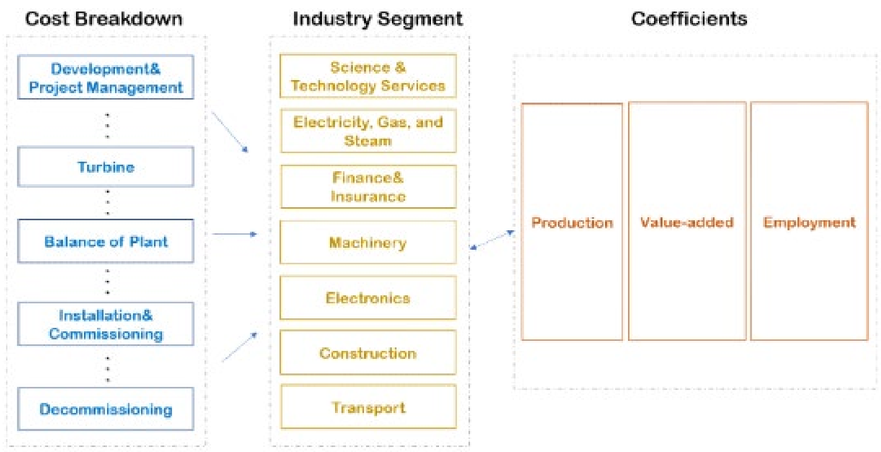

Figure 3.6 Analytical structure of economic impact using IO

*Reference: Kim, Yun, Im, Kim, & Lim (2022)

3.3.3. Economic Input Output Life-cycle Assessment (EIO-LCA)

3.3.3.1. Environmentally Extended Input Output (EEIO) Table Creation

Based on Kumar et al. (2016), the EEIO was created using emissions tables from the National GHG inventory. The development process follows the procedure shown in Figure 3.7 below.

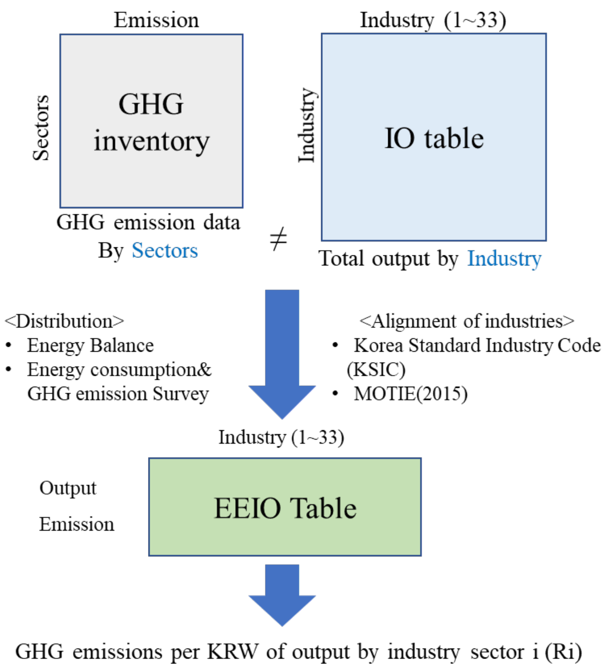

Figure 3.7 EEIO development process

National greenhouse gas inventory is calculated based on the framework of energy balance, with addition of methane gas and N_2O directly emitted from agricultural and waste treatment facilities (excluding fuel use). Hence, this approach provides a much more accurate estimation of total CO_2eq emissions compared to relying solely on energy balance. Appendix-3 provides a detailed sector classification for this inventory.

The energy and industrial process emission in the greenhouse gas inventory is based on the energy balance from the Energy Statistical Yearbook. The industrial sector in the energy balance is classified according to the KSIC. However, the greenhouse gas inventory is more aggregated than the IO sector, so a logical procedure is needed to allocate emissions to the appropriate IO sector. The following steps were taken to align the GHG inventory sectors with the IO sectors:

The connection between greenhouse gas inventory sectors and IO sectors was established using the "Greenhouse Gas Inventory - Energy Balance Items" linkage table, "Energy Balance Items - KSIC" linkage table, and "KSIC - IO Products" linkage table. Based on these steps, the industrial sectors in the greenhouse gas inventory and the IO sector were aligned as shown in the Appendix-3.

The division of solid fuels, manufacturing, and other energy industries into mining products, electricity, gas, and steam was based on the ratio of energy consumption (TOE) in mining and other energy sectors in the energy balance.

The allocation of emissions for the chemical, processed metal, other manufacturing, and commercial/public sectors was based on the emission ratios by industry in the "Industry Sector Energy and GHG Emission Statistics (KEA, 2021b)". However, electricity and heat consumption were excluded. The reason for basing the allocation on the "Industry Sector Energy and GHG Emission Statistics" is that the survey targets mining and manufacturing businesses with more than one employee according to the standard industrial classification (with a complete survey for businesses with five or more employees and a sample survey for businesses with five or fewer employees). On the other hand, the "Energy Consumption Survey (KEEI & KEA, 2022)" is conducted as a sample survey, separately estimating, and excluding emissions from large buildings. Moreover, the results of the "Industry Sector Energy and GHG Emission Statistics" are compiled for the mining and manufacturing sectors. There has been criticism that the "Energy Consumption Survey" lacks an adequate sample size for the commercial/public sector (Choi M. S., 2021).

Through the allocation process described above, the greenhouse gas emissions for each industry sector in the IO table were calculated as follows. The carbon emission coefficient $\boldsymbol{R_i}$ was calculated by dividing the sectoral carbon emissions $\boldsymbol{e_i}$ by the production output $\boldsymbol{x_i}$ of each sector (i) provided in the IO table.

$$\boldsymbol{R_i} = \frac{\boldsymbol{e_i}}{\boldsymbol{x_i}}$$

3.3.3.2. Lifecycle Carbon Emission

$\boldsymbol{R_i}$ is a diagonal matrix of carbon emission intensity (carbon emissions per KRW of output) by the industry sector, $(\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}$ is the Leontief Inverse or the total requirement matrix, and Y_i is a vector of the total demand. $\boldsymbol{R_i}(\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}$ is "n x n" matrix of carbon emission induced coefficient of each industry sector. Total carbon emission is estimated as $\Sigma\ \boldsymbol{B_i}$.

$$\boldsymbol{B_i} = \boldsymbol{R_i}(\boldsymbol{I} - \overline{\boldsymbol{A}})^{-1}\,\boldsymbol{Y_i}$$

The electricity production from a particular onshore wind farm depends on various factors such as capacity factor, nameplate capacity, duration of operation and curtailment.

The capacity factor is a measure of the average consumption, output, or throughput during a given period divided by the consumption, output, or throughput if it had operated at maximum capacity of a particular technology or piece of infrastructure.[22]

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[22] Science Direct (https://www.sciencedirect.com/topics/engineering/capacity-factor)

$$Capacity\ factor(\%) \ = \frac{Actual\ Energy\ Production(Wh)}{Nameplate\ Capacity(W) \times Time(h)} \times\ 100$$

As the capacity factor varies throughout the season, average capacity factor of a year is calculated as below.

$$Capacity\ factor(\%) \ = \frac{Yearly\ generation\ (Wh)}{Nameplate\ Capacity(W)\ \times 24\ \times 365} \times\ 100$$

Using the regional capacity factor, it is possible to calculate the corresponding facility capacity (maximum output capacity) for each region based on the desired production volume.

$$Yearly\ generation\ (Wh) = \frac{Capacity\ factor(\%)\ \times\ Nameplate\ Capacity(W) \times 24 \times 365}{100}$$

Total GHG gas emission per kWh of onshore wind farm is calculated as below.

$$Total\ generation\ (kWh) = \frac{Yearly\ generation\ (Wh)\ \times\ Operational\ Year}{1000}$$

$$CO2eq\ per\ kWh \ = \frac{Lifecycle\ Carbon\ Emission\ \Sigma\ \boldsymbol{B_i}}{Total\ generation}$$

3.3.4. Consumption-based, Production-based Emission Accounting

Since 2022, National GHG inventory disaggregated for the 17 Metropolitan cities and Provinces is published. Hence, multi-regional EEIO can be developed by following the above steps for National EEIO table development. However, since 'Industrial Sector Greenhouse Gas Emission Survey' does not provide regional-sectoral divisions due to corporate confidentiality, certain sectors cannot be allocated into 33 industries but into 17 industries as shown in the Appendix-3.

By following the steps below (Kim & Moon, 2019; Jiang & Kim, 2022), Multi-regional EEIO was formulated into Consumption-based Production-based Emission Matrix to analyze carbon emission responsibilities as shown in the Appendix-3. The sectoral emission intensities of CO_2eq in region r were determined by dividing the total CO_2eq emissions of sector i in region r by the overall output produced by that particular sector in the same region. This can be expressed as follows:

$$\boldsymbol{R_i^r} = \frac{\boldsymbol{e_i^r}}{\boldsymbol{x_i^r}}$$

$\boldsymbol{R_i^r}$ = CO_2eq emission intensity of sector i in region r
$\boldsymbol{e_i^r}$ = Total CO_2eq emission of sector i in region r
$\boldsymbol{x_i^r}$ = Total output from sector i in region r

$\boldsymbol{PBA^r} = \widehat{\boldsymbol{R^r}}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{p^r}$: production − based CO_2eq emission in region r

$\boldsymbol{CBA^r} = \widehat{\boldsymbol{R^r}}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{c^r}$: consumption − based CO_2eq emission in region r

$$\boldsymbol{p^r} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{0} \\ \vdots \\ \boldsymbol{y^{rr}} + \sum_s \boldsymbol{y^{rs}} \\ \vdots \\ \boldsymbol{0} \end{bmatrix}, \quad \boldsymbol{c^r} = \begin{bmatrix} \boldsymbol{y^{1r}} \\ \boldsymbol{y^{2r}} \\ \vdots \\ \boldsymbol{y^{rr}} \\ \vdots \\ \boldsymbol{y^{nr}} \end{bmatrix}$$

$\widehat{\boldsymbol{R}}$: diagonal matrix of $\boldsymbol{R}$ with each element on its main diagonal and all other cells designated to 0
$\boldsymbol{p^r}$: goods or services produced in region r
$\boldsymbol{c^r}$: goods or services produced in other regions and consumed in region r
$\boldsymbol{y^{rs}}$: goods or services produced in region r and consumed in region s

Production-based emissions account for the total pollutants emitted by the region's production of goods and services. Consumption-based emissions account for the total pollutants generated by the region’s total consumption of goods produced regardless of the region of production. The emissions categorized as Types 1 and 2, as shown in the diagram below, fall under production-based environmental responsibility. This means that only the environmental impacts related to the production processes within the region are taken into account, and any environmental burdens arising from the consumption of products originating from outside the region are not considered. On the other hand, consumption-based responsibility takes into consideration emissions resulting from the consumption demands of a region, regardless of the geographical origin of the supplied products. Therefore, a country's consumption-based responsibility encompasses Types 1 and 3 emissions, as illustrated in Figure 3.8 (Choi T. , 2016).

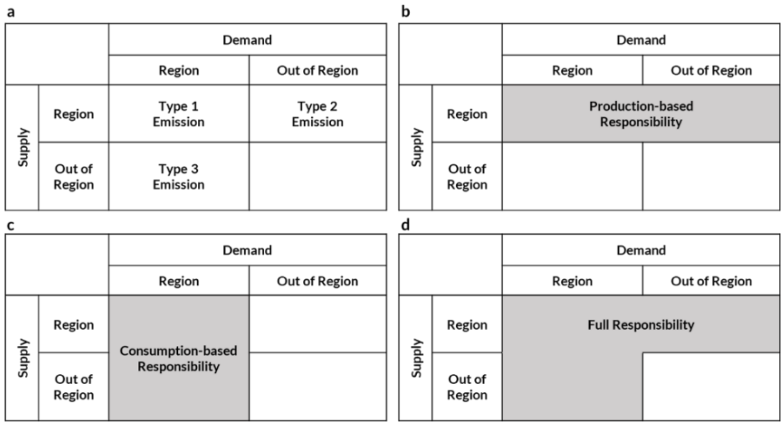


Figure 3.8 Topology of environmental responsibility

*Reference: adapted from Choi T. (2016, p. 227)

From, Consumption-based Production-based Emission Matrix, emission distribution (%) can be calculated by summing row and column emissions as shown in Table 3.10 below.

Table 3.10 Production-based and consumption-based emission distribution

Region	Production-based	Consumption-based
Seoul (S)	3.8%	12.9%
Incheon (IC)	7.9%	4.5%
Gyeonggi-do (GG)	10.5%	19.4%
Daejeon (DJ)	0.8%	1.9%
Sejong (SJ)	0.3%	0.5%
Chungcheongbuk-do (CB)	3.8%	3.3%
Chungcheongnam-do (CN)	22.0%	12.1%
Gwangju (GJ)	0.7%	2.0%
Jeollabuk-do (JB)	1.9%	2.8%
Jeollanam-do (JN)	13.0%	8.1%
Daegu (DG)	1.2%	2.7%
Gyeongsangbuk-do (GB)	9.7%	7.2%
Busan (BS)	1.9%	3.7%
Ulsan (US)	5.5%	6.2%
Gyeongsangnam-do (GN)	10.4%	8.8%
Gangwon-do (GW)	5.9%	3.3%
Jeju (JJ)	0	0.7%

Consumption-based Production-based Emission scatter plot was formulated based on the values above.

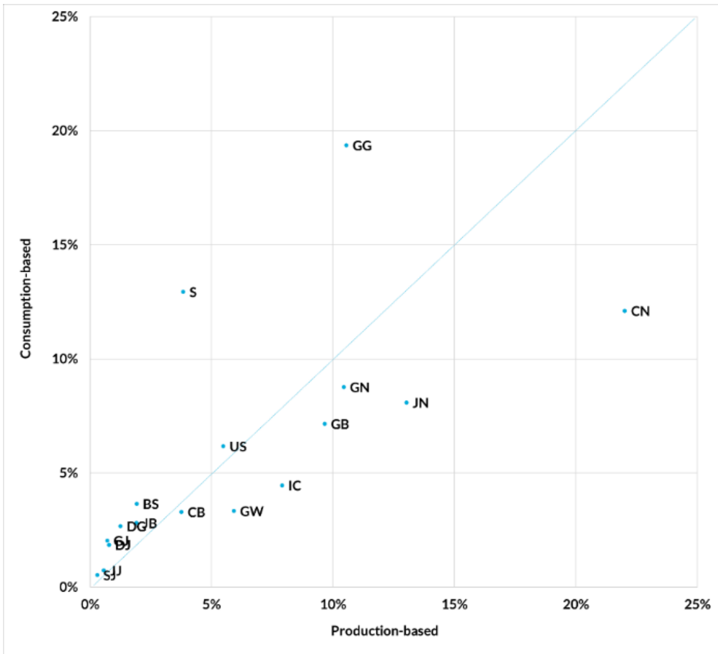


Figure 3.9 Consumption-based and Production-based Emission

Figure 3.9 represents the scatter plot of regional emissions based on the ratio of consumption-based emissions on the vertical axis and the ratio of production-based emissions on the horizontal axis. Regions located on the 45-degree line have equal production-based and consumption-based emissions. Regions below and to the right of the 45-degree line are production-oriented, while regions above and to the left are consumption-oriented. Major Metropolitan cities in Korea belong to the consumption-oriented regions, while CN, JN, GB, GN are considered production-oriented regions. GG is the most extreme consumption-oriented region, while CN is the most extreme production-oriented region. More than half of CN's emission carbon emission was related to other region's consumption. According to Table 3.10, CN, JN, GB, GN account for over half (55.9%) of the total domestic carbon emissions, indicating a substantial imbalance between production-based and consumption-based emissions of carbon emission. This evidence highlights the limitations of production-based policies, such as regulating production facilities, in adequately addressing pollution responsibility. Therefore, it is important to consider the perspective of consuming regions that rely on the related products.

In this particular study focusing on Jeju Island, we analyzed the consumption-based emissions using Table A.14 in Appendix-6. Table 3.11 below illustrates the carbon emissions produced in other regions to meet Jeju's consumption in 2015. This comprehensive data covers emissions from all industries. It is worth noting that Jeju is only accountable for 22.5% of its consumption, mainly due to its weak manufacturing sector.

Table 3.11 Consumption based emission of Jeju

Region	Consumption-based emission	%
Seoul (S)	127.1	2.60%
Incheon (IC)	599.3	12.40%
Gyeonggi-do (GG)	291.5	6.00%
Daejeon (DJ)	22.6	0.50%
Sejong (SJ)	10.2	0.20%
Chungcheongbuk-do (CB)	118	2.40%
Chungcheongnam-do (CN)	591.5	12.20%
Gwangju (GJ)	22.2	0.50%
Jeollabuk-do (JB)	96.6	2.00%
Jeollanam-do (JN)	350.6	7.20%
Daegu (DG)	35.1	0.70%
Gyeongsangbuk-do (GB)	297.4	6.10%
Busan (BS)	62.4	1.30%
Ulsan (US)	150.6	3.10%
Gyeongsangnam-do (GN)	323.5	6.70%
Gangwon-do (GW)	656.7	13.50%
Jeju (JJ)	1,093.10	22.50%
Total	4,848.40	100.00%

As discussed earlier, the operation of renewable energy systems necessitates flexibility options ESS, which are assumed to be sourced from other regions. Taking this into account, Chapter 6 will delve into the regional distribution of carbon emissions during the operation of renewable energy systems in Jeju Island.

3.4. Summary

This chapter explained and compared various IO approaches employed in the study. The choice of IO approach depends on which aspect of renewable energy deployment one wishes to focus on. This is summarized in Table 3.12 below.

Table 3.12 Summary of IO models in each chapter

Thesis	Shock (Expenditure)	IO Table	Impact	Research Objective	Parameters
Chapter 4	Jeju, Wind Energy	National EEIO 33 industries	Carbon emission	Primary sources of emissions	Capacity factor, Operational years, Value chain
Chapter 5	Jeju, Wind Energy	Jeju& Rest of Korea 2x2 IRIO 33 industries	Value added, Jobs	Regional Economic Impact (VA, Jobs)	Regional LC National LC Value chain
Chapter 6	The 17 Metropolitan cities and Provinces, PV and Wind	17 Regions 17x17 IRIO, National IO, National EEIO, 33 industries	Carbon emission, Jobs	Identify relationship between carbon emission and job creation	National LC Value chain - ESS/UBESS
	Jeju, PV and Wind	17 Regions 17x17 EEIO, IRIO, 17 industries	Carbon emission, Jobs		ESS production region during O&M phase

As depicted above, each chapter employs various scales and forms of IO models to conduct analysis based on their respective research objectives. Chapter 4 utilizes a national EEIO model comprising 33 industries to analyze the lifecycle carbon emissions of onshore wind energy expansion in Jeju. The single EEIO model provides more detailed sectoral classifications with 33 sectors, compared to the multi-regional EEIO model with 17 sectors. This is primarily due to the aggregation of regional industrial energy consumption to maintain corporate confidentiality. Since wind power involves multiple distinct industries, a detailed understanding of the impact of individual industries is crucial for identifying effective carbon mitigation solutions.

In Chapter 5, a 2x2 interregional model is utilized, consisting of Jeju and the rest of Korea, which also comprises of 33 industries. The purpose of aggregating the other 16 regions is to enable a meticulous application of local content variables. Otherwise, obtaining exact local content data for all 17 metropolitan cities and provinces for each value chain item would require numerous assumptions. The analysis in Chapter 5 focuses on the jobs and value added created within the region under various local content scenarios. The study also attempts to examine the dynamics within Jeju and the overall flow between Jeju and the rest of Korea.

For the first part of Chapter 6, a combination of a 17x17 interregional input-output (IRIO) model, a national IO model, and a national EEIO model, all consisting of 33 industries, are utilized. The 17x17 IRIO model is employed to analyze the impact of expenditure from renewable energy expansion within the region, while the national IO model examines the impact of expenditure outside the region based on regional and national local content. The EEIO model is used to analyze the carbon emission impact from renewable energy expansion under different national local content. This diverse combination of models is employed due to the similar premise of applying local content, as explained for Chapter 5.

The second part of Chapter 6 utilizes a 17x17 multi-regional EEIO and IRIO model, comprising 17 sectors, to analyze the regional distribution impact based on a consumption-based approach from renewable energy operation in Jeju within a single year. The study focuses on the O&M phase to examine long-term impacts and the application of ESS under a constant local content scenario. Although the sectoral accuracy delivered is limited to 17 sectors, it is important to compare the regional distribution from both carbon emissions and economic impact perspectives.

While all three chapters discuss the expansion of renewable energy in Jeju, each chapter modifies the IO table differently to explore the distinct characteristics of renewable energies more precisely within the model. The integrated interpretation from the Jeju perspective can be found in section 7.2.

Chapter 4. Carbon Emission Impact of Wind Energy: A Case Study of Jeju

Wind energy, which exclusively rely on natural resources, emerged as one of the leading clean energy alternatives due to their negligible carbon dioxide emissions during electricity generation. Replacing fossil fuels with wind energy offers substantial potential for emissions reduction.

To reduce carbon emissions further responsibly, it is important to consider the emissions from the entire lifecycle of renewable energy, including manufacturing, installation, operation& maintenance as well as flexible resources. No matter how much carbon emission an energy system can abate during operation, the emission along the value chain cannot be justified if significant harm is done to the environment.

Although, there are many indicators for environmental impact assessment; GHG emission, air pollution, land occupation, water use, material resources, ionizing radiation, and human toxicity, reducing GHG emission and preventing climate change is considered to be most urgent and has even led to the establishment of an international environmental treaty.

Hence this chapter will focus on estimating the carbon emission (in CO_2eq) and study the total emission over the entire lifecycle of onshore wind development using EIO-LCA. This method allows calculation of supply chain impact which is difficult in the original LCAs which are limited to direct emissions. The chapter will also identify the main sources of carbon emission and find potential for mitigating the environmental pressure. Emissions are considered per kWh of electricity produced to compare with conventional power sources of Jeju Island.

Due to abundant renewable resources, Jeju Island is a frontrunner in terms of renewable energy contribution to electricity generation, accounting for over 20% in 2022 and has an ambitious aim to reach carbon neutrality by 2030 through further expanding solar PV and wind power sources. This study will closely look into cases specific to onshore wind power energy installation in Jeju Island.

Jeju Island, just like the Korean peninsula, is an isolated region with an independent electricity network with very limited interconnection to external grid. Hence, flexibility options will also be considered for stable operation.

The specific research questions of Chapter 4. are as followed.

- How much carbon emission is produced from wind energy expansion? How does ESS impact carbon emission?
- What are the main sources of emission and how can it be improved?
- What is the carbon emission reduction potential of wind energy compared to conventional power sources of Jeju Island?

Figure 4.1 Jeju Gasiri onshore wind farm

*Reference: photo taken by author

4.1. Analytical Procedure

This study will be carried out using EIO-LCA as described in Chapter 3. sub-section 3.3.3 for 211MW onshore wind development in the following order and is illustrated in Figure 4.2.

- Build EEIO Table (2018 National Level) which contains GHG emission level as carbon dioxide emission equivalent (CO_2eq), abbreviated as carbon emission, for industry sectors
- Estimate carbon emission intensity (in CO_2eq per billion KRW) for each industry sector
- Formulate carbon emission induced coefficient (in CO_2eq per billion KRW) matrix
- Find total carbon emission produced from the onshore wind farm throughout the lifecycle using demand vector derived from cost analysis
- Identify main sources/industry of carbon emission by looking at supply chains or backward purchases in the carbon emission induced coefficient matrix. Also identify the emission impact of including ESS in the value chain
- Calculate total electricity generation (GWh) from the onshore wind farm during 25 years of operation using average capacity factor of Jeju Island (Refer to Appendix-2)
- Estimate carbon emission per kWh and compare with those of conventional power plants of Jeju
- Conduct sensitivity analysis for carbon emission per GWh by varying operational period, capacity factor and flexibility options
- Recommend measures to maximize carbon reduction potential of onshore wind farms.

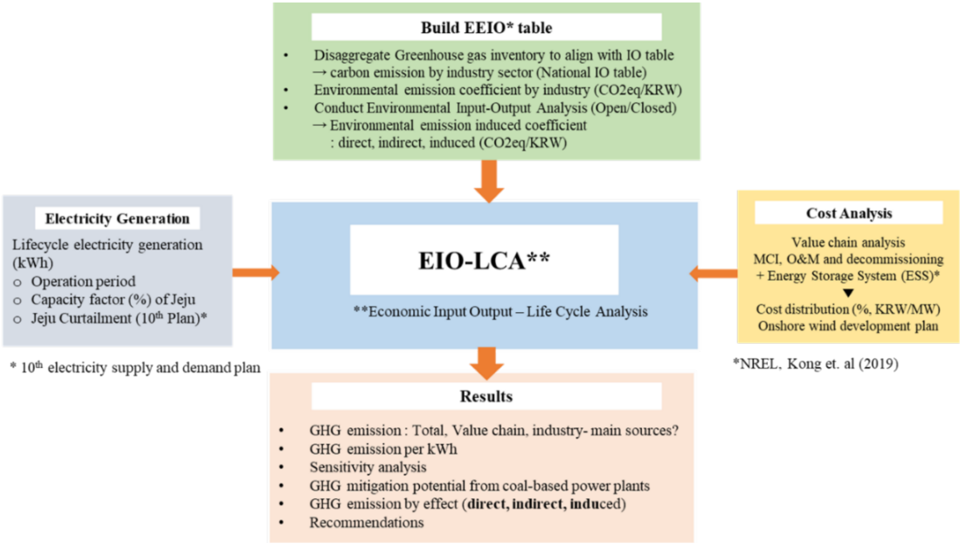


Figure 4.2 Analytical framework of Chapter 4.

Chapters 4. assesses the cabon emission impact of onshore wind power projects on Jeju Island, Korea. The study assumes a deployment of 211 MW by 2030, based on onshore wind installation target of 450 MW according to the CFI 2030 plan. It is the only plan that estimates onshore wind energy installation potential beyond 2025 provided by the municipality. According to Kong et. al (2019), the optimal capacity ratio between wind turbine and ESS battery is determined as 1:3 (kW:kWh). Since the wind capacity in this analysis is assumed to be 211MW, the total battery storage is calculated to be 633MWh.

This study will limit the regional scope to Korea and analyze the impact at the national level instead of the regional level. This is because climate change caused by carbon emissions is a national and an international concern. Carbon emission from a development work taking place in a region can cause climate change related natural disasters in regions not involved in the development. 2018 national IO table will be used as 2018 is the latest year in which detailed “Survey on Greenhouse Gas Emissions in the Industrial Sector” is publicly available. Value chain of onshore wind covered in this study is explained in Chapter 3. sub-section 3.1.1 and 3.1.3 which encompasses MCI, O&M, Decommissioning as well as ESS as flexibility option.

Energy used in manufacturing process or transportation will depend on the fuel or electricity mix of the country in question. For example, Oebels & Pacca (2013) found that because north-eastern coast of Brazil has electricity mix based on renewable energy sources (87%), the parts and components manufactured in Brazil will have lower carbon footprint resulting small environmental impact of wind farm which is an advantage for further installation. This study is limited with utilization of fixed IO table, hence does not incorporate the changes in power mix. However, this in turn signifies that our GHG emission values will be the upper limit and future emissions from onshore wind will only decrease as the power mix becomes more carbon neutral. In the study, all demands are considered to be sourced internally, leading to emissions being confined within the boundaries of Korea.

4.2. Results

4.2.1. Lifecycle Electricity Generation

By following the steps described above, total electricity generated from 211MW of onshore wind through 25 years of operation under capacity factor of 22.1% was calculated. The average capacity factor of Jeju is officially provided by Korea Electric Power Corporation[23] detailed in Appendix-2.

On the other hand, without the use of flexibility options such as ESS, electricity produced from wind turbine is bound to face curtailment hence, reduced contribution to the electricity grid. According to 10th national electricity supply and demand plan (2022~2036), wind power in Jeju suffered from 64 events of curtailment in 2021. The plan also estimates around 19% curtailment rate by 2030 for renewable energy and 24~25% between 2031 to 2036 when renewable energy installation according to CFI plan is completed. The yearly curtailment rate in Jeju used in this study is based on the plan which is suggested as Table 4.1 below.

Table 4.1 Curtailment scenario

Year	Curtailment Rate	Year	Curtailment Rate	Year	Curtailment Rate
2021	0	2032	25.06%	2044	24.57%
2022	0	2033	24.99%	2045	24.57%
2023	1.08%	2034	24.83%	2046	24.57%
2024	0	2035	24.65%	2047	24.57%
2025	0.07%	2036	24.57%	2048	24.57%
2026	0.77%	2037	24.57%	2049	24.57%
2027	2.20%	2039	24.57%	2050	25.40%
2028	4.42%	2040	24.57%	2051	25.40%
2029	8.12%	2041	24.57%	2052	25.40%
2030	18.98%	2042	24.57%	2053	25.40%
2031	25.54%	2043	24.57%	2054	25.40%

Total electricity generation for onshore wind without ESS was calculated using

[23] Electric Power Statistics Information System (http://epsis.kpx.or.kr/epsisnew/selectKnreMain.do)

equation below by multiplying curtailment rate for each year of operation to that yearly generation.

$$Total\ generation\ (kWh) = \frac{Yearly\ generation\ (Wh)\ \times\ Operational\ Year * Curtailment\ (\%)}{1000}$$

The total generation for three value chain types 1) Onshore wind, 2) Onshore wind with ESS was calculated as Table 4.2 below.

Table 4.2 Total electricity generation over lifecycle in kWh under 25 years operation in Jeju

Value chain	Capacity factor (%)	Nameplate Capacity (MW)	Yearly generation (kWh)	Total generation during lifetime (kWh)
Onshore wind	22.1	211	322,410,335	8,060,258,379
Onshore wind + ESS/UBESS	22.1	211	408,487,560	10,212,189,000

4.2.2. Lifecycle Carbon Emission

From developing and operating (25 years) to demolishing 211MW of onshore wind power, around 25.4 1000T CO_2eq of carbon emission was emitted without ESS. However, if ESS is included in the impact assessment, 414.06 1000T CO_2eq of carbon emission was emitted.

Table 4.3 Lifecycle carbon emission by value chain activity (1000T CO_2eq)

Onshore wind Value chain		GHG emission (Direct)	GHG emission (Indirect)
Engineering and Project Planning	Legal services	0.01	1.03
	Certificate, permits, assessments	0.02	1.55
	Engineering (Design)	0.1	7.5
	Finance, contingency, miscellaneous	0.02	1.35
Manufacturing	Tower	0.56	17.26
	Shaft, nacelle housing	0.39	12.08
	Rotor blade	0.59	18.12
	Gearbox, rotor bearings	0.14	10.4
	Generator	0.06	3.53
	Transformer	0.06	3.53
	Power converter	0.08	4.71
	Yaw drive, pitch system	1.25	2.37
Construction& Installation	Construction (Foundation Road)	0.38	15.59
	Erection/Installation	0.59	24.43
	Electrical infrastructure	0.09	5.73
	Management/supervision/monitoring	0.06	4.13
Grid Connection	Electrical interconnection	0.47	28.98
Operation and Maintenance	Field Salaries	0.02	2.82
	Administrative and management	0.01	1.64
	Vehicles	0.06	1.68
	Fees, Permits, Licenses, Insurance	0.04	3.23
	Utilities	14.82	0.16
	Replacement parts/consumables/tools	2.13	48.98
	Fuel	0.26	0.21
	Land Cost	0.02	2.25
Decommissioning	Demolition	0.06	2.37
ESS MCI	Battery manufacturing	1.04	63.79
	Electrical works (local)	0.34	20.86
	Installation, Construction	0.68	27.95
	Development	0.45	32.93
	Legal works	0.02	1.13
ESS O&M	Operation and maintenance	0.31	22.97
	Replacement parts	0.31	18.79
SUM		25.44	414.06

As can be seen in Table 4.3 above, battery manufacturing was the single largest source of carbon emission which mandates the utilization of UBESS. To calculate carbon emission for UBESS, emissions from battery manufacturing under ESS, MCI and replacement parts under ESS O&M were removed. A typical UBESS is shown in Figure 4.3 below.

Figure 4.3 Reused battery from EV as UBESS in EUREF Campus Berlin

*Reference: photo taken by author

Figure 4.4 below illustrates the carbon emission of value chain items that are grouped and put in descending order. It shows that even with UBESS, there was substantial increase in carbon emission due to development and infrastructure works related to operation of UBESS. Also, the manufacturing of turbine elements during its first installation as well as replacement during the entire lifecycle produced large emission.

It is also important to note that majority of carbon emission is produced as indirect emission (94.2%) which indicates that most of the emission is produced by the supply chain activities of each value chain item. Therefore, efforts to identify the source of indirect emission through analyzing the supply chain or backward purchases must be preceded.

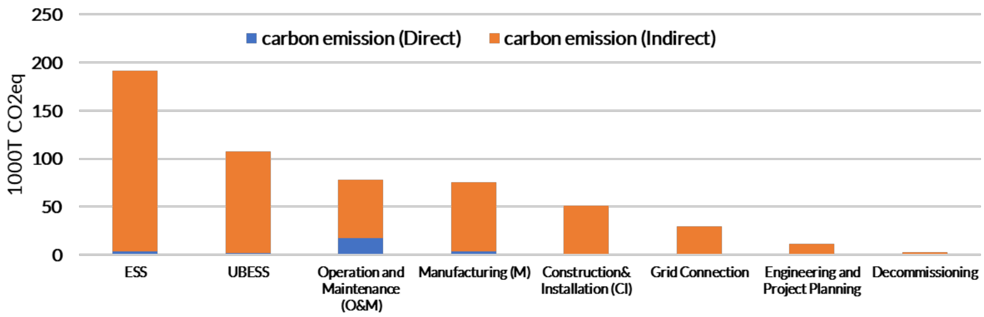


Figure 4.4 Total GHG emission by phase

Table 4.4 shows the direct and indirect carbon emission under grouped value chain items in 1000T CO_2eq.

Table 4.4 Lifecycle carbon emission (1000T CO_2eq)

Value chain	Carbon emission (Direct)	Carbon emission (Indirect)
ESS	3.13	188.42
UBESS	1.79	105.83
Engineering and Project Planning	0.15	11.44
Manufacturing (M)	3.13	72.01
Construction& Installation (CI)	1.12	49.88
Grid Connection	0.47	28.98
Operation and Maintenance (O&M)	17.37	60.96
Decommissioning	0.06	2.37

$$1000\,T\,CO2eq\ per\ kWh = \frac{Lifecycle\ Carbon\ Emission\ (1000\,T\,CO2eq)}{Total\ generation\ \ (kWh)}$$

By applying the above equation, and assuming 22.1% capacity factor and 25 years operation, the calculated carbon emission per kWh of electricity produced from 211MW onshore wind development in Jeju Island was around **28.8 g CO_2eq/kWh**. If UBESS or ESS is included in the impact assessment, the range of carbon emission per kWh was **34.8 to 43.0 CO_2eq/kWh**. More detailed range is shown in the discussion (sub-section 4.3.1).

4.3. Discussion

4.3.1. Sensitivity Analysis

The g CO_2eq/kWh results are highly reliant on the capacity factor, lifespan, and percentage losses (Vélez-Henao & Vivanco, 2021; Noori et al., 2015).

Sensitivity analysis was conducted to changes in capacity factor and operational period as shown in Table 4.5 below. As operational period increased, both O&M spending (and therefore increase carbon emission during the increased period) and electricity generation (kWh) increased. However, within the same capacity factor, increasing operational period reduced the carbon emission per kWh. It is obvious that increasing capacity factor would reduce carbon emission per kWh as more electricity is generated. However, 20 years operation under capacity factor 32.1% scenario, the carbon emission per kWh was higher than that of 30 years operation under capacity factor 27.1% scenario. Therefore, it is critical that both a higher capacity factor and a longer operational period are required to maximize carbon emission reductions potential. Capacity factor can be improved by devising more efficient turbines appropriate to the site conditions. Operation period can be prolonged by good maintenance and appropriate policy schemes to guarantee up to 30 years and to incentivize durability of a turbine.

However, the above value assumed a fixed EEIO table throughout the years, hence could not consider the future changes in power mix or industrial structure. This in turn signifies that our carbon emission values will be the upper limit and future emissions from onshore wind will only decrease as the power mix becomes more carbon neutral.

Table 4.5 Total carbon emission per kWh under 25 years operation

g CO_2eq/kWh		Without ESS	Used Battery ESS	ESS
capacity factor 22.1%	20 years	35.6	41.0	50.8
	25 years	28.8	34.8	43.0
	30 years	24.2	30.7	37.8
capacity factor 27.1%	20 years	29.0	33.5	41.5
	25 years	23.5	28.4	35.1
	30 years	19.8	25.0	30.9
capacity factor 32.1%	20 years	24.5	28.3	35.0
	25 years	19.8	24.0	29.6
	30 years	16.7	21.1	26.0

To verify the results, the values were compared to those of existing studies as below. Our results without ESS which gives a range of 16.7 to 35.6 g CO_2eq/kWh fairly corresponds to the literature.

- Kumar et al. (2016): 14.5~28.5 g CO_2eq/kWh (GHG) in US
- Lundie, Wiedmann, Welzel, & Busch (2019): 11.7~18.3 g CO_2eq/kWh (GHG) in Germany
- Noori et al. (2015): 12~25 g CO_2eq/kWh (GHG) in US

The addition of ESS is required to reduce curtailment issues. Curtailment not only results loss to wind power operators as they cannot be compensated but also results in not meeting national GHG reduction targets such as Nationally Determined Contribution (NDC) since electricity produced from renewable energy is not consumed in the demand sector but wasted away.

Although ESS reduces the curtailment issues and loss of generated electricity, in the lifecycle perspective it produces more CO_2 over the entire lifecycle of wind power generation. This is because ESS, battery production is a very energy intensive process. Hence, recycling the battery part can improve lifecycle carbon footprint but even then, it will produce slightly more carbon emission that the system without ESS. Although the analysis did not incorporate other flexibility options that are in development such as P2G such as electrolyser, ammonia production and power-to-heat (P2H) such as heat pumps, it can be deduced that while supporting stable wind power generation, these flexibility infrastructures will also enhance total carbon emission. Hence, other flexibility options that does not require large infrastructural change must be prioritized such as plus demand response (DR) that makes use of existing Vehicle-to-Grid (V2G) infrastructure. Also, better prediction of power supply from renewable energy, Virtual Power Plant (VPP), market flexibility (Lee T. , 2020) have the potential to effectively reduce lifecycle carbon emission of onshore wind power.

From backward calculation, ESS capacity for UBESS addition in the value chain that amounts to the carbon emission coefficient of that of wind power without ESS was found to be 1kW:1.845 kWh ratio as shown in Figure 4.5 below. This can be interpreted as the UBESS capacity that can be installed to support onshore wind power production without increasing total lifecycle carbon emission. However, the rest of flexibility capacity of 1.155 kWh/W must be supplied by other flexibility options that does not require infrastructural change.

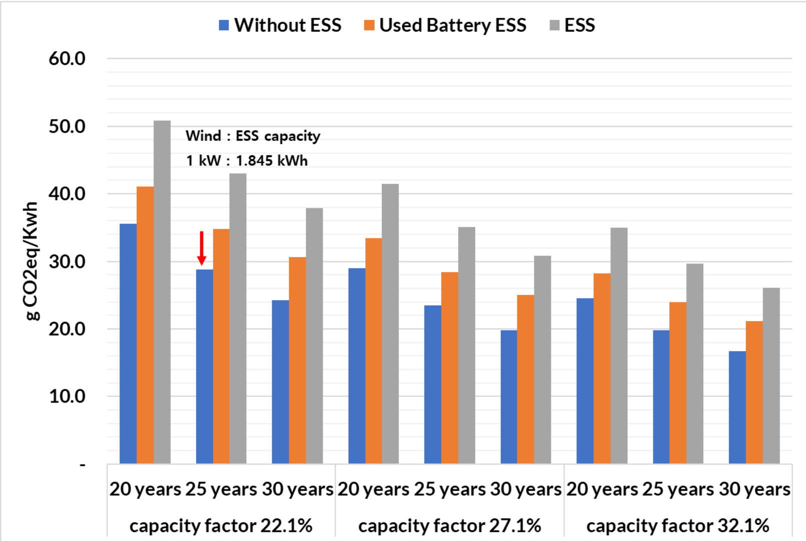


Figure 4.5 Sensitivity Analysis

4.3.2. Emission by Industry

In the results section, it was found that battery manufacturing is the single largest source of carbon emission. And, apart from ESS, manufacturing of turbine elements during its first installation as well as replacement during the entire lifecycle produced substantial emission. Figure 4.6 below depicts proportion of each value chain component (without ESS). It shows that MCI phase takes about 67% of the entire lifecycle emission.

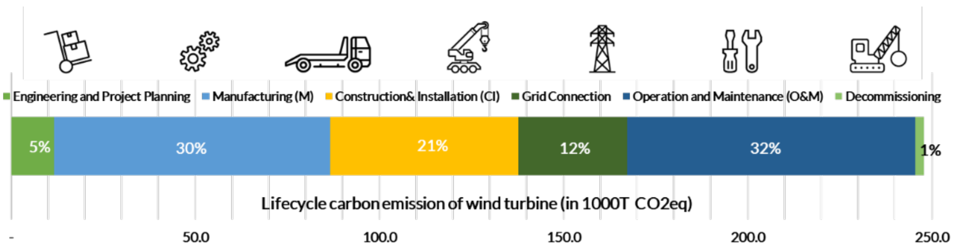


Figure 4.6 Lifecycle carbon emission of wind turbine (1000T CO_2eq)

It was also found that majority of carbon emission is produced as indirect emission (94.2%) which indicates that most of the emission is produced during supply chain activities of each value chain item. Therefore, efforts to identify the source of indirect emission must be preceded as these value chain do not release GHG emission on their own. Hence, it is important to identify which part of the supply chain are responsible for these three industries.

In this section, industry emission was analyzed in detail by looking at supply chains or backward purchases by utilizing the carbon emission induced coefficient matrix[24] described in Chapter 3. sub-section 3.3.3. The overall lifecycle emission impact by each individual value chain component and supply chain industries

[24] produced from multiplying a diagonal matrix of carbon emissions per KRW of output by the industry sector to the Leontief inverse matrix.

responsible for the emission in each component is visualized into a Sankey diagram of carbon emission flow shown as Figure 4.7 below.

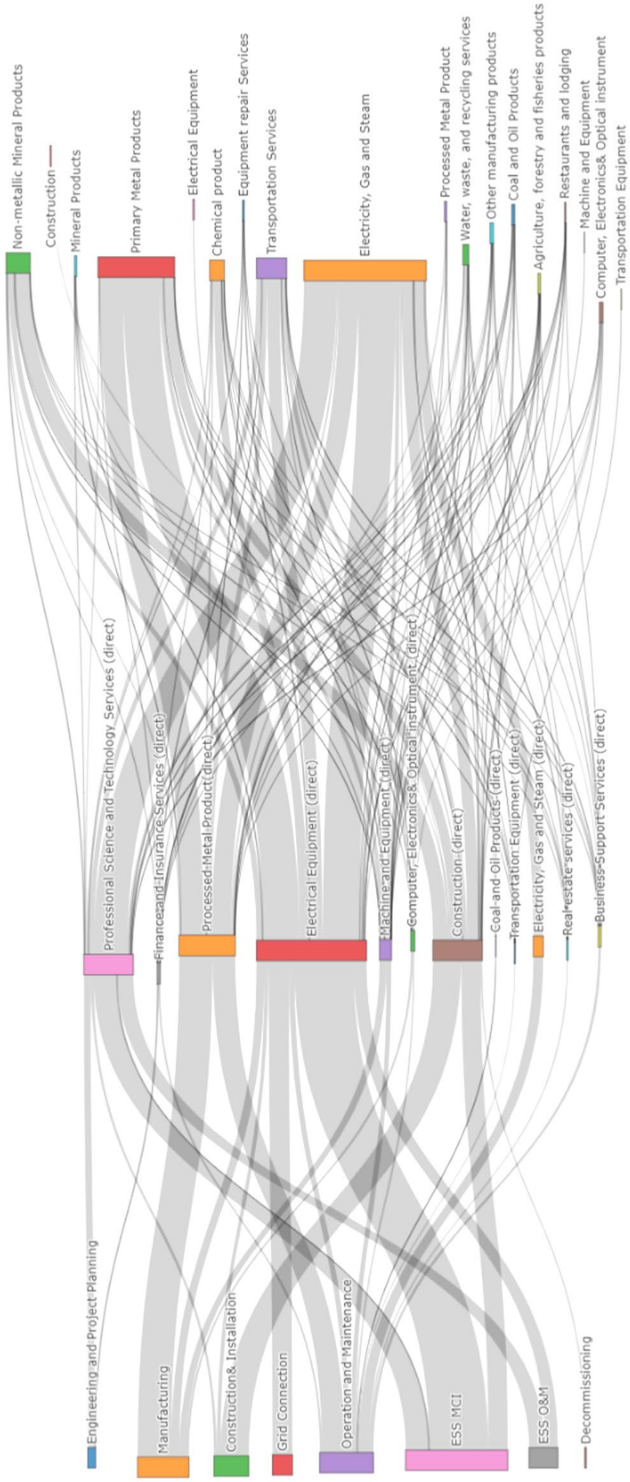


Figure 4.7 Sankey diagram- 211MW onshore wind and 633MWh ESS

When looking at the carbon emissions from above, five notable industries were found to produce most carbon emission. These are 1) 'Electricity, gas and steam' supply, 2) 'Primary metal products' (Steel production) 3) 'Non-metallic mineral products' (Cement production), 4) Transportation Services, 5) Chemical Product (Petrochemicals) as illustrated in Figure 4.8 below. Induced effect was excluded to identify pure supply chain effects or backward purchases in releasing carbon emission to the atmosphere.

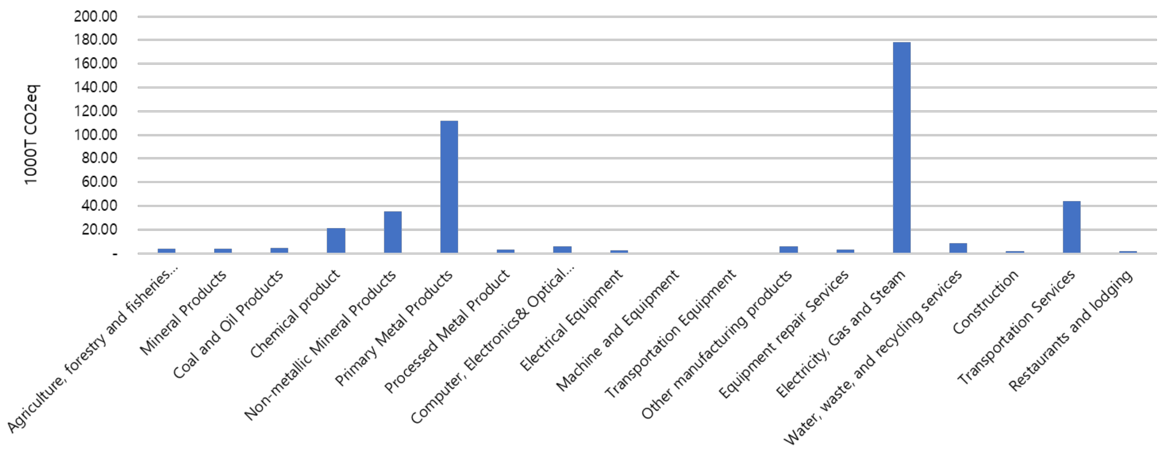
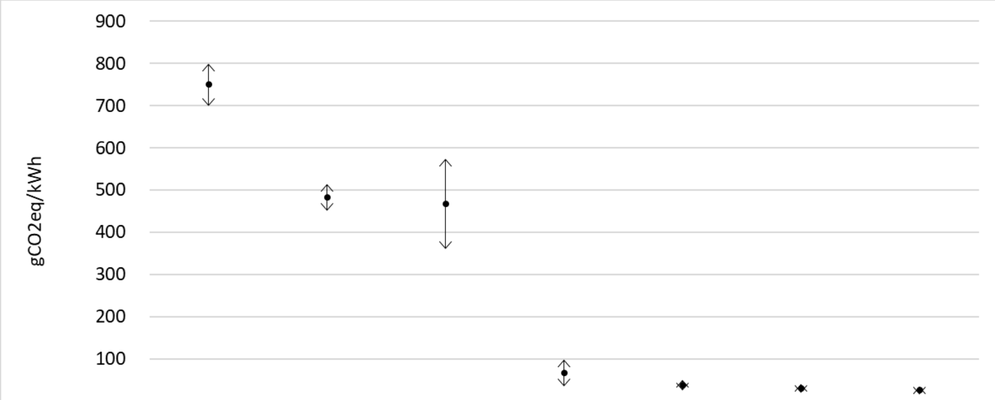


Figure 4.8 GHG emission source by IO industry

This provides several important implications. It all comes down to the question of how green or carbon neutral the electricity generation, transportation fuel and metal production are. In the year of 2018, the electricity was powered by almost 68% of fossil fuel generation. Moreover, the transportation sector has a long way to go in terms of carbon neutrality. Production of primary metal production which mainly represents steel production is responsible for 40% of total industry sector scope 1 emission. This is due to blast furnace production process that consumes a lot of coal and electric furnace powered by fossil fuel combustion. Most representative non-metallic mineral product is cement which is responsible of almost 14% of total industry sector carbon emission. Hence it is crucial to not only increase renewable energy contribution in the electricity generation sector, but also to transform unsustainable industrial processes especially in steel and cement industry. One of the most promising alternative processes for green steel production is Direct Reduced Iron (DRI) process that uses green hydrogen instead of coal. Acquiring commercial level of the technology as well as green hydrogen should become the national priority. Moreover, transportation sector must be transformed so that the vehicles and freights are either electrified or fueled with green hydrogen. Furthermore, recycling the waste from end-of-use wind farms can potentially reduce environmental pressure. According to IRENA & ILO (2022), it is theoretically possible to recycle approximately 85-90% of the foundations, towers, and wiring utilized in the wind industry. By improving the design, it is feasible to decrease materials required and enhance their recyclability.

4.3.3. Carbon Emission Reduction Potential

As shown in Figure 4.9 below, the lifecycle carbon emission in gCO_2eq per kWh electricity production for wind energy is compared to various conventional power sources available in Jeju Island. The conventional sources include, oil-fired, natural gas-fired and biofuel which consist of roughly 50% of domestic waste and 50% of imported palm oil in Korea. Although biofuel is partially considered as climate neutral as the biomass absorbs carbon emission during growth, intensive direct emission from Land Use Change (LUC) has caused high controversy (Ecofys, IIASA, & E4tech, 2015), which is incorporated as Bio-fuel + LUC in Figure 4.9. The values of the conventional sources were found from extensive literature review (Weisser, 2007; NREL, 2021; Singh, Olsen, & Pant, 2013).



	Oil-fired	Bio-fuel + LUC	Natural gas	Bio-fuel	Wind +ESS	Wind +UBESS	Wind
Minimum	700	451	360	35	26	21	17
• Average	750	483	468	67	38	31	26
Maximum	800	515	575	99	51	41	36

Figure 4.9 Lifecycle carbon emissions of wind and fossil fuel sources

If onshore wind replaces existing conventional power plants in Jeju Island, carbon emission by 92~97% for every kWh electricity is reduced. Hence, carbon emission reduction potential of onshore wind compared to fossil-fuel based generation plants is significant even with the inclusion of ESS but can be improved further.

4.4. Conclusion

Carbon emission is generated throughout various stages of wind energy lifecycle. These emissions occur during the development, manufacturing, installation, operation& maintenance, and demolition of a 211MW onshore wind power facility.

Along the value chain, battery manufacturing was the single largest source of carbon emission. Apart from ESS, manufacturing of turbine elements during its first installation as well as component replacement during the entire lifecycle produced substantial emission. Majority of carbon emission was produced as indirect emission (94.2%) which indicates that most of the emission was produced by supply chain activities of each value chain item. The carbon gas emission per kilowatt-hour (kWh) of the 211MW onshore wind farm was estimated to be 28.8 g CO_2eq/kWh without ESS and 43.0 g CO_2eq/kWh with ESS under capacity factor of 22.1%.

The results highlight the importance of reusing batteries from electric vehicles to further enhance mitigation efforts. Additionally, the UBESS capacity that can be installed to support onshore wind power production without increasing total lifecycle carbon emission was estimated to be 1kW:1.845 kWh ratio assuming the rest is supplied by flexibility options that utilizes existing infrastructure or that does not require infrastructural expansion such as plus DR with V2G. Sensitivity analysis reveals that maximizing carbon emission reduction potential requires increasing both the capacity factor and operational period of onshore wind farms.

Based on backward purchases analysis, most notable carbon emission contributors were identified as 1) 'Electricity, gas and steam' supply, 2) 'Primary metal products' (Steel production) 3) 'Non-metallic mineral products' (Cement production). Thus, it is crucial not only to increase the share of renewable energy in the electricity generation sector but also to actively transform unsustainable industrial processes, particularly in the metal production (steel) and cement industry. These transformations can involve electrification or the utilization of renewable-based fuels and feedstocks, such as green hydrogen. Ultimately, these implications emphasize the need for larger supply of renewable energy sources, such as wind power for production of renewable energy-based fuel and feedstock. Circular economy concept should be emphasized beyond the reuse of battery by including recycling the waste from end-of-use wind farms to further reduce environmental pressure.

Finally, comparison of onshore wind's carbon mitigation potential with that of fossil-fuel-based generation plants in Jeju showcased a significant reduction of 92-97% in emissions per kWh electricity produced.

The contribution of this study lies in its status as the first to assess the carbon emission impact of wind energy expansion in conjunction with flexibility options using EIO-LCA. It identifies the primary sources responsible for the carbon emissions associated with wind energy expansion. However, it is important to note that the study does not include a broader range of flexibility options, such as heat pumps, electrolyser, and transmission networks. Incorporating these options would also increase the environmental pressure stemming from the manufacturing and construction processes. Therefore, flexibility options that utilizes existing infrastructure such as DR or V2G is recommended.

Chapter 5. Regional Economic Impact of Wind Energy: A Case Study of Jeju

Due to abundant renewable resources, Jeju Island is a front runner in terms of renewable energy contribution to electricity generation, accounting for over 20% in 2022. Renewable energy resources are generally spatially dispersed, often located within close vicinity of the local community and livelihood causing acceptance issues.

Onshore wind energy in particular faces many conflicts with residents when receiving development permits due to potential issues such as environmental degradation during construction and noise from turbine operation. This has resulted in consistently delayed installation and increased development costs. Consequently, there is a high level of social interest in the impact of expanding renewable energy on local communities. Under this context, capacity building of renewable energy intended to create local jobs and garner social acceptance is also becoming a popular policy of municipalities. Calculating and visibly presenting the impact of onshore wind energy expansion on value added and employment during the entire lifecycle can provide meaningful insight to develop ways in which renewable energy can grow and coexist in the region.

However, Jeju Island is known to have a weak local manufacturing base and therefore weak inter-industry linkage effects. This can be a discouraging factor in developing renewable energy. This also implies that it may be more important to focus on the impact arising during operation phase in such regions.

This chapter focuses on analyzing the deployment of 211MW of onshore wind power projects located in Jeju Island of Korea based on 'Jeju Island CFI New& Renewable Energy Supply (Jeju & KEEI, 2019)' as illustrated in Figure 5.1 below.

The specific research questions of Chapter 5. are as followed.

- What is the spill-over effects of onshore wind energy expansion?
- Which industries are affected the most from onshore wind energy expansion in Jeju Island and how is it different from conventional energy?
- To what extent will jobs and value added be preserved in the region?

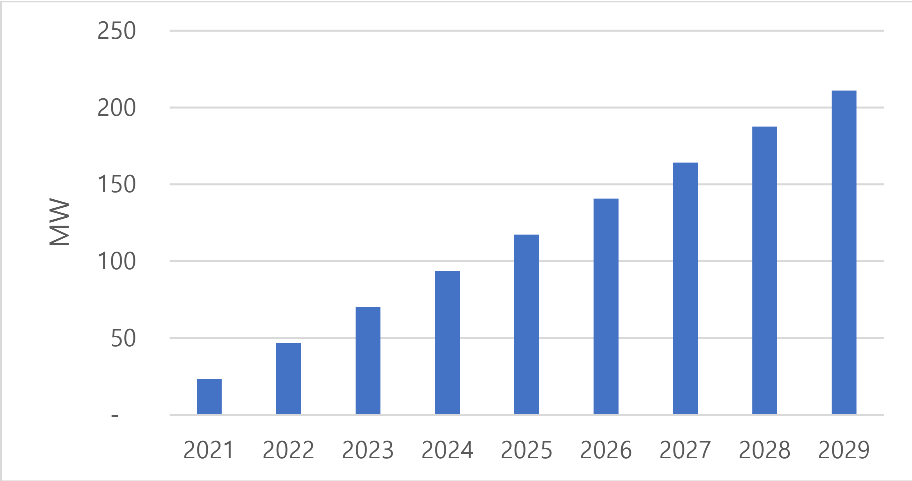


Figure 5.1 Onshore wind development plan (accumulated)

5.1. Analytical Procedure

The impact of onshore wind power installation planned in Jeju Island between 2020 to 2030 will be analyzed using value chain and cost analysis (sub-section 3.1.1) and interregional IO analysis (3.3.1) as described in Chapter 3. Data and Methodology for 211MW onshore wind development illustrated as Figure 5.2 below.

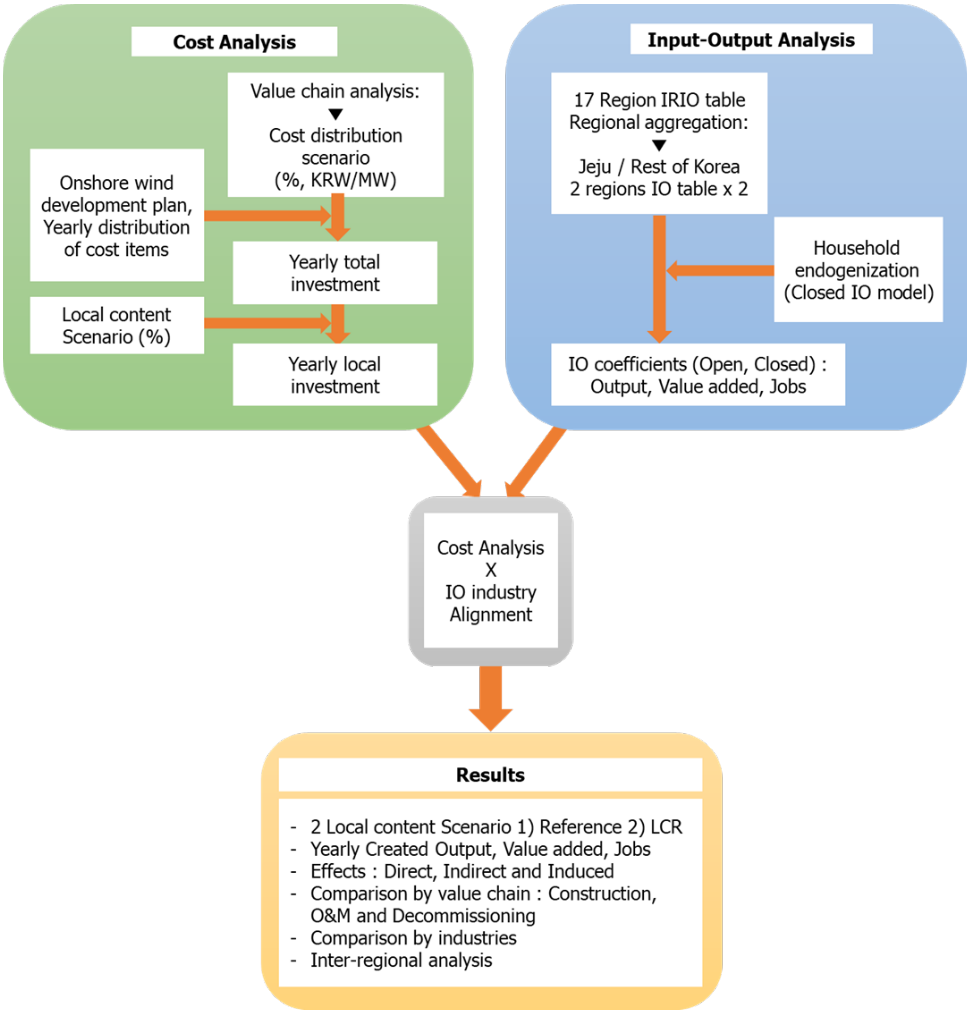


Figure 5.2 Analytical framework of Chapter 5.

- Build 2`x2 IRIO Table using 2015 IRIO table for Jeju vs. Rest of Korea
- Conduct endogenization of household in the IRIO table to derive induced coefficients for value-added and jobs, and quantify individual contribution (%) of direct, indirect, and induced effect.
- Find total value-added and jobs created from the onshore wind farm throughout the lifecycle using demand vector derived from cost analysis
- Identify job creation impact on regional industry in the O&M phase by looking at supply chains or backward purchases. Also identify the impact of including ESS in the value chain
- Compare the results with other regional industries, including conventional power plants of Jeju
- Analyze interregional feedback between Jeju Island and rest of Korea under various local content scenarios

Following assumptions are made.

According to Kong et. al (2019), the optimal capacity ration between wind turbine and ESS battery is determined as 1:3 (kW:kWh). However, in Chapter 4., ESS capacity for UBESS addition in the value chain that amounts to the carbon emission coefficient of that of wind power without ESS was found to be 1kW:1.845 kWh ratio. Hence this chapter will apply ESS with capacity of 389.2 MWh, assuming that the rest of flexibility required to prevent curtailment would be resolved with other flexibility measures that do not require infrastructure change. As mentioned in Chapter 2 and 3., local content (%) which determines the investment level in Jeju is assigned from consultation with wind power industry professionals and from previous studies as explained in Chapter 3 section 3.2.1.

Temporal aspect must be incorporated to fully understand how a RES system adoption in a region affects the regional society over time. As mentioned in Chapter 2., all technologies adoption follows a similar lifecycle from development to installation and operation and uninstallation stage (Llera Sastresa elt al., 2010). The development process of onshore wind has a specific order and including this in the model allows a more realistic picture to be presented when showing the economic impact. Following Table 5.1 depicts the sequence and duration for each cost items of onshore wind value chain. 'Certificate, permits, assessment' (#7) in CAPEX items is treated as an exception as there is no uniform duration as it can last from a minimum of 4 years to a maximum of 10 years. In the same context, cost in dealing with local complaints is not considered due to uncertainty and inconsistency. Hence, the CAPEX item is assigned to the corresponding timeline of wind farm development.

Table 5.1 Yearly distribution of cost component

CAPEX items		**Pre-construction**	**Construction**
		Year 1	Year 2
#1	Turbine equipment (turbine/blade/nacelle/tower)	#1	
#2	Construction (road, site, foundation, equipment)		#2
#3	Erection/Installation		#3
#4	Electrical infrastructure		#4
#5	Management/supervision/monitoring		#5
#6	Legal services (insurance, bonding etc.)	#6	
#7	*Certificate, permits, assessments**	#7	
#8	Electrical interconnection		#8
#9	Engineering (Design)	#9	
#10	Finance, contingency, miscellaneous	#10	
OPEX items		25 years	
Decommissioning (demolition)		1 year after operation termination	

*Reference: Kim, Y. & Kim, B. (2023)

There are inherent limitations within the IO analysis that must be acknowledged. It is crucial to exercise caution when examining the economic impact using this approach. It is essential to differentiate between operational effects and impacts during operation. Generally, operational effects pertain to changes in productivity resulting from factors such as price changes. However, this study is constrained by its use of fixed IO, neglecting considerations of labor or price substitution. Furthermore, the study fails to account for the substitution of conventional energy sources with renewable energy, thereby impeding an accurate demonstration of industry growth.

The analysis primarily focuses on the industries directly affected by renewable energy value chain integrate with flexible sources. In this context, relying solely on absolute numbers may not accurately capture the economic growth effects. However, these figures hold greater significance when comparing different scenarios involving local content and examining the range and types of job creation within the value chain, in contrast to traditional regional industries.

5.2. Results

5.2.1. Value-added

Installing 211MW of onshore wind in Jeju Island created value added ranges from 177 to 320 billion KRW which accounts for 0.9~1.6% of Jeju's GRDP 2020. As shown in Figure 5.3 below, the bump between 2021 and 2031 depicts manufacturing and construction phase.

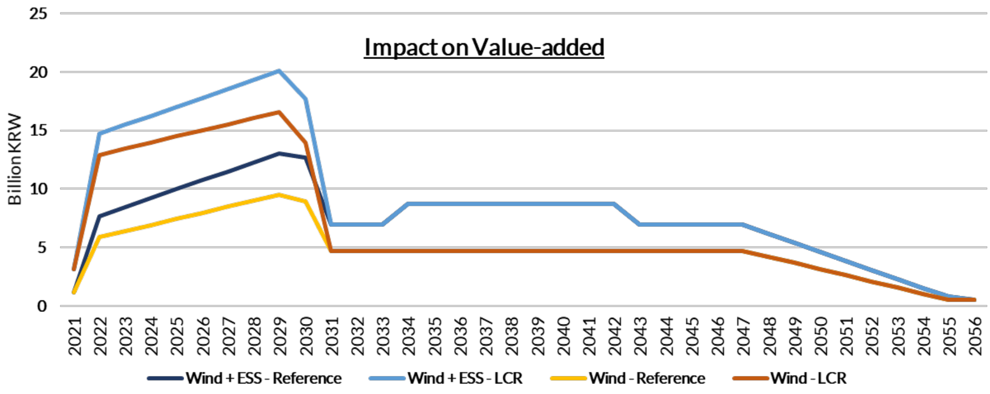


Figure 5.3 Impact on Value-added in Jeju

Table 5.2 below summarizes the value added and GRDP contribution under various regional LC.

Table 5.2 Impact on value-added

Billion KRW	**Wind + ESS**		**Wind**	
Regional scenario	Reference	LCR	Reference	LCR
Value added	319.6	383.0	177.1	240.5
2020 GRDP (%)	1.3%	1.6%	0.9%	1.2%

Unit: billion KRW

5.2.2. Job Creation

Job creation ranged from 2,057 to 4,402 FTE depending on the local content and inclusion of flexibility sources. Similarly, in Figure 5.4, the bump between 2021 and 2031 depicts manufacturing and construction phase.

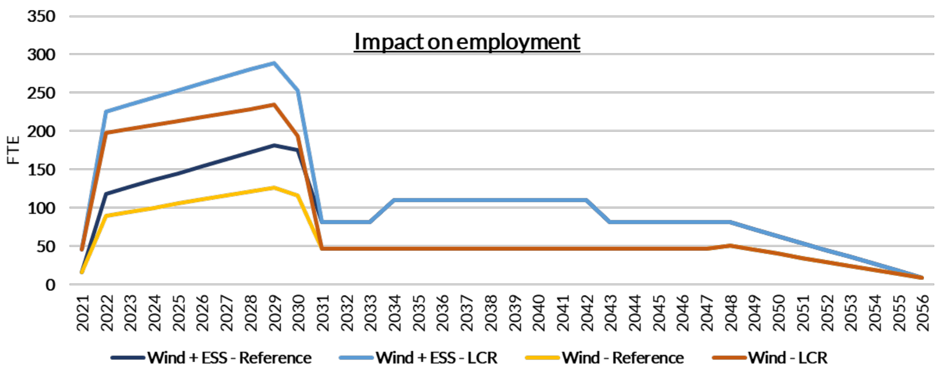


Figure 5.4 Impact on employment in Jeju

Table 5.3 below summarizes the job creation and GRDP contribution under various regional LC.

Table 5.3 Impact on employment

Full time equivalent	**Wind + ESS**		**Wind**	
Regional scenario	Reference	LCR	Reference	LCR
Jobs	3,431	4,402	2,057	3,028

5.3. Discussion

5.3.1. Industrial Impact

Distinct characteristics that separates renewable energy such as wind energy from conventional energy sources is that it does not require constant fuel supply but instead the system requires diverse range of sector coupling technologies such as energy storage system (ESS) for stable power supply. Also, since the operation period is as long as 25 to 30 years, it must mean that the job creation is relatively long-term and stable.

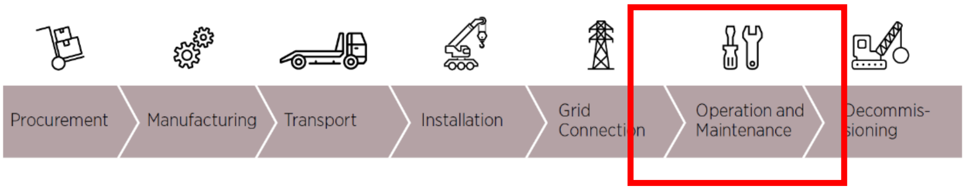


Figure 5.5 O&M phase for onshore wind

*Reference: modified from IRENA (2017)

To understand the impact on employment during operation period indicated in Figure 5.5, impact on employment in O&M phase was developed as shown in Figure 5.6 below.

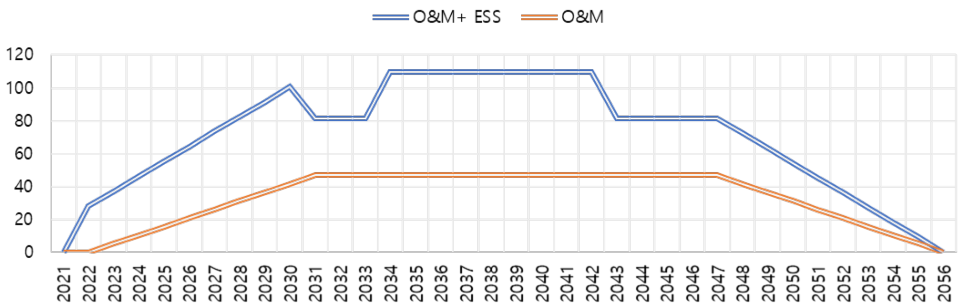


Figure 5.6 Impact on employment in O&M phase

It was found that 1,171 to 2,545 FTE between 2021 to 2056 was created depending on the inclusion of ESS as shown in Table 5.4 below. Around one third of the jobs were associated with supply chain effect and household consumption on service sectors from increased income. It is also indicated in Figure 5.6 that maximum of 110 long-term jobs are created between 2034 and 2044. Currently Jeju province development CO. which manages the Jeju's signature water brand 'Samdasu' as well as 'Jeju Mandarin' is employing around 941 employees[25] including two contingent employees.

Table 5.4 Summary of value-added and employment in O&M phase

O&M phase in Jeju	Wind + ESS/UBESS	Wind
Value added (billion KRW)	205.38	117.75
Value added/MW	0.97	0.56
Value added/billion KRW	0.64	0.57
Jobs (FTE)	2,545	1,171
Jobs/MW	12.06	5.55
Jobs/billion KRW	7.99	5.69

The results were also compared to Jeju's traditional industries with high GRDP contribution rates as shown in Figure 5.7 below. Induced value added of Wind O&M was comparable to construction, restaurant& hotel, agriculture& fisheries industries. Job creation per billion KRW investment of Wind O&M was relatively lower but still higher than Jeju's conventional power industry; Electricity, Gas& Steam.

[25] Jeju Special Self-Governing Province Development Co. (https://www.jpdc.co.kr/open/official/personnel.htm)

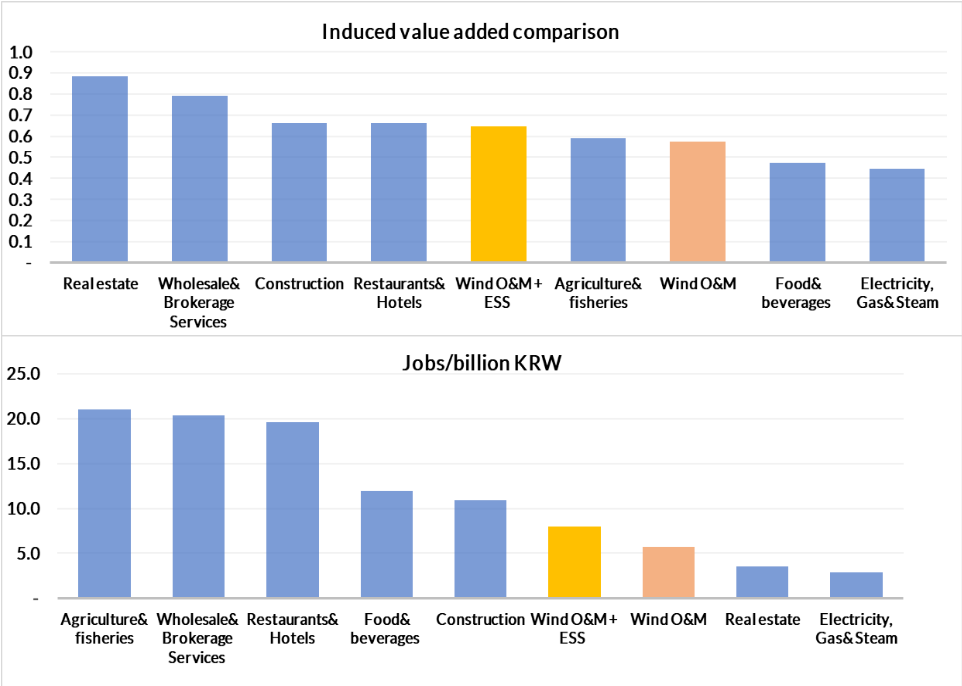


Figure 5.7 Comparison with other regional industries

Jeju's traditional industries, such as agriculture and tourism, face uncertainty. High value-added industries, such as low carbon companies utilizing local resources are required to promote sustainable industrial development and job creation (Ko, 2018; Han & Min, 2021). Wind energy not only utilizes local resources but also integrate new technologies creating jobs in various sectors due to its extensive value chain and dedicated supply chain (Han & Min, 2021). Anticipating the effects of onshore wind power development and identifying key industry sectors can inform policy decisions.

Sankey diagram was developed to identify specific jobs created in Jeju Island during O&M phase. Figure 5.8 below shows that addition of ESS in the operation period more than doubled the total number of jobs. Also, substantial number of jobs were created in service sectors unrelated to onshore wind (26~27%). It can be deduced that with increasing various flexibility options (V2G, heat pump, electrolyser, VPP etc.), renewable energy expansion can potentially create even larger impact.

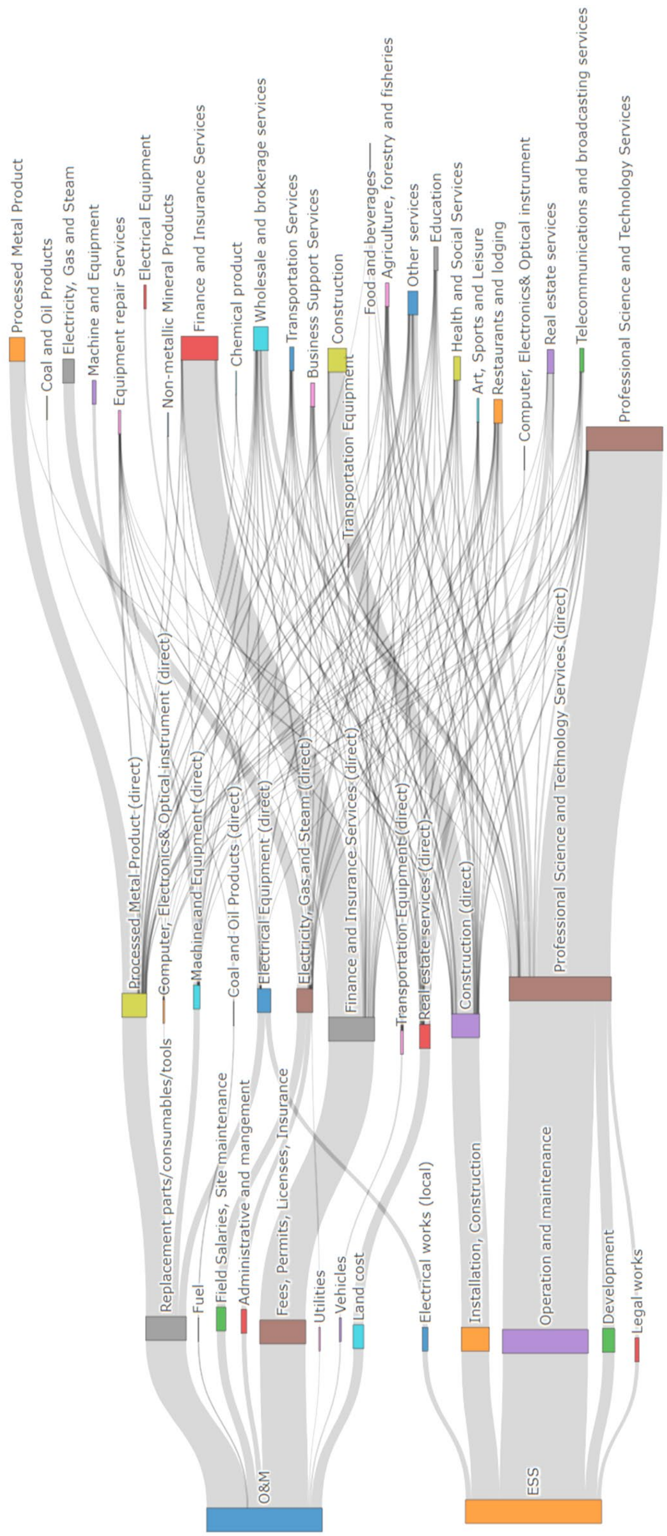


Figure 5.8 Sankey diagram of job creation in O&M phase

5.3.2. Comparison with Conventional Power Source

The impact on employment from Natural Gas power plant in Jeju producing equal amount of electricity produced by 211MW onshore wind for 25 years (408,487,560 kWh) was compared to the findings in previous section. Operation cost of gas-fired combined-cycle power plant is 81.39 KRW/kWh according to KEEI (2018). The full cost information is found in Table A.13 in Appendix-5. It was assumed that the current electricity, gas, and steam sector of 2015 represents natural gas-fired power plant operation. The results shown in Figure 5.9 indicate that expansion of wind energy generates employment opportunities across various sectors compared to Jeju's conventional power plants. The total number of employments under each scenario is shown in Table 5.5 and the employment distribution in different sectors are depicted in Table 5.6.

Figure 5.9 Job creation in O&M phase in Jeju (FTE)

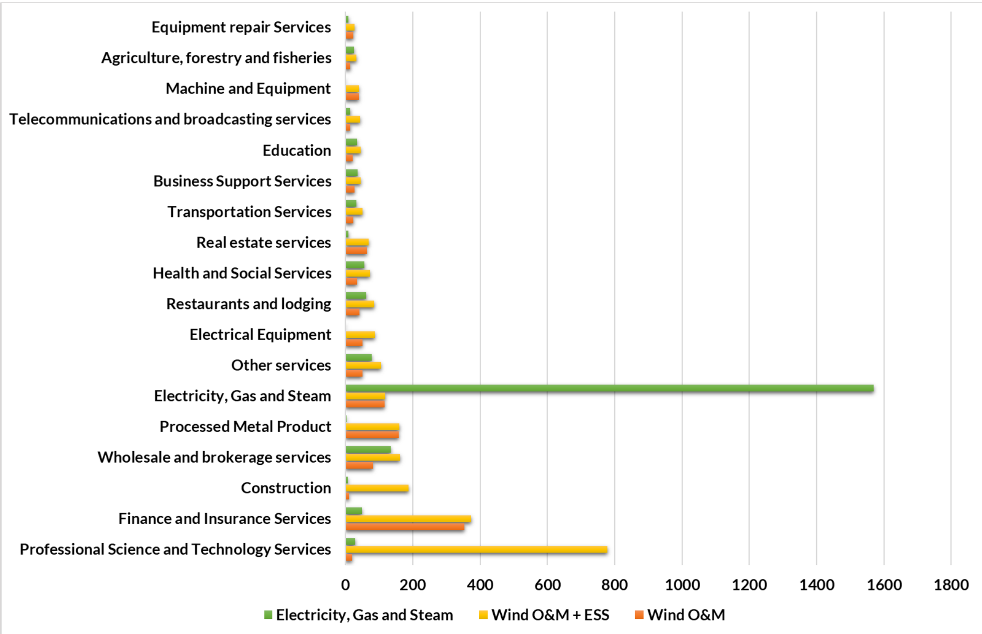


Table 5.5 Job creation comparison (FTE)

Power Source	Total Job creation
211 MW Wind O&M	1,171
211 MW Wind O&M + ESS (389.2 MWh)	2,545
Jeju Conventional	2,171

The results in Table 5.5 and Table 5.6 indicate that including ESS in wind energy operation increases both employment level as well as the diversity of involved sectors as compared to operation of Jeju's natural gas-fired power plant.

Table 5.6 Employment created in top 10 industries

Onshore wind O&M		+ESS		Natural Gas	
1,171 FTE (66~85%)		2,545 FTE (65~84%)		2,171 FTE (89~96%)	
Finance and Insurance Services	30% (353)	Professional Science and Technology Services	31% (778)	Electricity, Gas and Steam	73% (1570)
Processed Metal Product	14% (158)	Finance and Insurance Services	15% (374)	Wholesale and brokerage services	6% (134)
Electricity, Gas and Steam	10% (117)	Construction	7% (188)	Other services	4% (77)
Wholesale and brokerage services	7% (82)	Wholesale and brokerage services	6% (162)	Restaurants and lodging	3% (61)
Real estate services	5% (63)	Processed Metal Product	6% (160)	Health and Social Services	3% (55)
Electrical Equipment	4% (50)	Electricity, Gas and Steam	5% (117)	Finance and Insurance Services	2% (48)
Other services	4% (50)	Other services	4% (106)	Business Support Services	2% (37)
Restaurants and lodging	3% (40)	Electrical Equipment	3% (86)	Education	2% (35)
Machine and Equipment	3% (39)	Restaurants and lodging	3% (86)	Transportation Services	1% (32)
Health and Social Services	3% (33)	Health and Social Services	3% (72)	Professional Science and Technology Services	1% (29)

*Jobs in FTE is indicated inside bracket

Renewable energy relies on a diverse range of suppliers and service providers due to extensive range of value chain activities. The inclusion of ESS further reinforces this trend, as the intermittent nature of renewable energy stimulates industries such as battery storage, heat-pump, and smart grid technology.

The decentralized and non-dispatchable nature of renewable energy operations also necessitates tailored approaches to suit specific locations. This allows for the involvement of small and medium-sized enterprises as well as innovative start-up companies. In the case of Jeju, a renewable energy IT company called VPP lab provides customized maintenance services by predicting the power generation of renewable energy resources. In addition, the company provides a ‘Plus DR’ service for electric vehicles users to consume power and earn revenue when excess power generation is expected.

As the electrification trend continues to grow in various sectors such as heating, cooking, transportation, and industry, various opportunities for renewable electricity utilization in the form of sector coupling will only increase. Sector coupling involves the increased integration of energy end-use and supply sectors with one another (Van Nuffel et al., 2018) as explained in Chapter 2 section 2.1.2.

In contrast, conventional centralized power sources primarily focus on ensuring a stable supply of imported fuels for combustion. Once installed, conventional power sources like gas-fired power plants have limited potential for job creation, as their operations are vertically integrated within specialized departments and supply chains. Power generation, distribution, and sales are often centralized within a single entity, such as a national power utility company (Bank of Korea, 2019).

Hence, the expansion of wind energy is noteworthy due to its capacity to generate employment opportunities across various sectors, distinguishing it from conventional power plants (Hong, 2023, p. 316). Recognizing this aspect of the renewable energy industry, the government has established a specialized classification for the "Renewable Energy Industry," expanding it beyond traditional manufacturing to include construction, supply, and service sectors. As part of this initiative, national statistics on the overall industry status have been surveyed and published since 2020.

However, Ram, Osorio-Aravena, Aghahosseini, Bogdanov, & Breyer (2022) argues that the various categories of the value chain creating job opportunities will present a challenge due to the increasing demand for personnel with diverse skill sets and talents. Consequently, significant efforts in training and education will be necessary to equip the labor market with the required skillsets. The implicated result from the analysis is taking place in reality in Germany where there is significant lack of skilled workforce to install heat pumps, roof-top solar PV and ESS which would put decarbonization goal at risk (Meza, 2022). As stated in EHI (2022), to achieve the REPowerEU targets by 2030, the number of heating system installers will need to rise by 50% compared to the year 2022. Additionally, installers will need to require new competencies such as digitalization, hybridization, electrification, system optimization, knowledge of refrigerants, and handling decarbonized gases. Another area for future research involves exploring the implications of industrial diversification from renewable energy expansion on regional economic competitiveness, growth, and employment stability.

5.3.3. Impact of Local Content

An investment made in Jeju Island affects not just Jeju Island but on other regions and vice versa. For this purpose, the IRIO table that was initially segregated into the 17 Metropolitan cities and Provinces and regions was aggregated to formulate a 2x2 matrix consisting of: Jeju x Rest of Korea. Repeating the analytical procedure using the coefficients of impact on output, value-added and employment in the above matrices as well as local content (%) for Rest of Korea, following demand and supply flows between Jeju Island and Rest of Korea was illustrated as shown in Figure 5.10 below.

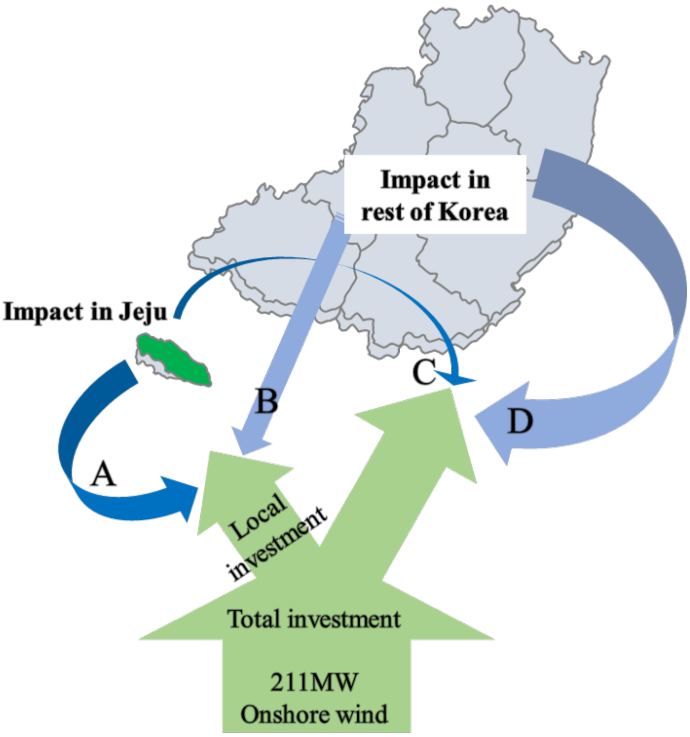


Figure 5.10 Demand and supply flows between Jeju and rest of Korea

The impact of onshore wind energy expansion in Jeju Island and in rest of Korea was quantified under various national and regional local content scenarios as summarized in Table 5.7. It was found that increase in regional local content decreased the total no. of jobs created in the country only marginally by 0.03~0.05%. Increase in national manufacturing increased no. of regional jobs by 0.16~0.34%. Regional local content can therefore be effectively used to resolve local acceptance issues of renewable energy. In any scenario, rest of Korea enjoyed at least 63% of job creation from onshore wind development and the rest remained in Jeju Island.

Table 5.7 Regional and total jobs (FTE)

Local Content		Value chain		
National Scenario	Regional Scenario	Wind	Wind +UBESS	Wind +ESS
20% Manufacture	Reference	2,087 (8,478)	3,478 (13,120)	3,491 (15,193)
	LCR	3,047 (8,473)	4,438 (13,115)	4,452 (15,187)
50% Manufacture	Reference	2,094 (9,623)	3,485 (14,265)	3,498 (16,338)
	LCR	3,055 (9,618)	4,445 (14,260)	4,459 (16,333)

Regional Jobs (Total Jobs)

The relationship between regional and national local content with total lifecycle employment for onshore wind energy coupled with UBESS is illustrated as Figure 5.11 below.

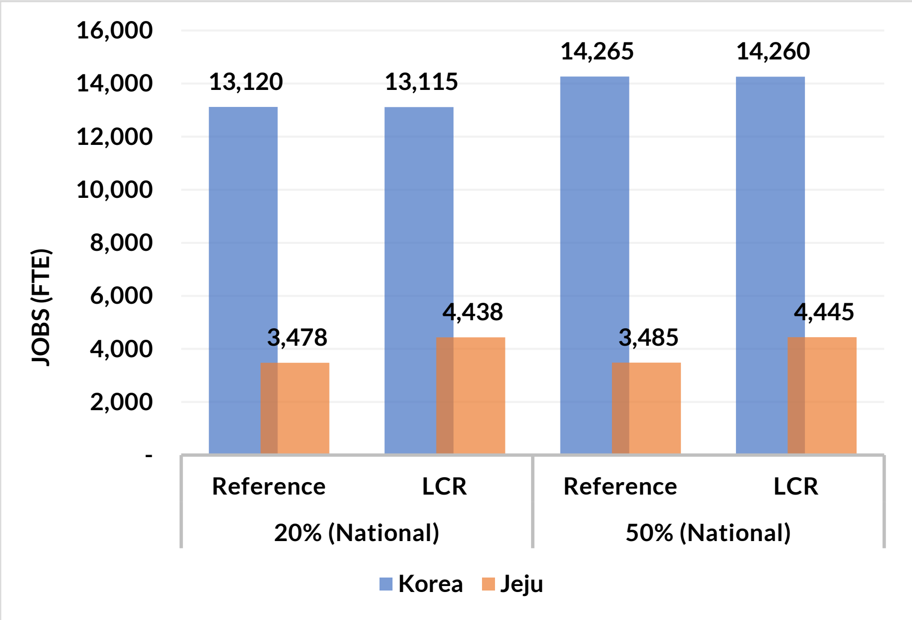


Figure 5.11 Lifecycle job creation (211MW Wind + 389.2 MWh UBESS)

5.4. Conclusion

Chapter 4. focused on assessing the potential carbon emission reduction achieved through the installation and operation of onshore wind farms. Despite its effectiveness in reducing carbon emissions, onshore wind energy encounters conflicts with local residents, leading to a high social interest in regional job creation. Consequently, Chapter 5. examined the economic impact of a 211 MW onshore wind energy project and a UBESS of 389.2 MWh in Jeju Island and the rest of the country, considering various levels of local content.

The installation of 211 MW of onshore wind energy in Jeju Island resulted in an increase in its GRDP ranging from 0.90% to 1.6%, depending on the local content scenario and the inclusion of UBESS. The impact during the operation phase was thoroughly studied, revealing that the induced value added by wind O&M is comparable to that of Jeju’s construction, restaurant and hotel, and agriculture and fisheries industries.

Moreover, renewable energy's extensive value chain activities, involving diverse suppliers and service providers, created employment opportunities across various sectors, even beyond those directly related to onshore wind energy, distinguishing it from conventional power plants. The addition of 211 MW of onshore wind energy represents only 5.2% of Jeju's planned total capacity of 4,085 MW according to the CFI 2030 new& renewable energy deployment target. With the continued growth of electrification in various sectors, the utilization of renewable electricity is expected to increase further. Consequently, finding personnel with diverse skill sets and talents will be a significant challenge.

Furthermore, the study quantified the impact of onshore wind energy expansion in Jeju Island and the rest of Korea under different national and regional local content scenarios. The results indicate that an increase in regional local content has a minimal effect on the total number of jobs created in the country (0.03% to 0.05% decrease), while an increase in national manufacturing leads to a rise in regional jobs (0.16% to 0.34% increase). Regional local content can therefore effectively address local acceptance issues associated with renewable energy.

So far in the literature, the concept of energy system integration, also known as sector coupling, in terms of its impact on regional economies has been rarely discussed quantitatively. Therefore, the study contributes to the academic field by providing a quantitative foundation for understanding the industrial diversification resulting from the expansion of renewable energy.

Chapter 6. The Impact of Renewable Energy in Korea

Chapter 6 builds upon the preceding studies to conduct a comprehensive analysis of the impact of renewable energy expansion across Korea to provide national implications under multi-regional setting. Specifically, the focus is on understanding the relationship between carbon emissions and economic impacts. Therefore, we expand the scope to solar PV and wind installation to the 17 Metropolitan cities and Provinces.

The chapter analyses the impact of roof-top solar PV and onshore wind in the 17 Metropolitan cities and Provinces on carbon emission and job creation under various local content scenarios and flexibility options to establish a relationship between these parameters.

Then the chapter explores the regional distribution impact from roof-top solar PV and onshore wind expansion in Jeju coupled with ESS sourced from different regions. So far, most of the emission mitigation measures relied upon statistics based on production-based emission. However, as elucidated in Chapter 3, it is crucial to evaluate renewable energy expansion from a consumption-based perspective due to the evident disparity between consumption-based and production-based emissions. This will enable to further explore the relationship between carbon emission and jobs in a multi-regional setting which will aid developing effective strategies and optimizing supply chains to encourage sustainable practices (Kim & Moon, 2019; Jiang & Kim, 2022). The specific research questions of Chapter 6. are as followed.

- How does solar PV and wind energy expansion in Korea affect carbon emissions and job creations?
- How does the level of local capacity building and flexibility options impact carbon emissions and spill-over effects?
- How does expansion of renewable energy in Jeju affect other regions?

6.1. Analytical Procedure

6.1.1. Analytical Steps and Assumptions

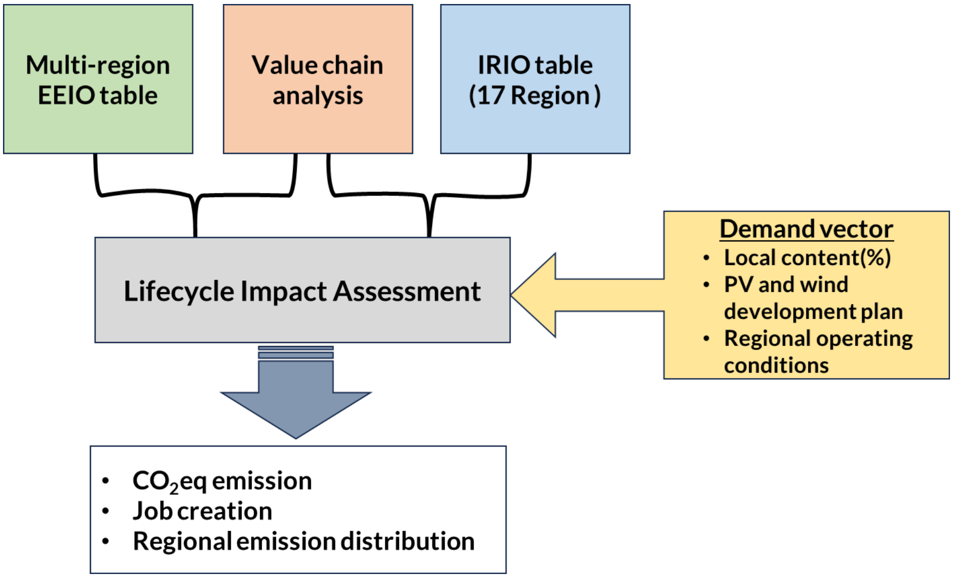


Figure 6.1 Analytical framework of Chapter 6

The impact of onshore wind and solar PV will be analyzed by combining methodologies from previous studies as illustrated in Figure 6.1. The IO-based analytical procedure is detailed in Chapter 3 Data and Methodology.

- Find total jobs and carbon emission created from solar PV and the onshore wind farm throughout the lifecycle under various local content scenario using demand vector derived from cost analysis. Also identify the impact of including energy storage system (ESS)
- By applying regional capacity factor, calculate carbon emission per kWh electricity produced. Compare the results with other conventional power sources of Korea
- Based on Multi-regional EEIO constructed as explained in Chapter 3, formulate consumption-based emission to understand regional emission

distribution from onshore wind and solar PV expansion in Jeju on other 16 Metropolitan cities and Provinces of Korea

- Identify key regions and industries that are affected the most from the impact

Assumptions for this study is as followed. Wind turbine is simplified as onshore wind farm as it is impossible for inland regions to build offshore wind farm for standardized analysis. Industry structure is assumed to be constant throughout the year. Land cost for each region widely differs from one another. Hence the cost of land is taken out of scope in this chapter. For the same reason, cost in dealing with local complaints is taken out of scope.

Local content (%) is an important factor that determines the investment level in each region. The proportion of the investment that can be supplied by companies within the region. However, it is difficult to find an exact value for each region. This research assumes 2 layers of local content 1) National capacity building associated with cultivating manufacturing industry – 20%, 50%, 100%, 2) Regional level capacity building associated with how much the region that supply its products and services without relying on other regions. Local content for cost items and regions based on literature review and consultation with industry professionals. Detailed explanation on local content rates are found in Chapter 3. Moreover, unlike Chapter 5. the impact assessment is limited to direct and indirect effect to focus on the supply chain effect.

6.1.2. Onshore Wind and Solar PV Potential in Korea

The study specifically focuses on onshore wind energy instead of offshore wind due to the availability of reliable cost information gathered from ten years of operation in Korea. Additionally, the study emphasizes the role of renewable energy as DER, considering the special law on distributed energy that limits the capacity of distributed energy sources to below 40 MW. Offshore wind energy tends to have larger scale installations in the GW range, which exceeds the capacity defined by the law. However, future studies may expand the analysis to include offshore wind, both bottom-fixed and floating systems.

Wind power development is relatively more complex and requires lengthy approval processes. This study will focus on 6.7 GW of onshore wind farms that have received development permits under the 9th electricity basic plan between 2020 and 2034. The 9th Power Supply and Demand Master Plan (MOTIE, 2020) is the most recent plan that reflects the Regional Energy Plan updated every five years by the respective Metropolitan Cities and Provinces of Korea. As for Jeju Island, development plan from Jeju CFI (Jeju & KEEI, 2019) is taken into consideration as the region is managed autonomously. The regions selected as research subject and the respective installation capacity is shown in Table 6.1 below.

Table 6.1 Total onshore wind potential

Region	**Total capacity (MW)**
Gangwon-do (GW)	3,267.4
Chungcheongbuk-do (CB)	45.6
Gyeongsangbuk-do (GB)	2,054.0
Jeollabuk-do (JB)	135.0
Jeollanam-do (JN)	1,031.9
Jeju (JJ)	**211.0**
Total	6,744.9

Solar PV has more flexibility in terms of installation sites compared to wind power but has also faced significant public concern when installed in farmland or mountains. Hence, this study limits the solar PV to roof-top solar PV installation specific to buildings in industrial complexes. The utilization of self-solar PV alleviates the need for separate grid interconnection, thus reducing the burden of transmission line installations. Several prominent nations, including the United States (California and Hawaii), Germany, Japan (Tokyo), and France have implemented regulations either mandating or providing tax incentives for solar panel installations on new buildings and residences (SFOC et al., 2023). This would also allow ease of generalization across regions as topology of each region varies dramatically if farmland or mountain installed PV is to be included in the study.

According to the 'Survey of the status of industrial complex' (KICOX, 2022), the total area of national industrial complexes is around 576.2 million m^2 from which a fraction is the building area with an approval of use within 20 years. Following Table 6.2 shows the total industrial complex area, building area (with an approval of use within 20 years), and installation potential of solar PV in the respective area for all the 17 Metropolitan cities and Provinces of Korea. This signifies that 12.3GW of solar PV can potentially be installed without the concern of social acceptance between 2020 and 2034.

Table 6.2 Total roof-top solar PV potential

Region	Total area of industrial facility (Thousand-meter square)	Total area of building (with an approval of use within 20years)	MW
Seoul (S)	2,300	486.819	49.17
Incheon (IC)	13,145	2,782.278	281.04
Gyeonggi-do (GG)	65,560	13,876.466	1,401.66
Daejeon (DJ)	6185	1,309.121	132.23
Sejong (SJ)	5,305	1,122.859	113.42
Chungcheongbuk-do (CB)	36,182	7,658.302	773.57
Chungcheongnam-do (CN)	59,362	12,564.594	1,269.15
Gwangju (GJ)	15,297	3,237.771	327.05
Jeollabuk-do (JB)	47,620	10,079.275	1,018.11
Jeollanam-do (JN)	77,732	16,452.798	1,661.90
Daegu (DG)	22,021	4,660.977	470.81
Gyeongsangbuk-do (GB)	67,095	14,201.365	1,434.48
Busan (BS)	21,763	4,606.369	465.29
Ulsan (US)	58,170	12,312.294	1,243.67
Gyeongsangnam-do (GN)	63,556	13,452.298	1,358.82
Gangwon-do (GW)	14,204	3,006.426	303.68
Jeju (JJ)	**703**	**148.797**	**15.03**
Total	576,200	121,958.810	12,319.07

The combined capacity in each region is visualized as Figure 6.2 below.

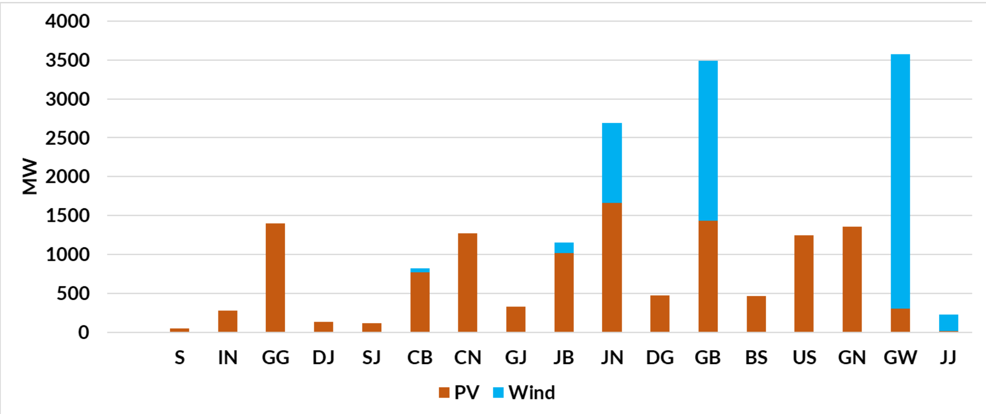


Figure 6.2 Total installation capacity

The study investigates flexibility options within the renewable energy system, with a specific focus on lithium-based energy storage systems (ESS) and their role in supporting the integration of renewable energy. Other infrastructures such as high-voltage direct current (HVDC), heat pumps, P2G or P2L technologies (involving hydrogen, methane, or ammonia), and pumped hydro-storage are not considered in the present study due to their lack of commercial viability in the foreseeable future and reliable cost information.

According to Kong et. al (2019), the optimal capacity ratio of solar PV: ESS and wind: ESS is determined as 1:3.3 and 1:3 (kW:kWh). Input parameters capacity factor and ESS capacity is showed as below.

Table 6.3 Capacity factor and ESS capacity

Power source	**Average capacity factor**	**operation**	**Optimal ESS capacity**
Roof-top Solar PV	14.5%	25 years	1:3.3 (kW:kWh)
Wind	20.9%	25 years	1:3 (kW:kWh)

6.2. Results & Discussion

6.2.1. National Impact of Renewable Energy

The study expanded the scope for solar PV and wind installation to the 17 Metropolitan cities and Provinces amounting to 12 GW and 6 GW respectively and assess the lifecycle impact on total carbon emission and job creation under various local content scenario and with consideration to full value chain. The value chain, cost analysis and respective local content is detailed in Chapter 3.

6.2.1.1. Carbon Emission Coefficient

Carbon emission coefficient of solar and wind energy under various flexibility options were analyzed as Table 6.4 and illustrated as Figure 6.3 below. Without storage for excess power, solar PV's carbon emission coefficient was roughly half of that of onshore wind.

Table 6.4 National average carbon emission coefficient of solar and wind energy (CO_2eq/kWh)

Power source	No ESS	+Used Battery ESS	+ ESS	ESS capacity
Roof-top solar PV	16.14	30.41	44.19	1:3.3 (kW:kWh)
Onshore wind	32.55	36.84	45.54	1:3 (kW:kWh)

This is because roof-top solar requires much less construction works and is less energy consuming O&M than onshore wind. However, solar PV requires larger power storage due to lower capacity factor than onshore wind.

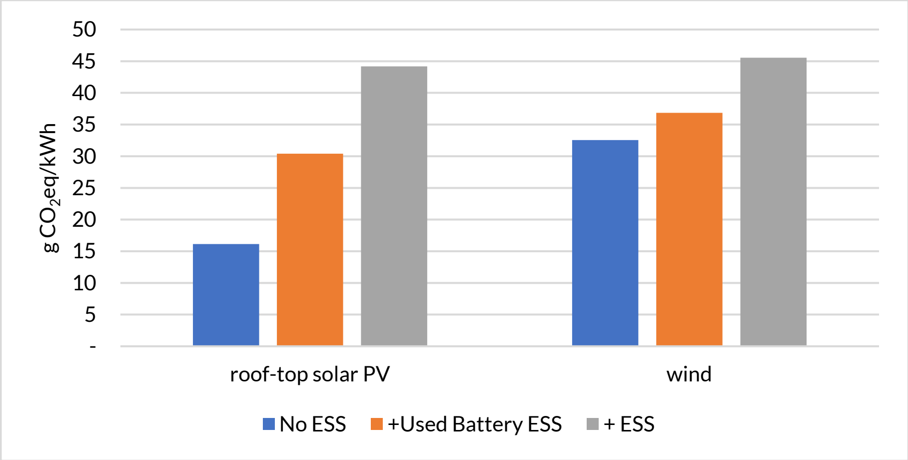


Figure 6.3 Carbon emission coefficient comparison

At country level, there are four main power sources according to 10th electricity supply and demand plan (MOTIE, 2023): Coal-fired, natural gas, nuclear and new& renewable energy. The average carbon emission coefficient from total solar PV and onshore wind installation was compared to conventional power plants as shown in Figure 6.4 below. It was found that solar and wind power can reduce carbon emission by 40.1% ~ 96.8% when they replace 1 kWh of conventional power production depending on the source.

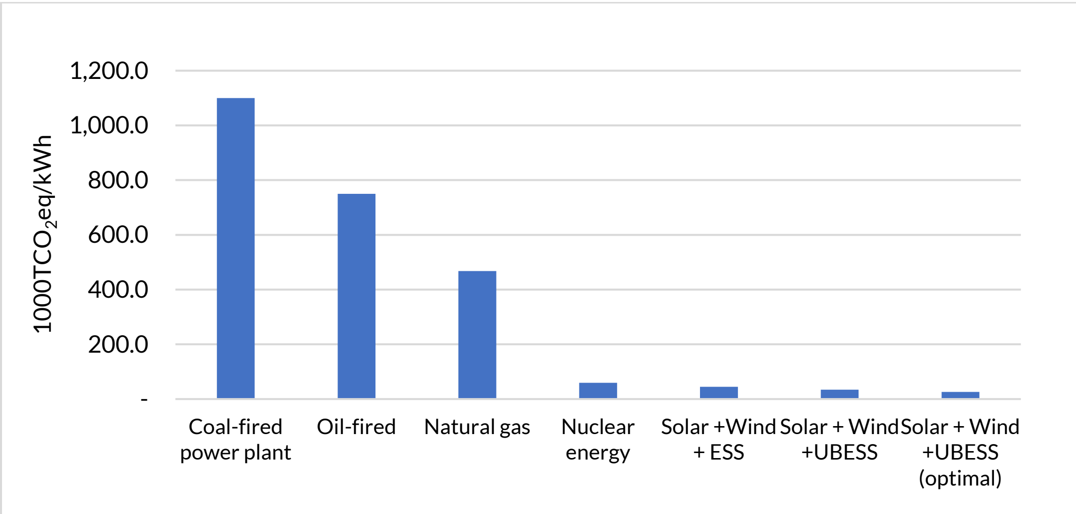


Figure 6.4 Average carbon emission coefficient

6.2.1.2. Impact of Local Content

Increase in national manufacturing increased total jobs but also carbon emission associated with increased manufacturing. Moreover, including ESS increased the carbon emission coefficient by twice the amount. Addition of UBESS increased total jobs but also reduced carbon emission by around 10 gCO_2eq/kWh compared to ESS. The results are summarized in Table 6.5 below.

Table 6.5 Impact on carbon emission and total job creation

Impacts	**20%**	**50%**	**100%**
CO_2eq/kWh (RE)	17	19	23
Total Jobs (RE)	313,639	339,630	383,414
CO_2eq/kWh (RE+UBESS)	29	30	33
Total Jobs (RE+UBESS)	1,030,450	1,056,442	1,100,226
CO_2eq/kWh (RE+ESS)	40	42	45
Total Jobs (RE+ESS)	1,249,387	1,275,378	1,319,162

Hence, local content can be increased for industrial competitiveness, but it will also increase carbon dioxide emissions. There exists a trade-off between these two factors as illustrated in Figure 6.5 below, and the outcome will depend on the specific choice made.

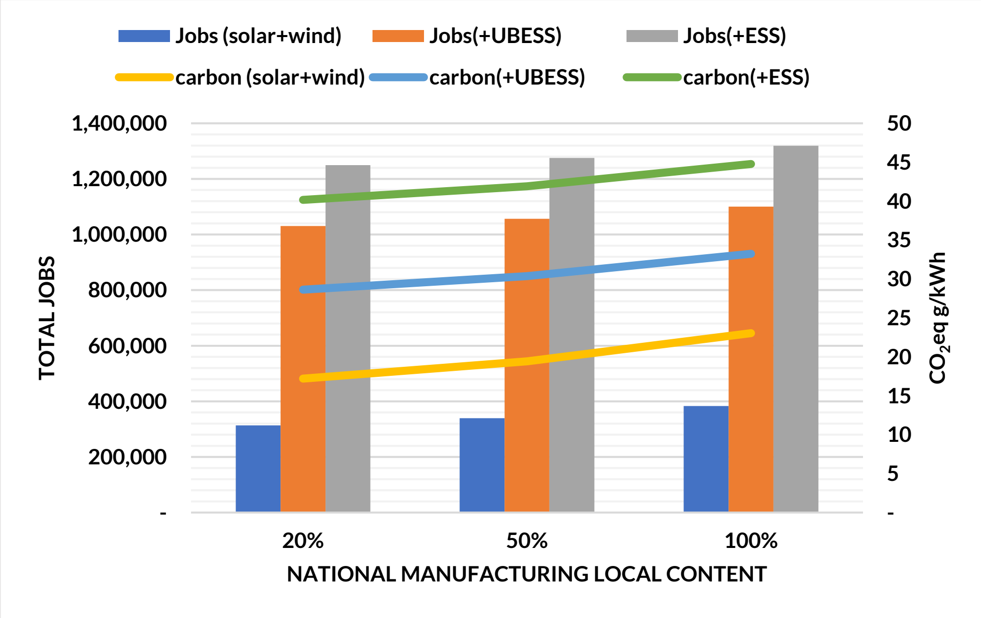


Figure 6.5 Jobs and carbon emission

However, it is crucial to evaluate the impacts from a multi-regional perspective. Examining the regional distribution of carbon emissions and job creation, taking into account variations in natural resources and industry structures across regions, can offer valuable insights for further comprehending the interplay between carbon emissions and economic impact. This understanding can assist in formulating effective strategies for carbon reduction while considering job creation.

6.2.2. Regional Distribution Effect of Carbon Emission

As discussed in Chapter 3, section 3.3.4, due to clear disparity between consumption-based and production-based emission, production-based policies, such as regulating production facilities, are inadequate in effectively mitigating pollution. Therefore, it is important to consider the perspective of a consuming region that rely on related products.

The operation of renewable energy systems necessitates flexibility options like Energy Storage Systems (ESS) sourced from other regions. Given this context, it becomes crucial to examine how carbon emissions are distributed in different regions caused the renewable energy consumption in Jeju. The results can enable developing effective emission mitigation strategies and optimizing supply chains to encourage sustainable practices (Kim & Moon, 2019; Jiang & Kim, 2022).

The case was specified for Jeju where electricity produced by 225MW onshore wind and solar PV power plant coupled with ESS in Jeju in a single year is 426,988,680 kWh. The value chain for renewable energy was limited to operation phase (O&M) and the local content was fixed to 50% national manufacturing. Optimal capacity of ESS was chosen instead of UBESS to identify the upper limit of the impact of ESS installation.

There are three types of ESS production depending on the region of production: CN (‘A’ company), CB (‘B’ company), US (‘C company’). To analyze how the origin of ESS production affects the carbon emission distribution, three RE scenarios were developed accordingly as depicted in the Table 6.6 below. The Final Demand in billion KRW in Table 6.6 indicates the cost expenditure required to operate the 225MW onshore wind and solar PV power plant for one year.

Table 6.6 Final demand by RE scenario

Power source	Jeju Final Demand	Electricity Production
(1) RE +ESS (CN)	32.3	426,988,680 kWh
(2) RE +ESS (CB)	32.3	
(3) RE +ESS (US)	32.3	
RE	13.6	

RE= Renewable Energy, Unit: billion KRW

Final demand for a particular scenario (1) RE +ESS CN is shown as Table 6.7 below. The cost is assigned to each region depending on the onshore wind and solar PV value chain and local content as explained in Chapter 3.

Table 6.7 225MW RE + ESS (CN)

Region	Industry	Jeju Final Demand
CB	Inverter replacement	0.04
CN	Battery manufacturing	9.11
	ESS installation, construction	1.17
	Development	3.78
GN	Wind turbine replacement parts/consumables/tools	1.76
JJ	Electrical works, Vehicles	3.58
	ESS installation, Construction	1.82
	O&M	10.94
	Fuel	0.09

Unit: billion KRW

The regional carbon emission produced when renewable energy of 225MW operation takes place in Jeju is calculated as Table 6.8 and illustrated as Figure 6.6 and Figure 6.7 below under 4 RE scenarios. Each scenario triggered different level of emissions in different regions.

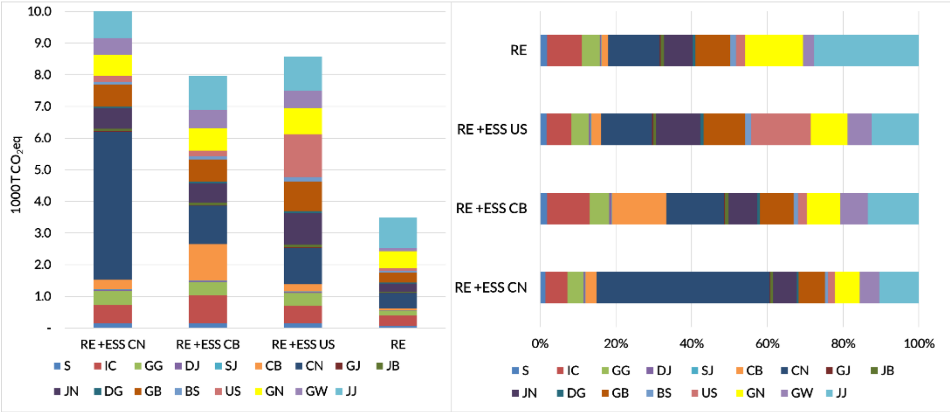


Figure 6.6 Regional composition of the consumption-based carbon emission due to Jeju's final demand

As evident, most of the emissions was generated outside of Jeju, indicating that while operating renewable energy (RE) would reduce the carbon emissions originating from conventional natural gas-fired power plants, it concurrently leads to an increase in carbon emissions in other regions as renewable energy expands in Jeju. Figure 6.6 on the right side illustrates the proportion of emissions, attributed to each region, that were stimulated by domestic final demand in various RE scenarios. For the 'RE' scenario, the highest emissions were observed from direct emissions produced by industries in Jeju. For three scenarios with ESS, highest percentage of emission was induced from the region that sourced the ESS.

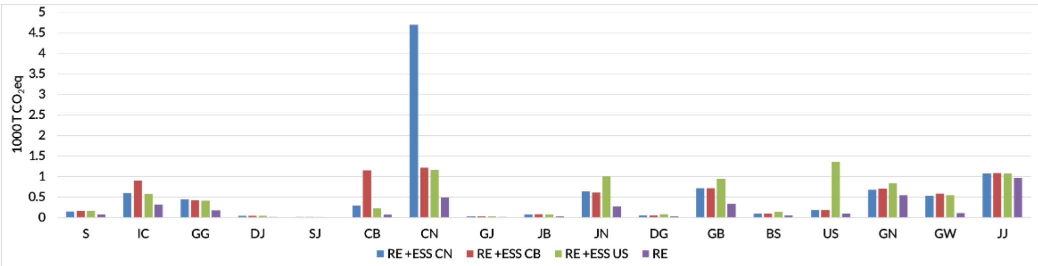


Figure 6.7 Carbon emission by region

Table 6.8 Regional distribution of carbon emission (1000T CO_2eq)

Region	RE +ESS CN	RE +ESS CB	RE +ESS US	RE
S	0.1	0.2	0.1	0.1
IC	0.6	0.9	0.6	0.3
GG	0.4	0.4	0.4	0.2
DJ	0.0	0.0	0.0	0.0
SJ	0.0	0.0	0.0	0.0
CB	0.3	1.1	0.2	0.1
CN	4.7	1.2	1.2	0.5
GJ	0.0	0.0	0.0	0.0
JB	0.1	0.1	0.1	0.0
JN	0.6	0.6	1.0	0.3
DG	0.1	0.1	0.1	0.0
GB	0.7	0.7	0.9	0.3
BS	0.1	0.1	0.1	0.1
US	0.2	0.2	1.3	0.1
GN	0.7	0.7	0.8	0.5
GW	0.5	0.6	0.5	0.1
JJ	1.1	1.1	1.1	1.0
SUM	10.23	7.96	8.56	3.49

Notable points can be drawn from above results. First, it becomes evident that as flexibility options are introduced, the proportion of emissions induced in other regions increases. Regions with a strong manufacturing base are expected to experience an increase in emissions mainly due to increased electricity demand from industrial activities. Therefore, expanding renewable energy in such regions is necessary. Second, ESS produced from CN caused largest total carbon emission, indicating that ESS production in CN is most carbon intensive. Third, all scenarios had strong dependency on CN for consumption-based emissions which indicates comparatively strong economic ties.

The carbon intensity of CN's ESS production is primarily caused by its reliance on coal-fired power generation in CN followed by the emission related to primary metal production supplied in manufacturing the ESS as indicated as carbon emission coefficients in Table 6.9 below.

Table 6.9 Carbon emission coefficient (1000T CO_2eq/billion KRW)

Sectors	IC	GG	CB	CN	US
Primary Metal Products	0.05	0.02	0.06	1.39	0.1
Electricity, Gas & Steam	2.9	1.24	0.23	7.46	0.99

In contrast, CB and US consumes electricity with lower carbon intensity either produced within or outside the region as shown in Figure 6.8 below. However, the reason for the increase in emissions in CN from both CB's and US's ESS production is due to outsourcing of electricity and carbon-intensive primary metal products required for ESS manufacturing from CN. Hence, the growing demand for ESS in CB and US consequently leads to an increased demand for CN's electricity and primary metal products, resulting in substantial emissions in CN.

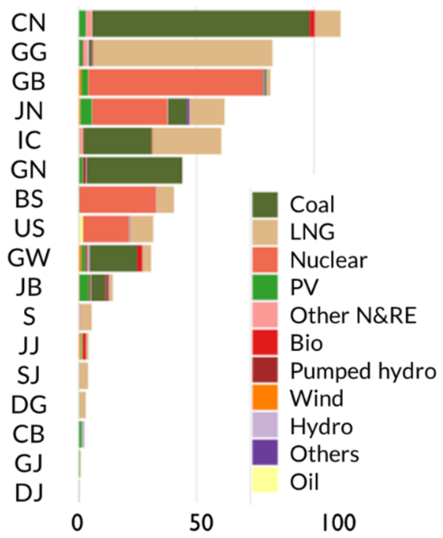


Figure 6.8 Power generation by region in Korea 2021 (KEPCO)

To ensure a more sustainable approach, it is crucial to prioritize cleaner electricity and sustainable primary metal production in the overall ESS manufacturing process. This entails minimizing carbon emissions by refraining from importing ESS from CN, unless the region undergoes an energy transition.

By adopting consumption-based emission perspectives, suppliers and production methods that minimize environmental impact can be selected, leading to a more sustainable supply chain. These perspectives serve as incentives for corporations to adopt sustainable practices such as RE100, especially when there is joint engagement with the municipality.

Changes in regional jobs were analyzed under the same settings as Figure 6.9 and Figure 6.10 below.

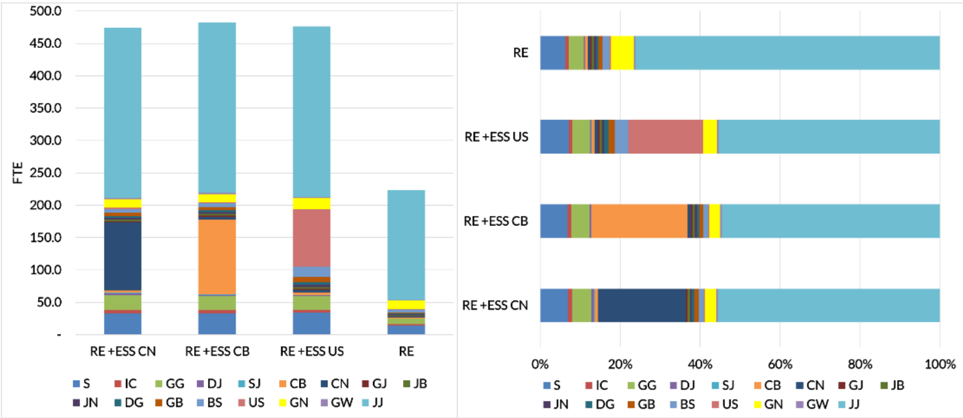


Figure 6.9 Regional composition of the consumption-based job creation due to Jeju's final demand

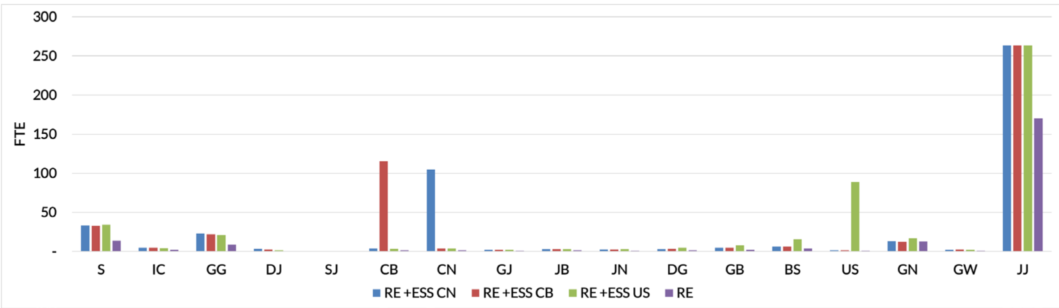


Figure 6.10 Job creation by region

Although there exists a direct correlation between the level of emissions and job creation, where both are generated in ESS production, the job creation is slightly larger in CB compared to CN and US. This suggests that outsourcing ESS from CB can be preferable in terms of job creation and minimizing carbon emissions. Contrary to emission changes observed, there is job creation in Seoul and Gyeonggi when renewable energy, coupled with ESS, operates in Jeju. This is primarily due to the increased demand for service sectors such as commercial, professional, and transportation in S and GG which have a relatively significant employment-inducing effect. This analysis indicates that carbon-emitting industries do not necessarily entail a trade-off with economic impacts, such as job creation.

It is also important to note that renewable energy expansion benefits Jeju with more jobs and less carbon emission compared to the rest of the 16 Metropolitan cities and Provinces. This can be deduced from the fact that service-related sectors have higher job induced coefficient and lower carbon emission coefficients.

This analysis was limited to operation phase, not taking account of the impact of manufacturing, construction, and installation part of the value chain. Hence the study can be improved in the future by expanding to the entire lifecycle which requires further information on cost and local content of various energy sources which was beyond the scope of the thesis.

Indeed, there is a trade-off associated with increasing local content, which can result in higher emissions within the national boundary. However, by aligning clean energy production with clean industry practices, it is possible to minimize the impact of emissions while simultaneously ensuring national competitiveness and revitalizing the regional economy.

6.3. Conclusion

This chapter built upon preceding studies and provided a comprehensive analysis of the impact of solar PV and onshore wind expansion throughout Korea. The analysis utilized IRIO, EIO-LCA, and consumption-based emission accounting.

The installation of solar and wind power totaling 19GW, which accounts for nearly 10% of total national electricity generation, generated a total employment range of 313,639 to 383,414 (FTE) jobs nationally, depending on the local content. When the optimal capacity of ESS was included, the job creation increased to 1,249,387 to 1,319,162 FTE jobs, approximately 3.4 to 4.0 times the number of jobs created without ESS. This demonstrates the significant impact of sector coupling in effectively utilizing renewable energy, benefiting both the regional and national economy.

However, while sector coupling resolves curtailment issues, the inclusion of flexibility options can increase carbon emissions, contradicting the primary goal of renewable energy expansion. Therefore, developers must be aware of this consequence and consider employing a diverse range of sector coupling options that do not require significant infrastructural development. Additionally, increasing the local content rate can enhance industrial competitiveness, but it can also lead to increased carbon dioxide emissions. There is a trade-off between these two factors, and the outcome depends on the specific choices made.

To assess the impacts from a multi-regional perspective and understand the regional distribution of carbon emissions and job creation, the case of Jeju was examined in-depth. The analysis focused on the operation phase of the renewable energy value chain under constant local content. Three scenarios were developed to analyze how the origin of ESS production, affects the distribution of carbon emissions. When flexibility options were introduced, such as ESS, the proportion of emissions induced in other regions increased. Regions with a strong manufacturing base are expected to experience an increase in emissions mainly due to increased electricity demand from industrial activities. Therefore, expanding renewable energy in such regions is necessary.

ESS produced in CN resulted in the largest emissions due to heavy reliance on coal-fired power generation. The results would enable the selection of suppliers and regions that minimize environmental impact, promoting a more sustainable supply chain. These perspectives serve as incentives for corporations to adopt sustainable practices such as RE100, especially when joint engagement with the municipality occurs. The implementation of the 'Distributed Energy Enablement Special Act' will further enhance these incentives.

Combining the analysis on changes in regional jobs, it was apparent that there exist a direct relationship between the level of emissions and job creation in certain regions. However, this does not necessarily imply a trade-off between carbon emission reduction and economic impacts, as the increased demand for service sectors in regions like S and GG has a relatively significant employment-inducing effect while inducing low carbon emissions. Also, ESS produced in CB incurred higher total jobs but with substantially less carbon emission.

This study represents as the first attempt to apply the concepts of consumption-based accounting to renewable energy coupled with flexibility resources, aiming to understand the regional distribution of carbon emissions, jobs, and their trade-off. However, the analysis is limited to the operation phase and can be expanded to cover the entire lifecycle, requiring further information on the cost and local content of various energy sources, which falls beyond the scope of this thesis.

Overall, increasing local content and flexibility options as it can result in higher emissions within the national boundary. However, aligning clean energy production with clean industry practices allows for the minimization of emissions impact while ensuring national competitiveness and revitalizing the regional economy.

Chapter 7. Conclusion

7.1. Summary and Implications

Drastically reducing carbon emissions from energy use is imperative to ensure a sustainable future for upcoming generations. However, this poses a significant challenge for countries reliant on energy-intensive industries and imported fossil fuels. With the introduction of targets set by NDC, the RE100 initiative, and the European Union's CBAM, this challenge can no longer be overlooked, necessitating in-depth discussions.

Renewable energy sources such as wind and solar power, which exclusively rely on natural resources, emerged as leading clean energy alternatives due to their negligible carbon dioxide emissions during electricity generation. Replacing fossil fuels with these renewable sources offers substantial potential for emissions reduction. To responsibly minimize carbon emissions, it is essential to consider the emissions associated with renewable energy industries, encompassing full value chain as well as flexible resources, and propose strategies to maximize the efficacy of carbon reduction.

Moreover, renewable energy, being distributed energy source hence situated within proximity to residential areas, raised concerns regarding acceptability and generated significant public interest in the impact of renewable energy expansion on local economies. Recent global trade disputes related to green protectionism, such as the IRA in the United States, NZIA in the European Union, and the LCR, which favored domestic products like renewable energy, batteries, and electric vehicles, heightened the focus on enhancing the competitiveness of national renewable energy industries due to the anticipated job creation potential.

This thesis analyzed the impact of renewable energy expansion on carbon emissions and regional economy, considering the inherent characteristics of the renewable energy system such as the 1) lifecycle value chain, 2) capacity building,

3) regional characteristics such as natural resources, and industrial structure. By doing so, it proposed carbon emission reduction measures to ensure a sustainable future for generations to come. The study is divided into three main parts.

The first essay assessed the lifecycle carbon emissions resulting from the expansion of onshore wind power in Jeju Island utilizing EIO-LCA based on cost analysis and the national EEIO analysis.

Throughout the lifecycle, battery manufacturing was found to be the single largest source of carbon emission followed by manufacturing of turbine elements during its first installation, as well as component replacement during the entire lifecycle. The carbon gas emission per kilowatt-hour (kWh) of the 211MW onshore wind farm was estimated to be 28.8 g CO_2eq/kWh without ESS and 43.0 g CO_2eq/kWh with ESS under a capacity factor of 22.1%. The results highlighted the significance of carbon emission of flexibility options and the importance of employing various mitigation efforts such as reusing batteries from electric vehicles. The recently announced exemption of waste regulations for electric vehicle batteries and iron scrap is expected to promote the reuse of imported batteries. However, it is necessary to actively utilize flexible resources such as DR and V2G that require relatively little additional infrastructure construction. In addition, sensitivity analysis revealed that maximizing greenhouse gas emission reduction potential requires improving engineering features such as increasing both the capacity factor and operational period of onshore wind farms.

Based on backward purchases analysis, most notable carbon emission contributors were identified 1) ‘Electricity, gas and steam’ supply, 2) ‘Primary metal products’ (Steel production) 3) ‘Non-metallic mineral products’ (Cement production). Thus, decarbonization of electricity generation and manufacturing sectors is fundamental to net-zero renewable energy systems, particularly in the metal production (steel) and cement industry. These transformations can involve electrification or the utilization of renewable-based fuels and feedstocks which ultimately emphasize the need for more renewable energy sources. The circular economy concept should be emphasized beyond the reuse of batteries by including recycling the waste from end-of-use wind farms to further reduce environmental pressure. Under the current status, onshore wind's carbon mitigation potential with that of fossil-fuel-based generation plants in Jeju showcased a reduction of 92-97% in emissions per kWh electricity produced.

The second essay assessed the impact of onshore wind power expansion on Jeju Island's regional economy based on cost analysis and IRIO analysis. The study examined the economic impact of a 211 MW onshore wind energy project and a UBESS of 389.2 MWh in Jeju Island and the rest of the country, considering various levels of local content.

The installation of onshore wind energy in Jeju Island resulted in an increase in its GRDP ranging from 0.90% to 1.6%, depending on the local content scenario and the inclusion of UBESS. The impact during the operation phase was thoroughly studied, revealing that the induced value added by wind O&M is comparable to that of Jeju's construction, restaurant and hotel, and agriculture and fisheries industries.

Moreover, renewable energy's extensive value chain activities, involving diverse suppliers and service providers, created employment opportunities across various sectors, even beyond those directly related to onshore wind energy, distinguishing it from conventional power plants. The addition of 211 MW of onshore wind energy represents only 5.2% of Jeju's planned total capacity of 4,085 MW according to the CFI 2030 new& renewable energy deployment target. With the continued growth of electrification in various sectors, the utilization of renewable electricity is expected to increase further. Consequently, finding personnel with diverse skill sets and talents will be a significant challenge.

Furthermore, the study quantified the impact of onshore wind energy expansion in Jeju Island and the rest of Korea under different national and regional local content scenarios. The results indicate that an increase in regional local content has a minimal effect on the total number of jobs created in the country, while an increase in national manufacturing leads to a rise in regional jobs. Hence, regional local content can effectively address local acceptance issues associated with renewable energy.

The third essay built upon preceding studies and provides a comprehensive analysis of the impact of solar PV and onshore wind expansion throughout Korea utilizing IRIO and multi-regional EIO-LCA, with a focus on understanding the relationship between carbon emissions and economic impacts.

The installation of solar and wind power totaling 19GW, which accounts for nearly 10% of total national electricity generation, generated a total employment range of 313,639 to 383,414 (FTE) jobs nationally, depending on the local content. When the optimal capacity of ESS was included, job creation increased 3.4 to 4.0 times. This demonstrates the significant impact of sector coupling in effectively utilizing renewable energy, benefiting both the regional and national economy.

However, while sector coupling resolves curtailment issues, the inclusion of flexibility options can increase carbon emissions, contradicting the primary goal of renewable energy expansion. Therefore, developers must be aware of this consequence and consider employing a diverse range of sector coupling options that do not require significant infrastructural development. Additionally, increasing the local content rate can enhance industrial competitiveness, but it can also lead to increased carbon dioxide emissions within the country. There is a trade-off between these two factors, and the outcome depends on the specific choices made.

To assess the impacts from a multi-regional perspective and understand the regional distribution of carbon emissions and job creation, the case of Jeju was examined in-depth. The analysis focused on the operation phase of the renewable energy value chain only under constant local content. Three scenarios were developed to analyze how the origin of ESS production, affects the distribution of carbon emissions. In addition, ESS produced in Chungcheongnam-do resulted the largest emissions due to the heavy reliance on its coal-fired power generation and carbon-intensive primary metal production. The results would enable the selection of suppliers and regions that minimize environmental impact and serve as incentives for corporations to adopt sustainable practices such as low carbon technology R&D and RE100, and closely engage with the municipality. The implementation of the ‘Distributed Energy Enablement Special Act' is expected to strengthen these incentives by allowing distributed energy providers to directly supply electricity to users within the region. This will enable users to choose their electricity providers, thereby promoting the expansion and effective utilization of renewable energy. It is crucial to conduct further analysis in the future to examine the implications of these legal and institutional changes.

Combining the analysis on changes in regional jobs, it is evident that there is a direct relationship between the level of emissions and job creation in certain regions. However, this does not necessarily imply a trade-off between carbon emission reduction and economic impacts, as ESS produced in Chungcheongbuk-do resulted larger job creation than ESS from Chungcheongnam-do. Also, the increased demand for service sectors in regions like Seoul and Gyeonggi induced larger employment effect while with lower carbon emissions.

In conclusion, this study emphasized the integration of renewable energy expansion with sustainable industrial activities. While renewable energy presents advantages, it also entails complexities due to intermittency and distributed nature, especially in regions with limited grid connectivity. Sector coupling technologies play a crucial role in such areas, but they can have significant environmental and economic impacts. By aligning clean energy production with sustainable industry practices through identifying regional carbon emissions and job distribution in advance, sustainable production and supply chain strategies can be developed to mitigate emissions while simultaneously ensuring national competitiveness and revitalizing the regional economy.

The knowledge gained from this research can be extended internationally, particularly to emerging countries in Asia. These countries will increasingly face challenges in managing intermittent renewable energy due to poor electric grid infrastructure along with energy-intensive industries despite high renewable energy potential. For instance, Vietnam is recently experiencing curtailment issues, while Singapore has installed the largest energy storage system in Southeast Asia. In the future, there will be a growing need for flexible resources and sector coupling.

Korea's experience in renewable energy system coupled with low carbon flexibility options can contribute to supporting these countries in their transition towards clean energy transition, paving a way for a sustainable future for generations to come.

7.2. Policy Recommendations for Jeju

Chapter 4, 5 and section 6.2.2 of Chapter explored different characteristics of renewable energy system and suggested implications regarding renewable energy expansion in Jeju. Based on the findings, this section intends to propose recommendations for Jeju's energy transition policy.

In addressing the issue of curtailment in Jeju, there exist differing opinions on the expansion of LNG power plant which is indicated in the 10^{th} basic electricity demand supply plan. Supporters argue that the current policy and technological circumstances make it difficult to promptly prepare flexible resources for peak-time adjustments. Given that Jeju Island can be considered as an isolated power grid akin to the Korean Peninsula, it faces particular challenges in short-term resource readiness. On the other hand, opponents contend that natural gas-fired power plant expansion would further solidify the dominance of fossil fuel generation within the system, exacerbating curtailment challenges. Hence Jeju should maximize the availability of ESS along with other flexibility resources (SFOC, Climate Analytics, 2023). The decision regarding this matter will carry a profound and lasting impacts at least for decades. Building upon the findings of this study, following recommendations can be made in the context of sustainable development.

First, in the pursuit of carbon emission reduction, it is crucial to ensure that the installation of natural gas generation does not impede the progress of renewable energy development and electricity generation. As Chapter 4 discovered, it would substantially produce more carbon emission than solar PV or wind energy.

Second, priority should be given to flexibility resources, such as demand response (DR) and vehicle-to-grid (V2G), which does not require extensive infrastructure expansion hence minimize carbon emission as compared to ESS. In Jeju, there exists significant lack of electricity during peak hours, typically in the evening when solar PV does produces very little while there is high electricity demand. Implementing measures to disperse this demand during peak hours can greatly contribute to carbon emission reduction. Hence, it is essential to address institutional challenges as a higher priority compared to facility expansion. Some suggest the need for tariff differentiation and an independent entity separate from the Korea Electric Power Corporation (KEPCO).

Third, consideration should be given to the manufacturing location of energy storage systems (ESS) and the environmental sustainability of their supply chains as discussed in Chapter 6. Providing incentives to promote decarbonization efforts in the manufacturing industry sector will facilitate the successful emission reduction not only in Jeju but also beyond. 'Distributed Energy Enablement Special Act', which will designate Jeju as a specialized area for distributed energy, allows for a free market for electricity transactions between producers and consumers. It is anticipated that the commercialization of diverse energy technologies will activate a new industrial ecosystem.

Last, from an economic standpoint, the installation of flexibility resources has the potential to generate significant employment opportunities as explored in Chapter 5. However, it is vital to develop a workforce with diverse skillsets in this field. In Germany, the lack of skilled workers for installing heat pumps, rooftop solar PV, and energy storage systems (ESS) poses a risk to decarbonization goals (Meza, 2023) and requires a 50% increase in heating system installers, with upgraded competencies in order to meet the REPowerEU targets by 2030 (EHI, 2022). Hence, it is important for Korea to establish educational and training programs that can adequately prepare individuals for the challenges and opportunities in this sector.

Accumulating experience in operating low-carbon sector coupling in Jeju Island can serve as a positive influence, not only on the Korean Peninsula but also on Asian developing economies. By sharing best practices, Jeju can contribute to promoting sustainable and decarbonized energy systems on a broader scale.

7.3. Research Contribution and Limitations

The study aimed to analyze the impact of renewable energy expansion by considering inherent characteristics of the renewable energy system, such as the lifecycle value chain, national and regional industry competitiveness, regional natural resources, and industrial structure. This research differentiates itself from existing studies in several ways.

One significant aspect of this research is its quantitative analysis of the impact of energy system integration, specifically renewable energy coupled with flexibility options, which is a topic that has been scarcely explored in the existing literature. As the penetration of renewable energy increases, flexibility options are essential for stable operation due to intermittency, and the absence of such options poses challenges in the form of curtailment. Although this study focused solely on energy storage systems (ESS), future research should encompass a broader range of flexibility options, such as heat storage, demand response (DR), transmission networks, and the hydrogen economy. The scale and type of flexibility options will depend directly on the regional economic structure and energy demand.

The research analyzed the regional distribution of carbon emissions resulting from renewable energy expansion and explored integrated carbon reduction strategies that consider both production and consumption perspectives. The study aimed to understand the regional distribution of carbon emissions, jobs, and associated trade-offs, leading to the development of effective strategies for sustainable practices. Expanding the current model to a global scale and incorporating international trade of goods and services would enhance its usefulness in the future.

Moreover, while it is recognized that the extensive value chain of renewable energy creates job opportunities across various sectors, there is a limited presence of quantitative discussions on the regional economic impact in the existing literature. This study aims to fill this gap by providing a quantitative foundation for understanding the industrial diversification resulting from the expansion of renewable energy, distinguishing it from conventional power plants. Future research could explore the implications of industrial diversification on regional economic competitiveness, growth, and employment stability.

This study is among the first in Korea to utilize IRIO analysis, assessing the economic and environmental impacts of renewable energy expansion at a regional and national level. In addition, unlike previous research, this study establishes a multi-regional EEIO table with regional carbon emission coefficients, providing a more accurate dataset. The findings have the potential to support the development of an open-source empirical tool, for estimating the impact of solar and wind energy systems on carbon emissions and economic outcomes. Such a tool could aid practitioners and local authorities in making data-driven decisions and identifying opportunities and challenges in renewable energy planning. While scenario analysis was not included, the developed emission and economic impact coefficients can serve as a foundation for future research.

However, it is important to note that the analysis in this study has a limitation due to the use of fixed input-output (IO) tables which do not consider changes in price, cost, and the power mix over time. Future studies should aim to improve the model by incorporating dynamic IO tables that account for these factors to provide a better understanding of the economic and environmental impacts of renewable energy expansion.

It is sincerely hoped that future researchers will continue to explore these research topics and improve upon the limitations identified in this thesis to provide more effective strategies for reducing carbon emissions for our future generations.

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Appendix

1. New& Renewable Energy Classification

Table A.1 Classification of new& renewable energy

Category	Energy Source	Details	Korea	IEA
New Energy	Hydrogen Energy		○	X
	Fuel Cell		○	X
	Liquified or gasified coal and gasified vacuum residue		○	X
	Other new energy		○	X
Renewable Energy	Solar	Solar PV, Solar thermal	○	○
	Wind		○	○
	Hydropower		○	○
	Marine energy		○	○
	Geothermal energy		○	Partly *
	Bioenergy	Biogas, biodiesel, black liquor, Bio-SRF, etc.	○	○
	Waste energy	Waste gas	○	X
		Industrial waste	○	X
		Municipal waste	○	Partly **
		Cement kiln fuel	○	X
		SRF	○	X
		Refined fuel oil	○	X
	Other renewables	Wastewater heat energy	○	X
		ESS	○	X

*Geothermal power generation only
**Recyclable waste only

*Reference: SFOC (2020)

2. Average Capacity Factor

Table A.2 Capacity factor of wind power (%)

Region	2018	2019	2020	2021	Average
Gangwon-do (GW)	24.5	24.0	24.5	23.7	24.2
Gyeonggi-do (GG)	11.5	10.4	12.1	10.0	11.0
Gyeongsangnam-do (GN)	18.2	17.4	17.0	15.7	17.1
Gyeongsangbuk-do (GB)	24.4	22.4	26.1	24.8	24.4
Incheon (IC)	10.0	10.2	12.3	9.1	10.4
Jeollanam-do (JN)	17.4	17.7	20.1	18.0	18.3
Jeollabuk-do (JB)	12.1	10.0	18.8	20.9	15.5
Jeju (JJ)	22.8	22.7	22.4	20.4	22.1

*Reference: based on EPSIS (2022)

Table A.3 Capacity factor of solar PV (%)

Region	2018	2019	2020	2021	Average
Gangwon-do (GW)	15.3	15.0	14.2	14.0	14.6
Gyeonggi-do (GG)	14.8	14.4	14.1	13.9	14.3
Gyeongsangnam-do (GN)	14.9	15.1	14.6	14.8	14.9
Gyeongsangbuk-do (GB)	15.3	15.2	14.9	14.5	15.0
Gwangju (GJ)	14.7	14.6	14.1	13.6	14.3
Daegu (DG)	15.4	15.0	14.7	14.4	14.9
Daejeon (DJ)	13.4	13.0	12.6	12.7	12.9
Busan (BS)	14.8	14.7	14.8	14.9	14.8
Seoul (S)	15.2	14.7	14.7	14.4	14.8
Sejong (SJ)	14.7	14.5	13.8	13.6	14.2
Ulsan (US)	15.0	15.4	15.8	15.2	15.4
Incheon (IC)	14.6	14.6	13.9	14.2	14.3
Jeollanam-do (JN)	15.2	15.2	14.7	14.7	15.0
Jeollabuk-do (JB)	14.9	14.8	14.2	14.0	14.5
Jeju (JJ)	14.1	14.4	13.9	13.9	14.1
Chungcheongnam-do (CN)	15.5	15.2	14.7	14.4	15.0
Chungcheongbuk-do (CB)	14.4	14.0	13.8	13.6	14.0

*Reference: based on EPSIS (2022)

3. National GHG Inventory Sector Classification

Table A.4 Industry sectors and emission type in GHG inventory

Criteria	Division	Industry	Industry Segmentation	GHG emitters/sinks
1. Energy	A. Fuel combustion	1. Energy Industry	a. Utility electricity and heat production	CO_2, CH_4, N_2O
			b. Oil Refining	
			c. Solid fuel manufacturing and other energy industries	
		2. Manufacturing & Construction	a. Steel	
			b. Nonferrous metals	
			c. Chemistry	
			d. Pulp, paper, and printing	
			e. Food and beverage processing and tobacco manufacturing	
			f. Others	
		3. Transportation		
		4. Others		
		5. Unclassified		
	B. Leakage	1. Solid fuel		CH_4
		2. Oil & Natural Gas		
2. Industrial Process	A. Minerals			CO_2
	B. Chemical Industry	1. Ammonia Production		CO_2
		2. Nitrate Production		N_2O
		3. Adipic Acid Production		N_2O
		4. Carbide Production		CO_2
		5. Other chemical production	a. Carbon Black	CH_4
			b. Ethylene	
			c. Ethylene Chloride	
			d. Styrene	
	C. Metals Industry			CO_2, PFCs, SF_6
	D. Other Industries			
	E. Halocarbon and sulfur hexafluoride production			HFCs
	F. Halocarbon and sulfur hexafluoride consumption			HFCs, PFCs, SF_6
3. Agriculture				CH_4, N_2O
4. LULUCF				CO_2, N_2O, CH_4
5. Waste management				CO_2, CH_4, N_2O

*Reference: GIR (2022)

Table A.5 Alignment of GHG inventory industry sectors and National IO industry sectors

<table>
<tr><th>IO Table</th><th colspan="3">GHG Inventory</th></tr>
<tr><td>Agriculture, forestry & fisheries</td><td>1-A-4-c. Agriculture/forestry/fishing</td><td>3. Agriculture</td><td></td></tr>
<tr><td>Minerals</td><td>1-A-1-c. Solid fuel manufacturing and other energy industries</td><td>1-B. Leakage</td><td></td></tr>
<tr><td>Food & beverages</td><td>1-A-2-e. Food and beverage processing and tobacco manufacturing</td><td></td><td></td></tr>
<tr><td>Textiles & Leather Goods</td><td>1-A-2-f-5. Textiles & Leather</td><td></td><td></td></tr>
<tr><td>Wood & Paper, Printing</td><td>1-A-2-d. Pulp, paper, and printing</td><td>1-A-2-f-3. Wood and lumber</td><td></td></tr>
<tr><td>Coal & Oil Products</td><td>1-A-1-b. Oil Refining</td><td></td><td></td></tr>
<tr><td>Chemical product</td><td>1-A-2-c. Chemistry</td><td>2-B. Chemical Industry</td><td></td></tr>
<tr><td>Non-metallic Mineral Products</td><td>1-A-2-f-1. Non-metals</td><td>2-A. Minerals</td><td></td></tr>
<tr><td>Primary Metal Products</td><td>1-A-2-a. Steel</td><td>A-2-b. Nonferrous metals</td><td>2-C. Metals Industry</td></tr>
<tr><td>Processed Metal Product</td><td rowspan="5">A-2-f-2. Assembled Metal</td><td></td><td></td></tr>
<tr><td>Computer, Electronics& Optical instrument</td><td>2-F. Halocarbon and sulfur hexafluoride consumption</td><td></td></tr>
<tr><td>Electrical Equipment</td><td></td><td></td></tr>
<tr><td>Machine & Equipment</td><td></td><td></td></tr>
<tr><td>Transportation Equipment</td><td></td><td></td></tr>
<tr><td>Other manufacturing products</td><td rowspan="2">1-A-2-f-6. Other Manufacturing</td><td></td><td></td></tr>
<tr><td>Equipment repair Services</td><td></td><td></td></tr>
<tr><td>Electricity, Gas & Steam</td><td>1-A-1-a. Utility electricity and heat production</td><td>1-A-1-c. Solid fuel manufacturing and other energy industries</td><td></td></tr>
<tr><td>Water, waste, & recycling services</td><td>5. Waste management</td><td></td><td></td></tr>
<tr><td>Construction</td><td>1-A-2-f-4. Construction</td><td></td><td></td></tr>
</table>

Wholesale & brokerage services	1-A-4-a. Commercial/Public		
Transportation Services	1-A-3. Transportation		
Restaurants & lodging	A-4-a. Commercial/Public		
Telecommunications & broadcasting services			
Finance & Insurance Services			
Real estate services			
Professional Science & Technology Services			
Business Support Services			
Public administration, defense, & social security		1-A-5. Unclassified	
Education			
Health & Social Services			
Art, Sports & Leisure			
Other services			
Others			

Table A.6 Alignment of GHG inventory industry sectors and MRIO industry sectors

Thesis	IO Table	GHG Inventory		
Agriculture, forestry & fisheries	Agriculture, forestry & fisheries	1-A-4-c. Agriculture/forestry/fishing	3. Agriculture	
Minerals	Minerals	1-A-1-c. Solid fuel manufacturing and other energy industries	1-B. Leakage	
Food & beverages	Food & beverages	1-A-2-e. Food and beverage processing and tobacco manufacturing		
Textiles & Leather Goods	Textiles & Leather Goods	1-A-2-f-5. Textiles & Leather		
Wood & Paper, Printing	Wood & Paper, Printing	1-A-2-d. Pulp, paper, and printing	1-A-2-f-3. Wood and lumber	
Coal & Oil Products	Coal & Oil Products	1-A-1-b. Oil Refining		
Chemical product	Chemical product	1-A-2-c. Chemistry	2-B. Chemical Industry	
Non-metallic Mineral Products	Non-metallic Mineral Products	1-A-2-f-1. Non-metals	2-A. Minerals	
Primary Metal Products	Primary Metal Products	1-A-2-a. Steel	A-2-b. Nonferrous metals	2-C. Metals Industry
Advanced Manufacturing	Processed Metal Product	A-2-f-2. Assembled Metal		
	Computer, Electronics& Optical instrument		2-F. Halocarbon and sulfur hexafluoride consumption	
	Electrical Equipment			
	Machine & Equipment			
	Transportation Equipment			
Other manufacturing	Other manufacturing products	1-A-2-f-6. Other Manufacturing		
	Equipment repair Services			
Electricity, Gas & Steam	Electricity, Gas & Steam	1-A-1-a. Utility electricity and heat production	1-A-1-c. Solid fuel manufacturing and other energy industries	
Water, waste, & recycling services	Water, waste, & recycling services	5. Waste management		
Construction	Construction	1-A-2-f-4. Construction		
Services (Commercial &Public)	Wholesale & brokerage services	1-A-4-a. Commercial/Public		

Transportation Services	Transportation Services	1-A-3. Transportation		
Services (Commercial &Public)	Restaurants & lodging	A-4-a. Commercial/Public		
Business Support Services	Telecommunications & broadcasting services			
	Finance & Insurance Services			
	Real estate services			
	Professional Science & Technology Services			
	Business Support Services			
Services (Commercial &Public)	Public administration, defense, & social security		1-A-5. Unclassified	
	Education			
	Health & Social Services			
	Art, Sports & Leisure			
	Other services			
	Others			

4. IO Industry Correlation

Cost components are aligned with IO industry at two levels. Large (33) and merged version (17) depending on the IO model used. Large classification was mostly used except for consumption-based accounting in Chapter 6. due to alignment with multi-regional sector GHG emission.

Table A.7 Onshore wind value chain - IO industry alignment

CAPEX Cost Distribution			**IO industry**
#1	Turbine equipment	Tower, shaft, nacelle housing, rotor blade	C08. metal products
		Gearbox, rotor bearings	C11. machine and equipment
		Generator, transformer, power converter	C10. electrical equipment
		Yaw drive, pitch system	C09. computer, electronics& optical instrument
#2	Construction (road, site, foundation, equipment)		F. construction
#3	Erection/Installation		F. construction
#4	Electrical infrastructure		C10. electrical equipment
#5	Management/supervision/monitoring		M. professional science and technology services
#6	Legal services (insurance, bonding etc)		M. professional science and technology services
#7	Certificate, permits, assessments		M. professional science and technology services
#8	Electrical interconnection		C10. electrical equipment
#9	Engineering (Design)		M. professional science and technology services
#10	Finance, contingency, miscellaneous		K. finance and insurance services
OPEX Cost Distribution			
#1	Field Salaries (i.e., onsite wind technicians, etc.), Site maintenance		N. Business support services
#2	Administrative and management		M. professional science and technology services
#3	Vehicles		H. transportation equipment
#4	Fees, Permits, Licenses, Insurance		K finance and insurance services
#5	Utilities		D. electricity, gas and steam
#6	Replacement parts/consumables/tools		Turbine equipment proportion
#7	Fuel		C04. coal and oil products
#8	Land Cost		L. Real estate services
Decommissioning Distribution			
#1	Demolition		F. construction

Table A.8 Solar PV value chain - IO industry alignment

CAPEX Cost Distribution		IO Classification
#1	Cell	17 Basic Chemicals
#2	Wafer	31 Semiconductor
#3	Module	37 Electrical Equipment
#4	Inverter	37 Electrical Equipment
#5	Electrical infrastructure	37 Electrical Equipment
#6	Management	72 Scientific and other professional services
#7	Construction	51 Civil Construction
#8	Supervision	72 Scientific and other professional services
#9	Legal services	71 Professional services for business
#10	Engineering (Design)	72 Scientific and other professional services
#11	Finance	65 Financial Services
#12	Insurance	66 Insurance Services
#13	Electrical interconnection	37 Electrical Equipment
OPEX Cost Distribution		**IO Classification (Medium)**
#1	Insurance	66 Insurance Services
#2	Operation and Maintenance	69 Business related professional services
#3	Inverter Replacement	37 Electrical Equipment
Decommissioning Distribution		**IO Classification (Medium)**
#1	Demolition	51 Civil Construction

Table A.9 ESS value chain - IO industry alignment

CAPEX Cost Distribution		IO Classification
#1	Battery manufacturing	C10. electrical equipment
#2	Electrical works (local)	C10. electrical equipment
#3	Installation, Construction	F. construction
#4	Development	M. professional science and technology services
#5	Legal works	M. professional science and technology services
OPEX Cost Distribution		**IO Classification**
#1	Operation and Maintenance	M. professional science and technology services
#2	Battery replacement	C10. electrical equipment

5. Jeju Data

Table A.10 Jeju curtailment projection in 10th electricity plan

Year	2023	2024	2025	2026	2027	2028	2029
Curtailment (%)	1.08	0.00	0.07	0.77	2.20	4.42	8.12
Year	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**
Curtailment (%)	18.98	25.54	25.06	24.99	24.83	24.65	24.57

*Reference: MOTIE (2023)

Table A.11 6th Regional energy plan for new& renewable energy in Jeju (2020-2025)

Unit: MW	Installed (2019)	Planned	Total
PV	245	291.2	536.2
Onshore wind	239	120	359
Offshore wind	30	325	355
Fuel Cell	-	1.5	1.5
Ocean/Hydro	0.5	3	3.5
Bio/Waste	7.2	21.2	28.4
Bio-fuel	350	-	350
Total	871.7	761.9	1633.6

*Reference: Jeju (2020)

Table A.12 Jeju CFI new& renewable energy development update

	CFI (2012)	CFI updated (2019)
PV	1411	1411
Onshore wind	450	450
Offshore wind	1900	1895
Fuel Cell	520	104
Geothermal	10	-
Ocean	10	10
Bio/Waste	10	40
Bio-fuel	-	175
Total	4311	4085

*Reference: Jeju & KEEI (2019)

Table A.13 2017 Gas combined-cycle power generation cost

Levelized Cost of Energy	KRW/kWh
Construction	8.24
Operation and Maintenance	6.32
Transmission connection	0.19
Fuel Cost	66.64
Direct cost Total	81.39

*Reference: KEEI (2018)

6. MREEIO

Table A.14 Consumption-based Production-based emission matrix (1000T CO_2eq)

		Consumption-based ↓																	Total	
		S	IC	GG	DJ	SJ	CB	CN	GJ	JB	JN	DG	GB	BS	US	GN	GW	JJ		
Production-based ↓	S	13,285	892	4,451	361	72	464	805	317	400	598	407	822	574	555	799	423	127	25,353	3.83%
	IC	7,591	12,506	10,543	849	201	3,014	1,904	1,402	2,524	1,974	1,922	1,826	1,025	1,069	1,456	1,892	599	52,297	7.90%
	GG	8,901	2,436	40,713	925	232	1,400	2,599	877	941	1,288	1,070	1,939	1,570	1,576	2,104	939	291	69,802	10.55%
	DJ	622	109	627	1,977	195	174	375	72	101	122	90	165	127	173	140	64	23	5,155	0.78%
	SJ	219	48	250	585	251	81	120	27	42	42	35	53	47	57	50	31	10	1,950	0.29%
	CB	3,137	1,088	4,989	578	319	6,688	2,089	373	398	419	518	1,211	741	874	879	456	118	24,876	3.76%
	CN	19,664	4,389	22,251	3,030	949	3,267	60,076	2,676	2,395	3,118	2,681	4,804	3,246	4,272	6,386	1,924	592	145,721	22.02%
	GJ	405	89	622	62	15	65	130	2,158	128	375	61	141	82	101	147	70	22	4,673	0.71%

JB	1,669	340	1,397	248	61	273	435	276	5,719	416	265	342	297	227	334	203	97	12,596	1.90%
JN	6,205	1,843	10,561	832	290	1,524	3,198	2,318	1,936	39,863	1,641	4,317	2,293	3,976	3,959	1,134	351	86,241	13.03%
DG	918	161	798	114	22	143	228	92	127	152	3,623	891	211	294	365	98	35	8,271	1.25%
GB	5,012	1,582	10,011	652	222	1,391	3,018	897	1,130	1,455	2,138	25,149	1,770	3,504	4,726	960	297	63,914	9.66%
BS	785	183	992	99	36	192	258	116	182	239	192	311	7,269	637	1,007	140	62	12,701	1.92%
US	2,807	782	3,754	354	103	601	1,241	340	579	715	694	1,339	1,012	19,915	1,506	397	151	36,291	5.48%
GN	8,730	1,608	8,749	978	227	1,311	1,911	972	1,155	1,451	1,505	2,039	2,583	2,409	32,167	989	324	69,107	10.44%
GW	4,844	1,359	6,883	589	288	1,164	1,686	489	751	1,226	751	1,917	1,228	1,151	1,907	12,322	657	39,212	5.92%
JJ	847	124	581	77	15	67	105	95	80	105	88	103	110	83	121	57	1,093	3,750	0.57%
Total	85,642	29,539	128,171	12,311	3,498	21,820	80,179	13,499	18,590	53,559	17,681	47,368	24,185	40,872	58,052	22,098	4,848	661,910	100.00%
	12.94%	4.46%	19.36%	1.86%	0.53%	3.30%	12.11%	2.04%	2.81%	8.09%	2.67%	7.16%	3.65%	6.17%	8.77%	3.34%	0.73%	100.00%	

Table A.15 Carbon emission coefficient by region-industry (1000T CO_2eq/billion KRW)

Sectors	S	IC	GG	DJ	SJ	CB	CN	GJ	JB	JN	DG	GB	BS	US	GN	GW	JJ
Agriculture, forestry & fisheries	14.58	0.31	0.44	0.19	0.24	0.40	0.50	0.34	0.51	0.44	0.18	0.37	0.19	0.9	0.30	0.29	0.15
Minerals	109.67	1.00	1.47	15.03	0.24	0.28	0.73	7.37	0.44	0.69	48.52	0.46	5.86	1.21	0.75	0.44	0.12
Food & beverages	0.02	0.05	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.01
Textiles & Leather Goods	0.00	0.01	0.03	0.01	0.00	0.02	0.01	0.00	0.07	0.01	0.04	0.03	0.00	0.04	0.01	0.01	0.10
Wood & Paper, Printing	0.00	0.03	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.04	0.02	0.00	0.03	0.02	0.01	0.03
Coal & Oil Products	-	0.14	-	-	-	-	0.29	-	-	0.11	-	-	-	0.13	-	-	-
Chemical product	0.18	0.17	0.01	0.02	0.01	0.01	0.29	0.03	0.02	0.35	0.01	0.03	0.02	0.31	0.01	0.02	0.00
Non-metallic Mineral Products	0.98	0.18	0.10	0.02	0.05	3.29	0.54	0.03	0.16	1.36	0.04	0.51	0.04	0.21	0.12	8.05	0.00
Primary Metal Products	0.07	0.05	0.02	0.02	0.01	0.06	1.39	0.00	0.07	2.66	0.02	1.29	0.05	0.10	0.05	0.05	-
Advanced Manufacturing	0.03	0.01	0.03	0.01	0.01	0.02	0.02	0.01	0.02	0.03	0.01	0.02	0.04	0.06	0.01	0.05	0.18
Other manufacturing	0.25	0.09	0.11	1.12	0.02	0.52	0.14	0.25	0.25	0.25	0.53	0.73	0.20	0.52	0.10	2.52	0.16

Electricity, Gas & Steam	0.39	2.90	1.24	0.50	1.51	0.23	7.46	0.34	0.55	1.00	0.93	0.52	0.43	0.99	8.71	5.03	1.69
Water, waste, & recycling services	1.26	-0.36	0.60	1.61	1.77	1.43	1.66	0.50	2.15	1.32	0.40	0.96	0.65	1.13	0.98	1.02	0.73
Construction	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.00	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.02	0.01
Services (Commercial &Public)	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01
Transportation Services	0.33	0.21	1.03	0.9	1.34	1.87	1.11	1.35	1.46	0.55	1.32	1.36	0.31	0.42	1.21	1.38	1.09
Business Support Services	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

국문초록

주요어: 재생에너지, 탄소배출, 지역경제, 풍력, 태양광, 유연성자원, Input-Output Analysis, Life-cycle Assessment

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지속가능한 미래세대를 위해 에너지 사용으로 인한 탄소배출을 대폭 감축해야 한다. 이 과제는 수입 화석연료에 의존하는 에너지 다소비 산업을 기반으로 성장한 우리나라에는 엄청난 도전이다. 따라서 충분한 논의가 선행되어야 한다. 풍력과 태양광 등의 재생에너지는 자연의 힘으로만 전력을 생산하기 때문에 전력 생산 과정에서 이산화탄소를 배출하지 않는 대표적인 청정에너지원이다. 그러나 재생에너지는 전통적인 중앙발전원과 큰 차이가 있으므로 상당한 변화를 수반한다.

재생에너지는 간헐성으로 인하여 유연성 자원이 필수적이다. 따라서 재생에너지의 광범위한 전후방산업에 의한 탄소배출량까지 고려할 필요가 있다. 한편, 재생에너지는 분산에너지원으로써 지역주민 생활반경에 가까이 위치하기 때문에 수용성 문제가 중요하며, 재생에너지 확대가 지역경제에 미치는 영향에 대한 사회적 관심도 매우 높다. 최근, 녹색 보호주의에 따른 무역분쟁이 전 세계적으로 심화되고 있고, 국가 재생에너지 산업경쟁력 육성 또한 강조되고 있는 추세이다.

본 연구는 재생에너지 시스템의 탄소저감 효과를 극대화하고, 지역사회와 상생할 방안을 마련하기 위하여 재생에너지 확대가 탄소배출과 지역경제에 미치는 영향을 전주기 가치사슬, 국가 및 지역

산업역량 강화, 지역적 특성 등 재생에너지의 고유한 특성을 고려하여 분석하는 데에 목적을 두었다. 본 연구는 크게 세 가지로 구분된다.

첫 번째 연구에서는 제주도에 211MW 규모의 육상풍력 발전이 확대됨에 따라 발생하는 전주기 탄소 배출량을 분석하였다. 방법론으로 비용 분석과 Environmentally-Extended Input-Output (EEIO) 분석에 기반한 Economic Input-Output Life-cycle Assessment (EIO-LCA)를 활용하여 주요 배출원을 파악하고 탄소배출 저감 방안을 제시하였다. 에너지저장시스템 (ESS)의 배터리 제조가 탄소배출의 가장 큰 발생원으로 나타났으며, 터빈 부품 제조가 그 뒤를 이었다. 이 결과는 유연성 자원의 탄소배출 저감 노력이 필요함을 시사한다. 또한 민감도 분석에 따르면 육상풍력 발전소의 설비 이용률과 운영기간 증가가 탄소 배출량 감축 잠재력을 더욱 높일 수 있는 요인으로 파악되었다. 주요 탄소배출 산업으로 1) 전기, 가스 및 증기 2) 1차 금속제품(철강 생산), 3) 비금속 광물제품(시멘트 생산)이 확인되었다. 궁극적으로 에너지산업의 재생에너지의 비중을 높이는 것뿐만 아니라 산업공정의 탄소 저감이 중요함을 시사한다.

두 번째 연구는 육상풍력 확대가 제주도 지역경제에 미치는 영향을 비용 분석과 Interregional Input-Output (IRIO) 분석을 활용하여 국가 및 지역 산업역량을 수준을 수치화한 국가 및 지역 자급률(%) 시나리오 아래 분석하였다. 육상풍력 및 유연성 자원 확대는 광범위한 가치사슬로 인하여 운영기간에 다양한 산업에 걸쳐 부가가치 및 고용 기회를 창출함을 확인하였다. 또한, 운영기간에 발생하는 부가가치 유발효과는 제주도의 건설업, 요식업·숙박업, 농수산업과 비슷한 수준으로 나타났다. 재생에너지 시스템은 육상풍력과 직접적으로 관련된 산업 외에도 다양한 분야에 걸쳐 일자리를 창출한다는 점에서 화력발전소와는 차별된다. 이는 향후 다양한 기술을 보유한 인력을

확보하는 것이 중요한 과제가 될 것임을 시사한다. 지역 자급률의 증가가 국가 전체 일자리 창출에 미치는 영향은 미미하지만, 국가 자급률의 증가는 지역 일자리 증가로 이어진다는 결과가 도출되었다. 따라서 일부 지역 자급률 정책은 재생에너지 관련 지역수용성 문제를 효과적으로 개선할 수 있을 것으로 사료된다.

세 번째 연구는 앞선 두 연구를 바탕으로 IRIO와 다지역 EIO-LCA를 활용하여 국내 19GW 규모 육상풍력 및 태양광 발전 확대를 중심으로 탄소 배출량과 경제적 영향의 관계를 분석하였다. 재생에너지 확대시 국가 자급률을 높이고 많은 유연성 자원을 통합할수록 고용이 상당히 증가하는 반면, 탄소 배출량도 함께 증가한다. 또한, 소비 기반의 배출량 관점에서 제주도의 육상풍력 및 태양광 발전 운영이 국내 타 지역의 탄소배출과 일자리에 미치는 영향을 분석하였다. ESS 조달 지역에 따라 탄소배출 및 고용 창출의 지역적 분포 및 총량이 상이함을 확인하였다. 따라서, 재생에너지 확대가 저탄소 공급망 전략과 연계된다면 탄소배출을 최소화하면서 일자리 창출을 극대화할 수 있다. 이는 기업이 저탄소 산업활동을 채택하도록 하는 유인책으로 작용할 수 있을 것이다.

결론적으로 이 연구는 재생에너지 확대와 저탄소 산업활동의 통합을 강조한다. 태양광과 풍력발전은 탄소배출을 매우 효과적으로 저감할 수 있는 에너지원이지만 간헐성과 분산성으로 인하여 탄소배출과 지역경제에 미치는 영향이 크다. 그러나 에너지산업 및 산업공정의 탈탄소화, 재생에너지 운영 조건 개선, 순환경제 및 저탄소 공급망 선별 등 재생에너지 확대를 저탄소 산업활동과 긴밀히 연계한다면 탄소배출 영향을 최소화하는 동시에 국가 경쟁력을 확보하고 지역 경제를 활성화할 수 있을 것이다.

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