탄소다배출 제조업의 탄소중립 실현을 위한 인센티브 제도 설계 연구

2024년 4월

산업통상자원부

양재원

차례

국외훈련 개요

1.훈련국: 영국

2.훈련기관명: 엑서터대학교

(University of Exeter)

3.훈련분야: 공공행정학

4.훈련기간: 2022.7월~2024.5월

훈련기관 개요

창립: 1851년

주소: Stocker Rd, Exeter EX4 4PY

전화번호: +044 1392 661000

학생수: 22,540명(2017년 기준)

Designing Incentive Schemes for Achieving Carbon Neutrality in Energy-Intensive Industries

Executive Summary

Global supply chains formed over a long period based on free trade and comparative advantage have become more complex than ever before, and the stability of supply chains has emerged as a critical factor for achieving carbon neutrality in each country. The stability of global supply chains is facing increasing risks due to global events and conflicts such as the COVID-19 pandemic, trade conflicts, high-tech competition between the United States and China, the Russia-Ukraine war, and the Middle East conflict. A stable supply chain of raw materials, logistics, and energy is essential for building a carbon neutrality realization system, but these global supply chain disruptions are having direct and indirect negative impacts on carbon neutrality.

Korea declared '2050 Carbon Neutrality' in 2020 and faces the challenge of maintaining a stable supply chain while overcoming the high dependence on foreign raw materials and energy to achieve carbon neutrality. To maintain Korea's supply chain resilience, it is necessary to analyze the carbon neutrality and supply chain policies of the United States and the European Union, which are closely related to the economy and security, understand their impact on Korean companies, and derive insights for complementing the current Korean system. The U.S. and the EU emphasize the connection between carbon neutrality and supply chain policies, highlighting the sustainability and resilience of the supply chain as key policy elements. Meanwhile, the EU is strengthening protection barriers for its carbon-intensive industries while striving for the

efficient realization of carbon neutrality through the Carbon Border Adjustment Mechanism, and the United States is doing so through the Clean Competition Act.

This study proposes the activation of public procurement from the demand side, job creation, and strengthened international cooperation to enhance the connection between Korea's carbon neutrality and supply chain policies, aiming to secure a sustainable and resilient supply chain. Additionally, in response to the enhanced implementation of carbon border adjustment mechanisms, it is proposed to suggest incentive design options based on the analysis of carbon-intensive industries.

1. Introduction

South Korea's (Korea) greenhouse gas emissions in 2019 contributed to 1.5% of the global total, totaling 698 million tons (Mt) CO_2eq, out of worldwide emissions of 48,117 MtCO_2eq (Kim & Lee, 2022). In the industrial sector alone, direct emissions reached 291 MtCO_2eq in 2019. When considering indirect emissions, the industrial sector's contribution exceeds 50% of the nation's total emissions.

Korea announced its '2050 Carbon Neutrality' initiative In December 2020, setting an 80.4% reduction target for carbon emissions in the industrial sector compared to 2018 levels. Additionally, three main policy directions and ten key challenges were outlined: 'Low-carbonization of the economic structure,' 'Establishment of a promising low-carbon industrial ecosystem,' and 'Fair transition to a carbon-neutral society.' With this, Korea has joined as a member of 137 countries, including the U.S., Japan, Canada, the EU, and China, that have committed to carbon neutrality.

To achieve carbon neutrality, Korea must consider its high trade dependence of 84.5% and the manufacturing-centric open economic structure, constituting 28.4% of the GDP (World Bank, 2022; MOTIE, 2023). The analysis and understanding of global value chains (GVC) in the industry, involving the extraction, processing, production, consumption of raw materials, energy usage, logistics, and recycling processes, form the foundation for building a carbon-neutral system. According to the Korea International Trade Association's (2020) analysis, Korea's GVC participation level ranks among the highest, at 55%, compared to France 52%, Germany 51%, Japan 45%, and the United States (U.S.) 44%.

The globally formed supply chain, based on efficient division of labor among nations, has become a sensitive structure where the success or failure of sourcing specific raw materials and components significantly impacts productivity and efficiency. Recent events, such as Japan's suspension of semiconductor core material exports to Korea and China's strengthened export restrictions on critical materials like gallium and germanium, have disrupted the normal operation of Korea's industries, causing a sense of crisis. Additionally, geopolitical risks like the escalating trade and technology disputes between the U.S. and China, the Russia-Ukraine war, and the Israel-Palestine conflict, act as factors decreasing the stability of Korea's industrial supply chain, including logistics and energy.

Due to these reasons, risk management of the supply chain for essential goods and materials of strategic industries, which must be secured at the national level, has become a mission that directly affects industrial competitiveness, diplomacy, and security (Lee, 2022). The design of systems to absorb supply chain shocks and the assurance of sustainability have become national priorities, transcending the corporate dimension. The U.S. has introduced the Inflation Reduction Act and Chips and Science Act, while the EU has announced measures like the Net-Zero Industry Act, Critical Raw Material Act, Carbon Border Adjustment Mechanism, and Corporate Sustainability Due Diligence Directive, presenting models for carbon neutrality and supply chain localization. Considering that the U.S. and the EU account for a significant portion of Korea's export volume, ranking second and fourth respectively as of 2023 (MOTIE, 2024), their policies have a critical impact on Korea's industrial and trade aspects due to political and economic influence. The carbon neutrality policies of the U.S. and the EU are already affecting Korean companies' product export strategies and localization, particularly in carbon-neutral industries such as semiconductors and secondary batteries.

In particular, carbon border measures such as the EU's Carbon Border Adjustment Mechanism (CBAM) or the US Clean Competition Act have a significant impact on carbon-intensive industries, namely Energy-Intensive Industries. The total import value of CBAM products into the EU amounted to 53 billion euros as of 2019, representing 3% of the total import value, with over 50% of this attributed to steel, 23% to aluminum, and 8% to fertilizers (Simola et al., 2021). The EU Commission (2021) notes that while the share of CBAM products in the EU's import volume is relatively low, the implementation of CBAM poses risks of exposure and vulnerability for developing and least-developed countries. This is because Energy-Intensive Industries possess characteristics of economies of scale, high energy, and capital intensity, requiring substantial resources for process transition and integration of innovative technologies in response to such regulatory changes, which are difficult to implement rapidly.

Therefore, analyzing the impact on the stability of Korea's supply chain and extracting lessons for strengthening the connection between carbon neutrality and supply chain policies requires multifaceted analyses of the policies of these countries. This study aims to review the elements of sustainability and resilience in the industrial supply chain, which are the prerequisites for achieving carbon neutrality, and propose insights into sustainability and resilience that need to be addressed in the design of Korea's carbon neutrality and supply chain policies, drawing from the policy analyzes of the EU and the U.S., which are enhancing the connection between carbon neutrality and supply chain policies. Additionally, this study aims to recommend incentive measures for achieving carbon neutrality in the Korean EII industry in response to the implementation of carbon border adjustment mechanisms in the EU and the US.

2. Policy background

2.1. The role of the supply chain in achieving carbon neutrality

The stable implementation of industrial decarbonization is contingent upon the sustainability of the supply chain. Sindhwani et al. (2023) emphasize that sustainability plays the most crucial role in the implementation of decarbonization in the supply chain. Taking measures to reduce carbon emissions in an inadequately optimized supply chain may lead to inefficient results or provide short-term benefits limited to corporate gains. Achieving sustainable changes in the overall decarbonization levels of the industry requires securing long-term benefits, which may not be ideal in terms of a company's operational space (Bechtsis et al., 2017).

Efficiency in realizing industrial decarbonization can be enhanced by leveraging the various advantages of a well-established supply chain. A well-structured supply chain enables efficient process synchronization (Bechtsis et al., 2018), profit maximization (Kazancoglu et al., 2018), and easier product customization (Ford & Despeisse, 2016). Identifying efficient elements in reducing carbon emissions in the supply chain, controlling processes that induce carbon appropriately, and ensuring the overall process functions seamlessly are crucial tasks that can be facilitated by utilizing these advantages (Eltayeb et al., 2011).

Moreover, the strong trend of greenhouse gas regulation enhances the importance of decarbonization management in industrial supply chains. Initiatives such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and Corporate Sustainability Due Diligence Directive, along with the proposed regulatory draft mandating emissions disclosure for listed U.S. companies, demonstrate an expanding scope of greenhouse gas emission management to include not only direct emissions (scope 1) but also indirect emissions (scope 2) and the entire supply chain emissions (scope 3).

2.2. Global supply chain environment

The measures of some countries to close their borders to prevent the spread of the COVID-19 pandemic caused disruptions in global logistics, interruptions in component procurement, and supply chain shocks. Lessons from this situation highlighted that supply chain issues, which were previously limited to strategic industries, could expand beyond universal materials, components, and raw materials to include final consumer goods. Disruptions in global supply chains not directly connected to Korea also underscored the potential for unforeseen ripple effects on Korea.

Contrary to the increasing importance of a stable supply chain for carbon neutrality, diplomatic and economic decoupling between the U.S. and China, strengthened control over critical raw materials by resource-rich countries, and logistical and geopolitical risks arising from wars in various countries are acting as significant variables in the stability and predictable establishment of a carbon-neutral system.

One of the major factors significantly amplifying the uncertainty in the current global supply chain is the diplomatic and economic conflicts between the U.S. and China. The GDP of both countries accounts for 42.7% of the world's GDP (World Bank, 2022), holding key positions in advanced and general-purpose technology, raw material supply, and production networks. The control and countermeasures between the two countries regarding critical strategic technologies and materials, spreading from artificial intelligence, semiconductors, and communication, to biotechnology, are causing inevitable changes to the existing global supply structure and order. The U.S., vigorously pursuing a strategy to exclude China from advanced strategic technologies and industrial supply chains, is progressing toward the internalization of manufacturing facilities, factories, and infrastructure (Lee, 2022). In response, China adopted the Export Control Act in 2020, expanding the scope of export control over raw materials and essential components. Despite concerns that these conflicts between the U.S. and China are hindering decarbonization (Shen, 2021), this trend is expected to intensify and prolong.

<Table 1. Strengthening China's raw material export controls >

Announcement and implementation	Statutory provisions	Main contents and features
2023.7.	Notice on Germanium and Gallium Export Controls	Announcement of export controls on germanium and gallium items
2023.1. enforcement	List of 2023 Import/Export Permit Management Items	New products such as iridium oxide and cobalt for fuel cells and stents for vascular dilation procedures have been added.
2023.1. enforcement	2023 Dual-Use Goods and Technology Import/Export Permit Management List	Addition of nuclear-grade graphite, potassium perchlorate, etc. as new items
2022.12.	Collection of opinions on the list of prohibited and export-restricted technologies	Addition of ingot and wafer manufacturing technology for the solar energy industry and rare earth permanent magnet manufacturing technology such as neodymium and samarium cobalt.
2021.1. presentation	Rare Earth Management Ordinance (draft)	The key content is strengthening control over the entire rare earth industry chain, from mining, smelting, production, distribution, and export. Previously, management was focused on rare earth production, but the export sector was

		added and the entire supply chain was expanded as a subject of control.
2022.1. enforcement	2022 Dual-Use Goods and Technology Import/Export Permit Management List	Military and civilian goods, including toxic chemicals, nuclear, bio, and missile-related items and technologies · Announcement of new HS codes added to existing items such as weapons chemicals, radioactive isotopes, and poisons
2022.1. enforcement	List of 2022 Import/Export Permit Management Items	HS codes for ozone-depleting substances and HS codes for chemical substances have been further refined compared to 2021 · Among rare earth items, two new items have been added
2021.1. (Promulgation and Enforcement)	Act to prevent unfair extraterritorial application of foreign laws and measures (ordinance)	· Specify standards for unfair measures by foreign countries based on the existing 'Foreign Investment Act' and present standards for reporting, unfairness review, and compensation for damages related to the application of foreign laws in China
2020.10. (Enforced in December 2020)	Export Control Act	Controls items related to the fulfillment of international obligations such as dual-use, nuclear, military supplies, national security and interests, and non-proliferation · Includes cargo, technology, services, technology-related data, etc.

*Eungyo Cho, (2023). 'Supply chain strategies of high-tech industries seen through China's export controls and our response: Focusing on the semiconductor and battery industries' p19.

The scope of industrial supply chains is not limited to raw materials, components, and final products alone. Countries heavily dependent on imported energy must invest time and resources to revamp their supply chains to prevent structural ruptures in the energy supply network. The Russia-Ukraine war, which began in 2022, sounded alarm bells for energy security worldwide, particularly for the European Union (EU), which relies on imports for 70% of its energy and is thus vulnerable to the weight of crises. The conditions of a country's energy self-sufficiency and external dependence act as direct factors influencing the stability of the supply chain. In the context of energy security, Knox-Hayes et al. (2013) identified availability, including supply stability and economic viability, as the first dimension among eight dimensions of energy security. Sovacool and Rafey (2011) prioritize fuel diversification, contingency planning, and limiting dependence on energy imports as dimensions within the four dimensions of energy security.

Threats to the stability of the supply chain, sparked by global competitive relations, have exceeded the response capacity at the corporate level. Governments have shown a tendency to formulate supply chain policies with an increased emphasis on national security. Acts enacted based on the US Inflation Reduction Act (IRA) and the EU's Green Deal Industrial Plan, along with related plans, demonstrate the convergence of carbon-neutral policies with economic and social security.

Through the IRA, the U.S. is strengthening the internalization of the supply chain by promoting the development of the green industry through environmentally related tax deductions, financial support, and subsidies. The plan aims to secure the energy production facilities supply chain, such as solar, wind, batteries, and hydrogen, within the U.S., promoting domestic production, procurement, and sales.

The EU, through the European Green Deal in 2019 and Fit for 55 in 2021, has announced policy packages for carbon neutrality and is proceeding with the implementation of each policy. The Green Deal Industrial Plan, released by the European Commission in February 2023, proposes four pillars as policy tools for promoting the clean technology industry: regulatory simplification, facilitating funding, strengthening technological capabilities, and diversifying supply chains through international cooperation. To enhance the implementation of the plan, the Commission announced the drafts of the Net-Zero Industry Act (NZIA) and Critical Raw Material Act (CRMA) in March 2023.

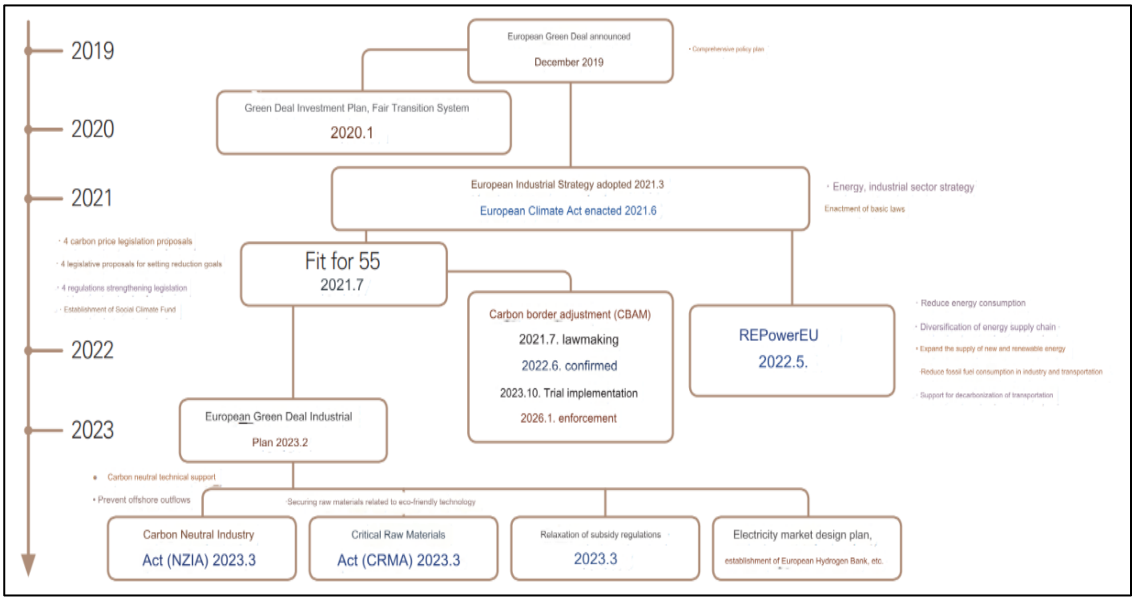

Fig. 1. Europe Green Deal major policy implementation progress

(Source: Yunhee Kim (2023), 'Inspection of global trade issues related to the climate crisis in 2023' p. 63.)

The Net-Zero Industry Act (NZIA) aims to secure over 40% of the domestic demand for strategic net-zero technology, as specified in the appendix of the legislation, by 2030. Additionally, it ensures the unhindered movement of carbon-neutral technology within the EU single market. On the other hand, the Critical Raw Material Act (CRMA) sets specific weightage targets for various stages of the supply chain related to core and strategic raw materials: 10% for domestic extraction and production, 40% for refining and processing, and 15% for recycling. Furthermore, it includes measures to reduce the dependency on a single importing country to less than 65% at each stage.

The policy trajectory, encompassing the U.S. IRA, EU's Fit for 55, Green Deal Industrial Plan, NZIA, and CRMA, places significant emphasis on the stability of industrial supply chains in the pursuit of achieving carbon neutrality by 2050.

2.3. Implementation of Carbon Border Adjustment Mechanism

The CBAM imposes carbon costs on products produced and imported from countries with high carbon emissions to prevent carbon leakage and to adjust for differences in efforts to reduce emissions between countries. Adjustment methods, considering regulatory costs within exporting countries, can include the imposition, exemption, purchase, or submission of taxes (tariffs, carbon taxes), or the utilization of emissions trading. The EU's CBAM serves as a complementary policy to the EU Emissions Trading System (ETS), aiming to prevent outsourcing of production to countries that do not adopt similar carbon pricing levels as the EU industries (Magacho et al., 2024). The targeted sectors include steel, aluminum, cement, fertilizers, and hydrogen, along with some screws, bolts, and iron/steel products. Approved importers to the EU are required to purchase CBAM certificates equivalent to the total amount of emissions embedded in the imported goods for CBAM-targeted sectors. The EU CBAM will be fully implemented from January 2026, following a transition period from October 2023 to December 2025.

According to export data by country to the EU, steel products are the most affected by CBAM applications, particularly impacting Turkey, the US, other BRICS countries (Brazil, India, South Africa), Korea, and Ukraine (Magacho et al., 2024).

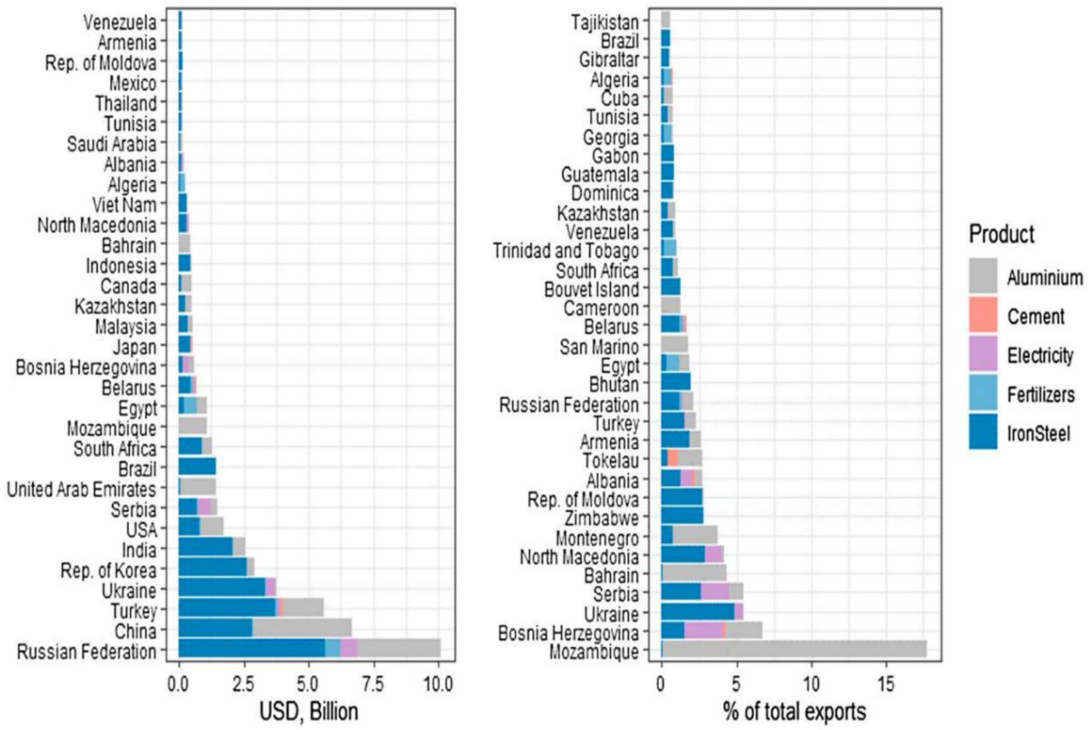

Figure 2. Exports of CBAM products to EU countries, by country (2019). (Source: Magacho et al., 2024. Impacts of the CBAM on EU trade partners: consequences for developing countries)

Moreover, carbon levies vary depending on the product's greenhouse gas emissions and the carbon intensity of each country. According to the distribution of emission intensities by-product shown in the figure below, except for fertilizers, all products have higher carbon intensities analyzed for non-EU countries compared to EU countries.

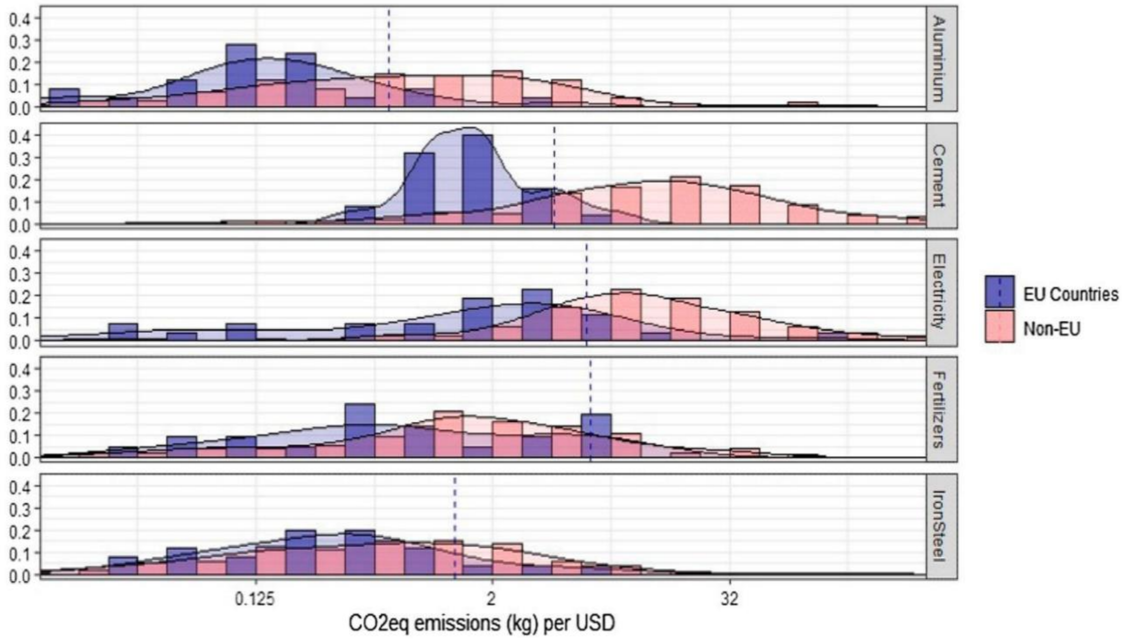

Figure 3. Distribution of emission intensity, by product (2015). (Source: Magacho et al., 2024. Impacts of the CBAM on EU trade partners: consequences for developing countries)

In the US, following indications of introducing carbon border adjustments in the USTR's annual trade policy report in March 2021, the FAIR Transition and Competition Act was introduced in the House of Representatives in July 2021, imposing carbon border taxes on carbon-intensive imports such as steel, aluminum, cement, and petrochemicals. In June 2022, U.S. Senators introduced the Clean Competition Act (CCA) for implementing carbon border adjustments, specifying a charge of $55 per ton of greenhouse gas emissions for 12 energy-intensive industries, including steel, glass, paper, and petrochemicals, starting from January 2025. Through the CCA, the US aims to provide a competitive advantage to its industries with lower emission intensities by imposing carbon costs on imports and domestically produced goods with higher emissions than the national average (Jung, 2023).

3. Theory and literature review

3.1. Decarbonization of Industrial Supply Chains

3.1.1. Research trends

Research on decarbonization strategies for supply chains has seen numerous studies focusing on efficient greenhouse gas reduction and sustainable implementation methods. The decarbonization of supply chains essentially involves adopting methodologies and plans that contribute to reducing carbon emissions (Sindhwani et al, 2022). As businesses increasingly strive to make their supply chains sustainable and environmentally friendly (Wong et al., 2013), the demand for achieving carbon neutrality has grown, prompting the need for in-depth research and implementation (Quere, 2015). Numerous companies across different sectors have commenced the establishment of eco-friendly supply chains by reducing raw material inputs and decreasing waste generation through recycling efforts (Sriyogi, 2016). Additionally, efforts have been directed toward adopting sustainable practices in supply chain management and establishing green supply chains (Shibin et al., 2016).

While there are various aspects in industries requiring carbon reduction measures, the prioritization of such actions is often based on the quantity of carbon contributed, as supply chains account for over 80% of carbon emissions in the industrial sector (Papadis & Tsatsaronis, 2020). Kayikci (2018) emphasized the mainstreaming of the need for decarbonization in industrial supply chains due to their significant contribution to industrial carbon emissions.

3.1.2. Decarbonization methods for the supply chain

The outcomes of research on supply chain decarbonization have brought forth various methods. Groundbreaking technological developments and utilization, the adoption of low-carbon alternatives for fuels and materials, strategies emphasizing efficient consumption and increased reuse, and circular resource models have been proposed and implemented (Material Economics, 2019; Wyns et al., 2018).

The World Economic Forum (2021) has presented a 9-step methodology for achieving supply chain decarbonization. Companies within the supply chain are encouraged to establish emission baselines for the value chain and exchange data with suppliers (Action 1), set reduction targets for Scope 1-3 emissions, and publicly report progress (Action 2). They are also advised to redesign products for sustainability (Action 3) and strategize value chain/sourcing (Action 4). Integrating emission metrics into procurement standards and tracking performance (Action 5), collaborating with suppliers to address emission issues (Action 6), and participating in sector-specific initiatives for best practices, certifications, traceability, and policy advocacy (Action 7) are part. of the methodology. Expanding purchasing groups to amplify demand-side commitments (Action 8) and introducing low-carbon governance to adjust internal incentives and enhance organizational capabilities (Action 9) are also emphasized. This methodology, derived from interviews with 40 CEOs and experts, underscores sustainability in Actions 3 and 4.

Recent studies show a trend towards focusing on smart supply chain management utilizing IT technology. It is evident that technological interventions will play a crucial role in decarbonization (Akbari & Hopkins, 2022), and IT technology is expected to be utilized for industrial conservation (He et al., 2021). Specific technologies like cloud computing and blockchain tend to be highly effective in achieving supply chain decarbonization (Stroumpoulis & Kopanaki, 2022). Cloud computing provides ways to decarbonize and activate supply chains by maximizing resource reuse processes for existing materials, thereby reducing energy consumption (Kumar et al., 2016; Shee et al., 2018). This approach is recognized for its capability to decrease carbon emissions by around 30% for major corporations and up to 90% for small businesses (Puica, 2020). Blockchain technology helps track real-time carbon emissions, facilitating easier waste management and reducing carbon footprints (Truby, 2018; Park & Li, 2021), and it provides advantages such as choosing vendors and managing the carbon emissions produced by businesses. The utilization of various technologies, including cloud computing, blockchain, big data, artificial intelligence, the Internet of Things, and robotics, can be a key factor in activating carbon neutrality (Krishnan et al., 2021).

Some research results on the impact of geopolitical changes on supply chains and carbon neutrality have also been identified. Research on major world trade flows indicates that Western economies import a significant amount of emissions from Asia (WEF, 2021). The study suggests that supply chain measures implemented by consumer companies in Europe and the U.S. can influence the emission paths of growing Asian economies. Although dynamics such as the U.S.-China trade conflict, the introduction of EU carbon border taxes, and nearshoring efforts due to COVID-19 may bring about changes in these regional dynamics, a fundamental shift in the dynamic relationship is deemed unlikely.

According to Rabbi et al. (2022), the majority of studies dedicated to achieving security and carbon neutrality primarily concentrate on ensuring a continuous energy supply and lowering carbon emissions. Rabbi's research aims to offer insights into the empirical factors that influence the energy transition at the EU level, contributing to the attainment of energy security and carbon neutrality. Firstly, it emphasizes the need to increase energy availability through diversification of energy sources. Secondly, it underscores the importance of boosting renewable energy generation to enhance the economic viability of energy. Thirdly, it highlights the contribution of energy conservation to achieving environmental impact reduction and stability at the national level. This study emphasizes the integration of these three strategies by 2030 to achieve energy security and carbon neutrality.

3.1.3. The challenges of decarbonizing supply chains

Despite efforts and research on decarbonizing the supply chain, there are still difficult challenges to overcome before achieving ideal decarbonization. One common problem is the limited transparency of emissions for many companies, and existing systems to establish greater transparency are immature (WEF, 2021). This lack of transparency implies uncertainty in the economic effects of decarbonization, leading to the perception that decarbonization efforts may not necessarily contribute to performance improvement or cost savings.

Another difficulty in decarbonizing supply chains lies in the challenge of identifying and addressing factors influencing the supply chain for decarbonization (Serra & Fancello, 2020). Previous research has tended to focus on how companies have strived to create sustainable supply chains, mainly emphasizing how supply chain decarbonization occurs and effective technologies for supply chain management. Sindhwani et al. (2022) argue that there has been insufficient emphasis on which factors work best and are ideal for achieving decarbonization in the supply chain.

Another factor making decarbonization of supply chains challenging is the difficulty in identifying the elements that contribute to it. The complexly formed global value chain largely hinders the realization of carbon emission reduction potential in energy-intensive industries (Oberthür, 2021). As raw materials and intermediate goods are widely produced and traded, producers face the burden of managing numerous trading companies worldwide. Consequently, as the industry becomes increasingly internationalized and complex, the tracking and control capabilities of basic material companies are inevitably limited.

Companies that disclose Scope 3 emissions are still rare, often having to rely on emission coefficient databases based on national averages and developing estimates based on information such as the quantity, weight, and expenditure of sourced materials (WEF, 2021). For companies that hold numerous individual products and generate significant revenue based on supplier-based operations, these challenges can be particularly daunting, and there may be a lack of high-level reliability regarding Scope 3 emissions. Despite the use of sophisticated digital procurement and resource planning tools in the market, with optimal features for environmental data sharing, widely accepted infrastructure for such purposes seems to be in its early stages of development.

Research on the necessity, methodology, and effectiveness of carbon neutrality in supply chains is gradually developing and verifying its results. Further research is needed to identify ideal reduction factors and ensure data reliability. Nevertheless, studies addressing the stability and sustainability of industrial supply chains from a national security perspective remain limited. It may not be long since the U.S. and the EU announced their national strategies for carbon neutrality and industrial supply chain security, so there may not have been much research conducted yet.

3.2. Decarbonization of Energy-Intensive Industries

3.2.1. Characteristics of Energy-Intensive Industries

Energy-intensive industries (EII) refer to industries such as iron and steel, non-ferrous metals (aluminum, etc.), basic chemicals, and pulp and paper (Bassi et al., 2009). Although the industrial scale of EII accounts for only about 7% of the global GDP, the energy used in EII in the EU, the US, China, Russia, and Korea represents 60% of global energy consumption. Typically, 60-80% of the energy used in EII comes from the production of basic materials (Fischedick et al., 2014). Additionally, globally, EII emit over 20% of total greenhouse gas (GHG) emissions, with iron and steel, cement, aluminum, and chemicals contributing to about 70% of industrial emissions (Kechichian et al., 2016).

EII are industries with high capital and energy intensities, requiring high initial costs for large-scale manufacturing plants due to the high-temperature chemical transformations or chemical bond disruptions required in raw material processing. Consequently, large-scale investment in such factories is essential to achieve economies of scale (Wesselinga, 2017). Companies in the EII sector face high fixed costs in highly cyclical markets with large variations in product margins and prices (SPIRE, 2013), resulting in long payback periods and uncertainty in the investment process. The investment cycle for large reinvestments typically ranges from 20 to 40 years (Worrell & Biermans, 2005), with periodic refurbishments of the plants to enhance productivity and energy efficiency.

The nature of these industries explains why investment in existing plants for enhancing production capacity is more common than building new facilities. Moreover, the high energy usage, capital intensity, and requirements for large-scale factories form significant entry barriers for this sector. In other words, transitioning from carbon-intensive industries to green industries (Mealy & Teytelboym, 2020) and implementing technological changes within the industry require substantial investments, imposing significant costs not only on individual companies but also on national economies (Ameli et al., 2021).

3.2.2. Decarbonization Strategies for Energy-Intensive Industries

Methods such as process transformation, changes in raw materials and fuels, and recycling are being utilized to reduce greenhouse gas (GHG) emissions from EII (Skjærseth et al., 2013). Industries can reduce GHG emissions through optimal decarbonization options, considering factors such as the transition to affordable low-carbon electricity and hydrogen, carbon capture capacity, availability of biomass, and expected changes in production capacity (Pee et al., 2018). According to this research, the decarbonization costs for the steel, cement, ammonia, and ethylene sectors are estimated to range from 11 to 21 trillion dollars by 2050, equivalent to 0.4 to 0.8% of global GDP.

Energy Efficiency

Research has predominantly focused on adopting Best Available Techniques (BATs) to mitigate carbon emissions in EII, aiming to enhance energy efficiency by reducing efficiency gaps through short to medium-term measures (Worrell et al., 2009). Increasing energy efficiency can reduce sector-specific fuel consumption by around 15-20%. Recent studies have quantitatively demonstrated material efficiency in reducing emissions in the cement industry (Shanks et al., 2019; Material Economics, 2019; Hertwich et al., 2019; Favier et al., 2018; European Commission, 2018).

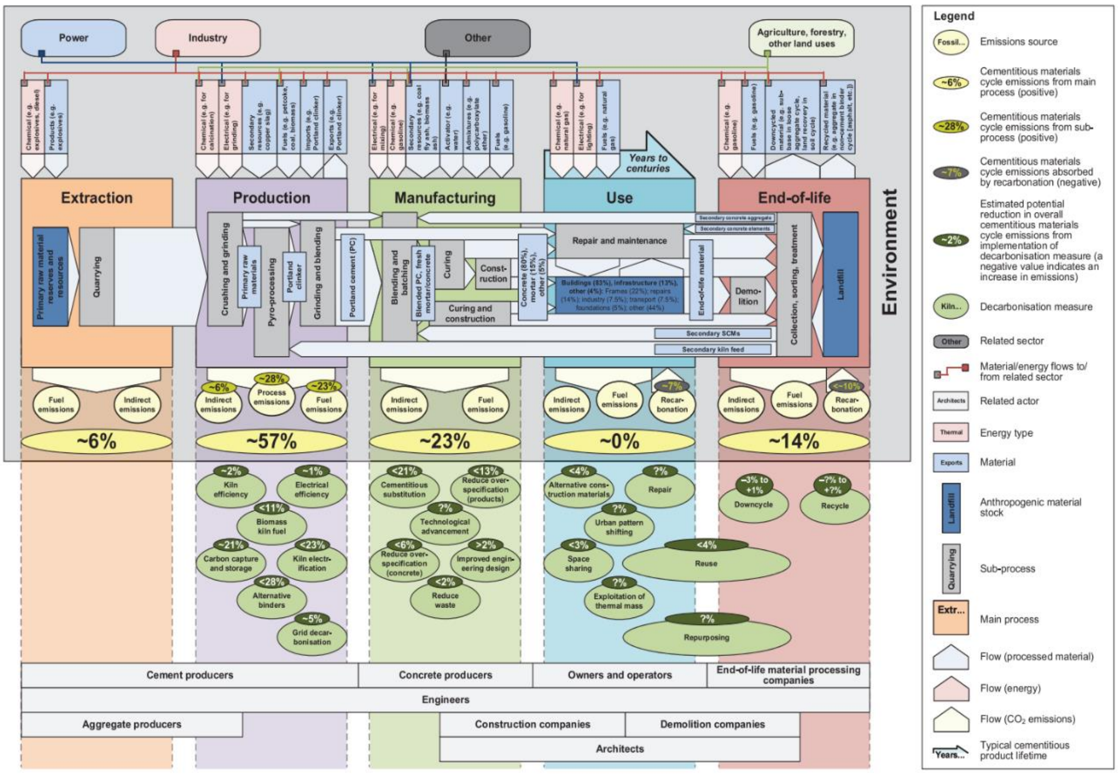

Figure 4. Cementitious materials (CMs) cycle. (Source: Pamenter et al., (2021). Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts. p.361.)

Energy efficiency varies across sectors and facilities within industries, and efficiency targets also differ by sector. For instance, in Portland cement production, pyro-processing is the most energy-intensive process, making kiln efficiency the focus of energy efficiency improvements (Panenter & Myers, 2021). However, despite the potential to reduce carbon emissions through energy efficiency improvements, some argue that achieving deep decarbonization remains challenging (Pee et al., 2018). Favier et al. (2018)

suggest that the decarbonization potential from energy efficiency may be limited in the future due to improvements already realized

Technology Development

Research and development (R&D) for EII is a crucial policy for enabling future emissions reduction. The International Energy Agency (IEA) (2015) emphasizes that as demand for basic materials is expected to continue rising, technological development is a key instrument for decarbonizing EII. Brook et al. (2015) suggest that the role of the United Nations Framework Convention on Climate Change (UNFCCC) should be further emphasized in global technology development efforts for sustainable energy.

Fischedick et al. (2014) argue that emissions from these industries can be reduced by 15-30% if the best available technologies (BATs) are applied on a large scale. To maximize the reduction effect, fundamental changes in key processes are necessary by integrating commercially viable innovative technologies. However, investment in technology development for EII has been relatively low compared to other industries (Hernandez et al., 2018), hindering the support for breakthrough technologies. Moreover, innovation in technology development has mostly focused on process improvements and product innovation rather than fundamental changes in processes and raw materials. New technologies require long periods for cost recovery, and operational disruptions for process adaptation and integration, making them less financially attractive (Hart, 2017; Fischedick et al., 2014). Additionally, the balance between basic research, applied research, and demonstration is crucial (Beard et al., 2009). Furthermore, a clear vision of the types of technologies, systems, and transition pathways is needed to provide clear direction for research aimed at emissions reduction.

Circularity

The circular economy differs from traditional linear systems by viewing economic activities as service-centered circulation systems (Korhonen et al., 2018). It holds economic value in service provision (WEF, 2016) and has the potential to enhance environmental sustainability for stakeholders. The concept of the circular economy is rooted in sustainable scientific research in the field of industrial ecology (Bocken et al., 2017). Carbon Capture and Utilization (CCU) differs from Carbon Capture and Storage (CCS) by using captured carbon dioxide as a feedstock for industrial processes such as chemical and fuel production. CCU is expected to make carbon capture more economically viable by generating revenue through the sale of captured carbon dioxide. However, addressing the significant energy consumption and high costs associated with converting carbon dioxide into useful chemicals is necessary for its realization (Pee et al., 2018).

Emissions Trading Scheme

The EU has prevented carbon leakage by directly compensating for free emission allowances through taxes and allocation exemptions via the Emissions Trading Scheme (ETS) (Åhman et al., 2017). The absence of evidence of carbon leakage suggests that the scheme has been effective (Bolsher et al., 2013). However, while the results of the ETS may be interpreted differently on a global scale, the application of a carbon pricing mechanism in one country can affect domestic production and consumption patterns and influence international market competitiveness through adjustments in relative costs and trade (Fragkos et al., 2021). The cost-effectiveness of emissions trading schemes may lead to negative outcomes by reallocating emissions to regions with weak environmental regulations (Paroussos, 2014). Carbon leakage can occur in both the energy sector and industrial sectors due to international energy price adjustments, affecting energy-intensive and trade-exposed industries. Regulatory implementation can lead to increased production costs for energy-intensive and trade-exposed industries in regulated countries, potentially causing them to relocate to countries without regulations. As a result of changes in production, exports, and trade conditions, industries in regulated countries may lose competitiveness, potentially resulting in delays or weakening of climate policies (Carbone & Rivers, 2017).

Carbon Contracts for Difference (CCfD)

While essential technological alternatives have matured to a commercial scale (Material Economics, 2019), they are often currently only used in pilot plant formats. Moreover, innovative investments are required for the realization of low-carbon processes, with uncertainty in revenue from carbon reduction or surplus allowances sales in the carbon market being a hindrance. Carbon dioxide prices have not been consistently high enough over the long term to confirm the economic viability of EII decarbonization projects (European Commission, 2021; Material Economics, 2019). Predicting future carbon prices is also challenging due to uncertainties in carbon market regulations and the unpredictable evolution of low-carbon technologies (Gerres et al., 2020).

Carbon contracts were initially proposed by Helm and Hepburn (2005) to address the volatility of government regulations in setting carbon reduction targets or carbon prices and to compensate for the long-term scarcity of the carbon market. Carbon Contracts for Difference (CCfD) are policy instruments that can be used to mitigate risks for project planners of carbon emission reduction projects such as cement and steel by providing subsidies or risk mitigation (Hoogsteyn, 2024). This concept was proposed by Richstein (2017) to raise funds for sectors with difficulty in reducing carbon emissions, such as steel, through carbon capture and storage, electrification projects, and hydrogen-based decarbonization. CCfD is a structure where the contracting authority, such as the central government, commits to a strike price (carbon contract price) with the corporate partners during bidding. In this structure, if the ETS price is insufficient, the contracting authority compensates for the shortfall, and if the actual carbon price is higher, the company reimburses the government for the difference.

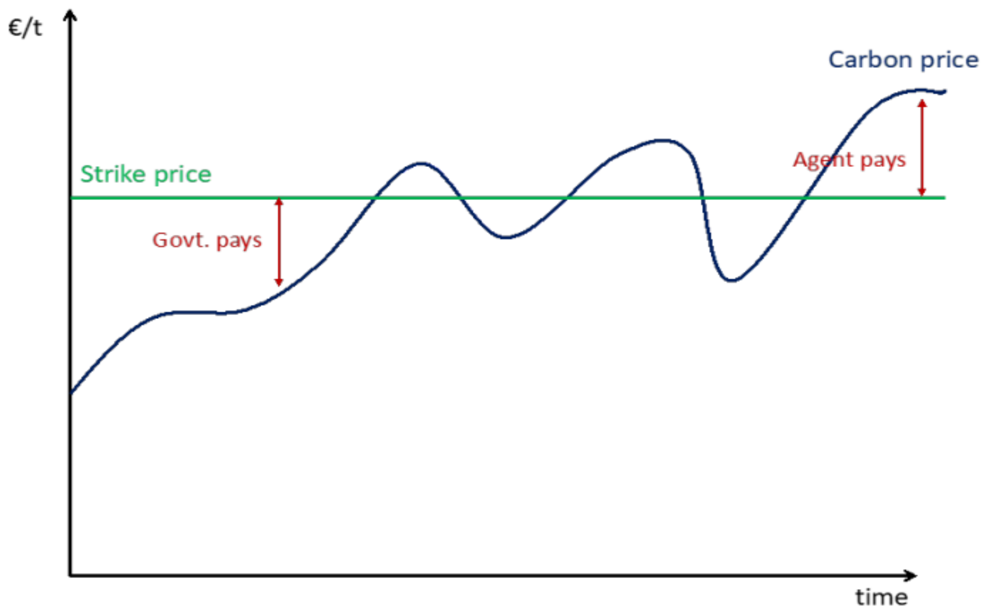

Figure 5. Strike Price and Redeem Mode of CCfD (Source: Gerres et al, (2020). Carbon Contracts for Differences: their role in European industrial decarbonization, Climate Friendly Materials Platform, p.2.)

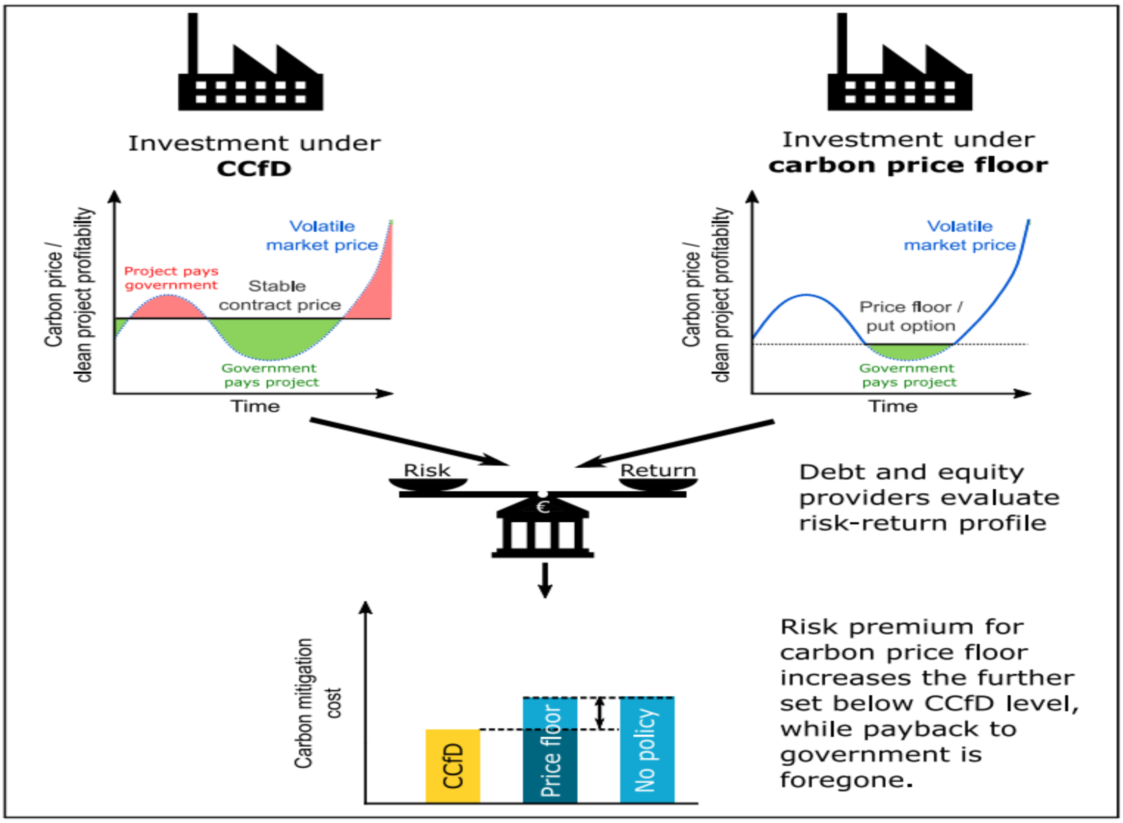

Figure 6. Design structure of CCfD (Source: Richstein et al, (2022). Carbon contracts-for-difference: How to de-risk innovative investments for a low-carbon industry? p.1.)

At low carbon prices, existing technologies lack competitiveness compared to innovative ones at high carbon prices. The dual nature of contracts allows new technologies to gain competitiveness at lower policy costs compared to unilateral put options (Richstein and Neuhoff, 2022).

CCfD operates as a government commitment mechanism, positively impacting innovation (Chiappinelli & Neuhoff, 2020), and providing certainty to low-carbon project investors about a portion of project returns, thereby reducing investment risk. Observations show a 30% reduction in the overall cost of renewable technologies in renewable CFDs (May & Neuhoff, 2017), while research by Richstein and Neuhoff (2022) indicates that easing policy and marketing costs could reduce fundraising costs for the steel industry by 27%.

CCfD may be considered similar to existing Renewable Energy Support (RES) schemes, but there are two important differences (Gerres, 2020). RES CfDs cover all revenue sources from investments, while CCfD only covers carbon revenues, one of the revenues of industrial production facilities. CCfD mitigates limited revenue risk, while CfDs address all revenue risks. Additionally, while the price differential in RES schemes is an essential part of contracts for producing electricity when needed, in CCfD, while efficient operation in the carbon market is necessary, it is not necessarily a crucial element.

Global Cooperation

Achieving decarbonization of EII requires international cooperation to mobilize sufficient resources and prevent unfair competition and carbon leakage. Given the high carbon and trade intensity, technological challenges for decarbonization, and strategic importance for economic development, a sectoral approach is essential for international cooperation (Åhman, 2017). Global cooperation on finance and technology can help overcome barriers related to process transition, facility investment, and new technology adoption (Oberthür, 2021). Mobilizing international and multinational funds can efficiently address the high costs required for innovation technology and solution development in developing countries while avoiding subsidy competition. For example, constructing new large-scale low-carbon demonstration plants in developing countries through fund procurement can reduce financial burdens, while advanced economies can secure circular economy-related technologies.

To date, the global climate policy regime has not produced innovative and long-term policies necessary for decarbonizing EII (Åhman, 2017). Previous policies have supported energy efficiency and emissions reduction and protected EII through exemption and compensation systems. Achieving a global agreement on emissions reduction is unlikely, and current declarations are insufficient to achieve the Paris goals (Fragkos, 2020), leading individual countries to implement unilateral climate policies (Böhringer, 2012). Unilateral policies may lead to a loss of cost-saving effects through location flexibility (Weyant, 1999) as the most efficient mitigation options are not observed across sectors and regions.

Demand-Side Policies

Demand-pull policies for EII would include public procurement systems that require a certain level of low-carbon materials, consumption taxes on materials, and electricity-like supply taxes (Åhman, 2017). Neuhoff et al. (2015) suggest that demand-based incentives should be reflected in carbon pricing under the EU ETS, along with carbon taxes on material consumption and free allocation of emission rights. However, demand-side policies may face challenges in encouraging innovation throughout the value chain of industries because EII are inherently B2B, and companies tend to perceive sustainability as a competitive disadvantage (Åhman, 2017). Companies in EII perceive greenhouse gas regulations as factors that weaken global competitiveness and have negative impacts on employment and management.

In contrast, companies in B2C sectors such as the food and automotive industries perceive sustainability as an important means of differentiation for competitive products (Wells & Nieuwenhuis, 2012; Spaargaren & Oosterveer, 2013). Sustainability as a means of differentiation presents a unique hurdle for the transition of EII to decarbonization. Therefore, while governments support R&D and decarbonization efforts throughout the demonstration phase, support for scaling through demand incentives and effective regulations is lacking. A combination of technology-driven policies and demand-side policies does not currently exist, and there are few companies attempting technology development with the goal of zero emissions.

4. Carbon neutrality and supply chain policy of Korea

4.1. Stabilization of Industrial Supply Chains

4.1.1. Industrial supply chain in carbon neutral policy

Since the prominence of global supply chain issues in 2018, Korea has consistently formulated policies on carbon neutrality, making it a national agenda. Among these, the Vision and Strategy for Carbon-Neutral Industrial Transition and the Carbon-Neutral Green Growth Promotion Strategy specifically address issues related to industrial supply chains.

The Vision and Strategy for Carbon-Neutral Industrial Transition, announced in 2021, aims to achieve a secure nation within the carbon-neutral supply chain impact. It proposes strategies such as developing tailored supply stability plans for essential items crucial for achieving carbon neutrality, preemptively managing supply chain issues arising from industrial transitions, and building a resilient mineral resource network through global competition preparation, secured stockpiles, and recycling.

This policy is based on the recognition of the potential perpetuation of supply chain uncertainties due to the structural transformation of industries under carbon neutrality, changes in global value chains, and logistics bottlenecks. The plan identifies 338 key items based on current import values and dependency rates for supply chain management, intending to select items with excessive dependence on specific countries or those closely related to citizens' daily lives.

Additionally, it involves utilizing overseas embassies and trade offices to analyze regulatory changes and impactful issues in other countries, and establishing a supply chain information hotline among the GVC Integration Support Center, companies, associations, and the government. The strategy also includes creating or expanding dedicated bases to stockpile rare metals as a core safety net, increasing the average stockpile days from the current 56.8 days to 100 days, and planning to extend it to a maximum of 180 days in the future.

In the Carbon-Neutral Green Growth Promotion Strategy announced in 2022, the direction is set for promoting low-carbonization in industries, providing comprehensive support for the industrial sector, and enhancing the circular economy. It emphasizes the need to formulate measures to curb the increase in greenhouse gas emissions in the industrial sector, considering the increase in emissions due to both greenhouse gases and the recovery from the COVID-19 pandemic.

Under the low-carbonization section, the strategy proposes replacing fossil fuels with low-carbon and zero-carbon fuels, transitioning production processes to decarbonized and digitally intelligent facilities and processes, and transforming the industry into environmentally friendly, high-value-added items like zero-emission vehicles. In the industrial support section, it designs reduction technologies for industries with significant emissions as emerging growth source technologies, expanding deductions for Research & Development (R&D) and facility investments, and supporting green policy loans for carbon-neutral private investments. The circular economy part focuses on using easily recyclable materials from the design stage of products, setting recycling targets for different industries, enhancing environmental information through carbon footprint and recycled product labeling, and constructing a future recycling system for waste resources such as batteries, solar panels. , and marine plastics.

The Special Measures Bill on Carbon-Neutral Industrial Protection and Competitiveness Enhancement, introduced in 2023, responds to the protectionist trend arising from the enactment of the IRA in the U.S. and NZIA in the EU. This legislation is designed to contribute to the robust development of the national economy and energy security, as well as the sound development of the national economy, by establishing an economic foundation for responding to the climate crisis and transitioning to a carbon-neutral society through efficient support for domestic carbon-neutral industries.

Recognizing concerns about the deterioration of domestic employment and industrial cooperation due to increased overseas investment by domestic companies, the bill promotes and strengthens domestic investment in carbon-neutral industries such as electric vehicles, renewable energy, and green products. It also outlines directions for creating an economic foundation for transitioning to a carbon-neutral society.

This Act focuses on enhancing the competitiveness of carbon-neutral industries based on the formulation of a basic plan for fostering carbon-neutral industries, a survey of the current situation, and predictions for future development. To secure technology and strengthen competitiveness in carbon-neutral industries, the government is empowered to pursue the

National Carbon Neutrality Technology Development Project, which includes research and development activities in the field of carbon-neutral industries, strategic surveys and analyses of domestic and foreign patents and intellectual property rights, and joint R&D projects among industries, academia, and research institutions. Additionally, the Act allows for the selection or exemption of projects related to carbon-neutral industry support zones and national carbon neutrality technology development projects if approved. Moreover, it supports the creation and operation of the foundation and production facilities for carbon-neutral industries and enables the effective operation of projects aimed at enhancing competitiveness, utilizing special accounts and funds.

Under this Act, companies involved in carbon-neutral industries can apply to the government for regulatory improvements related to research and development, testing and evaluation, verification, and production activities. The government oversees projects that have received regulatory improvements. Policies may be developed and implemented to recruit and nurture experts in carbon-neutral industries, and support for carbon-neutral industry investment can be facilitated through the utilization of venture investment consortia. Furthermore, to promote domestic investment in carbon-neutral industries, tax reductions must be provided in proportion to the investment amount or production volume of related companies, as specified by relevant Acts such as the Special Tax Reduction Act and the Local Tax Reduction Act.

This Act places a strong emphasis on internalizing Korea's production infrastructure through the establishment of carbon-neutral industry specialized zones, the creation and operation of infrastructure and production facilities, and support for human resources and technology development for companies. However, its limitations include a lack of comprehensiveness due to its focus on only six categories of industries: electric vehicles, renewable energy facilities, zero-carbon hydrogen and production facilities, energy-saving projects, green products, and recycled resources. Additionally, it does not cover aspects such as securing raw materials, external cooperation, supply chain monitoring, and contingency planning for shocks.

4.1.2. Supply chain stabilization strategy and legislation

The Korean government's policy for stabilizing the supply chain is the 'Industrial Supply Chain 3050 Strategy' announced in December 2023. announced in December 2023. This strategy is closely linked to the Act on Special Measures to Strengthen Competitiveness and Stabilize Supply Chain of Materials, Components, and Equipment Industry. Among the 4,458 imported items in Korea's material, parts, and equipment categories, 1,719 items have an import value exceeding one million dollars or exhibit a specific country import dependency of 50% or more, or the import dependency of specific three countries comprise 70% or more. Among them, 185 items with high import dependency on specific countries or significant impact on the domestic economy are defined as supply chain stabilization items. The strategy aims to reduce the import dependency on specific countries for supply chain stabilization items from an average of 70% in 2022 to 50% or below by 2030. To achieve this goal, the strategy introduces ten implementation tasks and outlines eight leading projects for the industrial supply chain, focusing on secondary battery materials, semiconductor materials, semiconductor rare gases, rare earth permanent magnets, elements, magnesium, and molybdenum.

<Table 2. 10 major implementation tasks>

Management system	■ Establishment of systems and promotion systems for supply chain response ■ Advancement of early warning system and operation of rapid response system in case of crisis
Independence	■ Expansion of independent production base for core items ■ Linkage with early development of core technologies and construction of production facilities ■ Strategic foreign investment/U-turn expansion to expand domestic production capacity
Diversification	■ Diversification of import sources to disperse supply chain risks ■ Overseas M&A and P-turn support to diversify production bases
Securing resources	■ Support for expanding public stockpiling of key minerals and securing private stocks ■ Expanding the basis for cooperation with resource-rich countries and supporting private projects ■ Recycling technology development and system establishment

* Source: Ministry of Trade, Industry and Energy (2023), 'Industrial Supply Chain 3050 Strategy' press release, p.7.

Firstly, for resource procurement, the strategy proposes expanding the public stockpile of key minerals, supporting companies in securing inventories, strengthening cooperation with resource-rich countries, and supporting private projects. Additionally, it emphasizes the development of recycling technologies and systems while expanding core mineral stockpiles from 56.8 days to 100 days for 20 key minerals and 35 items. An investment of approximately 1.8 billion dollars will be made to establish a dedicated base for stockpiling national core minerals by 2026. Furthermore, to support companies' overseas core mineral acquisition projects, the strategy expands the special loan support ratio for overseas resource development from 30% to 50% of the project cost and introduces a 3% corporate tax deduction for overseas investments in mining rights acquisition. The strategy also supports the development of alternative materials such as silicon anodes and lithium metals to replace graphite, as well as recycling technologies for used batteries and permanent magnets. To enhance the circular utilization of core resources, the strategy introduces a system designating recycled resources, alongside establishing a battery life cycle integrated management system.

Second, to mitigate supply chain risks, efforts are underway to strengthen domestic self-reliance and promote diversification of production hubs and import sources. A budget of 1.5 billion dollars is allocated to attract foreign investment for seven strategic industries and ten specialized complexes in materials, parts, and equipment. Incentives include a corporate tax deduction of 5-10% for mergers and acquisitions involving foreign companies to diversify production hubs. Additionally, financial support for feasibility studies and costs related to finance, legal, and logistics is provided when domestic companies relocate overseas production hubs to third countries.

Thirdly, an advanced Early Warning System utilizing AI will be developed, along with short-, medium-, and long-term response scenarios for specific products. Joint government crisis response simulations are planned, alongside the establishment of a Supply Chain Cooperation Platform with partner countries to facilitate collaboration, select cooperative items through platform utilization, and conduct stress tests.

Moreover, the Special Act on National Resources Security (National Resource Security Act), enacted in February 2024, addresses the growing challenges in securing the safety of resource supply chains due to the recent heightened dependency of the domestic economy on foreign resources. It acknowledges global trends, such as the US promoting carbon neutrality through the Inflation Reduction Act, Japan designating rare earths and major minerals as specified important materials for management under the Economic Security Enhancement Act, and the reinforcement of protectionist measures globally.

This Act defines Essential Resources as those with significant impacts on daily life, or with substantial economic effects on national economic activities or industrial production. It includes energy sources, minerals, materials for renewable energy facilities, and components designated by the government. The establishment of a resource security framework involves the formulation of the Basic Plan for Resource Security, the designation and establishment of a dedicated agency and association, and the construction of an integrated information system for comprehensive management of resource security information. To strengthen the core resource supply chain, specific business plans are subject to preliminary feasibility studies and exemptions related to environmental protection. The Act also includes provisions allowing the government to perform international cooperation, research and development, human resource training and education, and promotional activities as part of the infrastructure for resource security.

Additionally, the Act establishes a Resource Security Early Warning

System as a preventive and contingency measure for resource security crises. This system aims to diagnose the current status and trends of national resource security, inspect and analyze supply chains. The government is empowered to formulate contingency plans for core resource stockpiling, designate and manage emergency mobilization mines, designate and manage key supply agencies and demand organizations in times of crisis. In the event of a resource security crisis, the government can issue crisis alerts, establish and operate a Resource Security Crisis Headquarters. Moreover, to ensure the supply and price stability of core resources, regulations are in place for the importation of overseas-developed core resources, the release and utilization orders for stockpiled resources, and measures for the stable supply of core resources.

The Basic Act on Supply Chain Stabilization Support for Economic Security (Supply Chain Stabilization Act), enacted in December 2023, aims to establish a comprehensive government response system for supply chain crises. This system is designed to prevent and effectively respond to various supply chain risks arising from various domestic and international factors. Its purpose is to contribute to national security, maintain safety related to national economic activities, and promote the development of the national economy.

The Economic Security Items specified in the Supply Chain Stabilization Act refer to materials, raw materials, parts, equipment, or software with high import dependence on specific foreign countries or regions or essential for the production of goods necessary for people's lives or vital for the stability operation of the national economy. Unlike the National Resource Security Special Act, this Act distinguishes itself in its provision for the Supply Chain Stabilization Fund. This fund is utilized to support the acquisition and supply of economic security items, domestic and foreign facility investments, and operations for supply chain stabilization, technology development, commercialization, and to provide emergency support to affected companies due to supply chain shocks.

<Table 3. National Resource Security Act and Supply Chain Stabilization Act >

Regulations	Special Act on National Resources Security	Supply Chain Stabilization Act
Management target	• Core resources Resources that have a significant impact on people's lives or have a large national economic ripple effect, such as economic activities or industrial production	• Economic security items Items that are indispensable to people's lives or essential to the stable operation of the national economy, such as materials that are highly dependent on imports from specific countries or regions overseas, or raw materials, parts, facilities, devices, equipment, or software required for their production.
Core resource management	• Development, purchase, and procurement of core resources • Stockpiling of key resources Installation and operation of supply infrastructure • Diversification of key resource supply countries • Recycling of core resources	• Selection of leading business in supply chain stabilization • Technology development support • Stockpiling and management of economic security items • Support for domestic and overseas production base

	• Designation of emergency mobilization mine • Designation and management of key supply organizations Designation and management of core demand organizations	• Support for diversification of importing countries • Establishment of the Supply Chain Stabilization Fund
Early Warning System	• National Resource Security Integrated Information System - Supply chain inspection and analysis	• Early warning system - Inspection of supply chain risks
Crisis response	• Resource security crisis warning issued • Organization and operation of resource security crisis response headquarters • Order to bring in overseas development core resources • Release and use of reserve resources • Mining of emergency mobilization mines Adjustment orders to organizations supplying and demanding core resources • Setting the maximum selling price of core resources • Measures to stabilize supply and demand	• Designated as a crisis item • Establishment and operation of crisis response headquarters • Creation and operation of a crisis response manual • Emergency supply and demand adjustment measures • Emergency procurement

4.1.3. Implications

Recent policies and legislation related to Korea's carbon neutrality and supply chain stabilization have evolved towards greater integration and the presentation of concrete implementation methods compared to previous initiatives. Particularly, the two Acts concerning supply chain stability strategically respond to the restructuring of resource supply chains. They also present new systems for resource security, early warning, supply and demand management of essential resources, and crisis response mechanisms, all aimed at ensuring the nation's safety and sustainable development of the economy. These Acts, including previous individual legislations such as the City Gas Business Act, Petroleum and Alternative Fuels Business Act, Mining Act, and Overseas Resource Development Act, provide an integrated and effective response system for the supply of raw materials, components, and equipment, addressing challenges comprehensively.

However, despite these advancements, the carbon neutrality policy, supply chain stabilization strategy, and associated legislation do not demonstrate a strong interconnection. The policies and Acts related to carbon neutrality allocate minimal focus on the sustainability and resilience of the supply chain, while policies and acts addressing supply chain stabilization lack clear goals and visions for establishing and realizing carbon-neutral systems.

Recognizing the significant impact of carbon neutrality and supply chain stabilization on medium to long-term strategies and economic security, there is a growing need to strengthen the connections between these policies. This involves a reevaluation of the interconnectedness of carbon neutrality and supply chain stabilization, emphasizing efficient resource allocation and strategic execution across policies.

4.2. Policies for Energy-Intensive Sectors

The content of Korea's policies related to EII can be categorized into technology development for energy and material efficiency, industrial transition, CCUS, and carbon price incentives.

From the perspective of technology development, the ‘Carbon Neutral Green Growth Technology Innovation Strategy’ (announced in October 2022) proposes to select 100 key technologies for achieving carbon neutrality in Korea, considering factors such as carbon reduction contribution, cost-effectiveness, and feasibility. In the EII sector, plans are in place to develop 48 environmentally friendly fuel and material technologies to replace high-carbon fuels and materials at critical stages of carbon emissions. Additionally, to support low-carbon transition in EII sectors facing significant burdens, reduction technologies are designated as new growth/core technologies, qualifying for tax deductions for R&D and facility investments.

<Table 4. Carbon neutral 100 core technologies (draft)>

Sector	Carbon neutrality focus areas	Core technologies (draft)
Steel	Hydrogen reduction steelmaking	(Raw material conversion) Hydrogen reduction manufacturing, 2 new electric furnaces, etc.
	High-speed electric furnace	(High efficiency) A total of 2, including the use of low-carbon new heat raw materials
	By-product upcycling	(Resource circulation) 2, including upcycling of steel by-products

	Low carbon blast Furnace, converter	(Conversion of fuel and raw materials) 2 carbon-reducing blast furnaces and converters, etc.
Petrochemical	Fuel conversion	(Process electrification) 2 electric heating furnace systems
	Raw material conversion	(Bio-based raw materials) 5 including bio naphtha
	Resource circulation	(Waste plastic raw materials) Sorting and pre-processing of mixed plastics, etc. 4
	Low-carbon chemical process	(High-efficiency) 4 low-energy separation processes, etc.
Cement	Use of mixed materials	(Raw material conversion) 2 things including increasing the content of mixed materials in OPC
	Limestone raw material replacement	(Raw material conversion) Non-carbonate raw materials 5 pre-processing technologies, etc.
CCUS	Capture	(Securing economic feasibility) 4, including post-combustion capture
	Save	(Large-scale) Storage exploration and evaluation, etc. 4
	Uses	(Securing economic feasibility) A total of 3, including mineral carbonation
General Industry	Alternative fuel application	(Fuel conversion) 2 chemical fuel replacement electrification, etc.
	Raw material process replacement	(Raw material conversion) 3 items including the replacement of high GWP process gas
	Process energy efficiency	(High efficiency) 2, including improving the efficiency of electric motors and power converters

* Source: Ministry of Trade, Industry and Energy (2022), 'Carbon Neutral Green Growth Technology Innovation Strategy', p.8.

Regarding industrial transition, the 'Carbon Neutral Industrial Transition Vision and Strategy' (announced in December 2021) is conducting feasibility studies on core technologies for industrial carbon neutrality and aims to accumulate operational experience and technology through proactive industrial transition. To achieve this, partnerships between the government, construction companies, financial institutions, and green plant overseas ventures are being established, and the government supports these efforts through ODA, overseas reduction projects, and global partnerships.

To promote the circular economy, the ‘Energy Carbon Neutral Innovation Strategy’ (announced in December 2021) aims to establish roadmaps for maximizing the use of recycled materials and sets targets or strengthens the utilization rates of renewable resources by industry to promote raw material savings. For example, goals include increasing the utilization target of steel scrap from the current 50% and expanding the use of recycled plastics in the petrochemical sector. Additionally, innovative materials such as carbon fibers and graphene are being developed to replace steel and plastics, while efforts are being made to reduce the use of petroleum-based plastics through bio-plastics and carbon capture plastics.

In particular, regarding CCUS, the ‘CCUS Industry and Technology Innovation Promotion Plan’ (announced in April 2023) presents the vision of commercializing CCUS with the participation of Korean companies and public institutions and proposes a Two-track strategy, where companies pioneer the market and research institutions secure technology.

Initial plans have been outlined for each section of capture, storage, and utilization. For capture, commercial technology acquisition and large-scale demonstrations are planned to achieve over 30% cost reduction compared to current levels. Through innovative technology development, plans include reducing carbon capture costs, commercializing optimized capture technologies based on emission characteristics (concentration, sector), securing quasi-commercial (1,000 tons/day) and commercial (3,000 tons/day) capture technologies, and establishing large-scale integrated demonstration systems for CCS integration in the East Sea and West Sea to pursue large-scale integrated demonstrations of 1 million tons/year. For storage, efforts are being made to secure domestic storage of 1 billion tons through advanced exploration and evaluation techniques, and comprehensive exploration and drilling surveys of domestic continental basins will be initiated early on. Overseas, efforts are underway to secure CO2 storage by preempting depleted oil and gas fields.

Plans have been presented to integrate and demonstrate already secured unit technologies to secure CCUS commercialization technology and expand business. Integrated demonstrations of quasi-commercial CCU combining capture and utilization will be conducted, and a platform for technology development, demonstration, and commercialization will be established to promote the localization and competitiveness enhancement of core materials and process technologies for carbon-neutral industries.

Regarding carbon price incentives, the ‘Carbon Neutral Industrial Transition Vision and Strategy’ (announced in December 2021) proposes to explore a support system for complementary carbon price analysis to reduce the investment burden on companies. This includes utilizing research results from specialized institutions for reduction consulting for companies and responding to CBAM, as well as reviewing carbon price incentive measures for industries facing difficulties in reduction, such as steel.

The ‘Carbon Neutral Green Growth Promotion Strategy’ (announced in October 2022) aims to improve emission trading schemes to facilitate cost-effective reductions by expanding paid allocation and emission efficiency standards (BM) allocation for emissions rights trading. Furthermore, plans involve gradually expanding participation by emission rights market participants and diversifying trading products to activate the emissions rights market. Additionally, plans are in place to utilize income from paid emission rights allocation to support the introduction of carbon-neutral facilities, new technologies, and innovative processes.

5. Carbon neutrality and supply chain policies in the U.S.

5.1. Carbon neutrality and supply chain policy

Since 2018, the shift in the U.S. approach toward China has marked the decisive beginning of a major transformation. The acceleration of this change gained momentum with the activation of the Executive Order on ‘America’s Supply Chain’(E.O. 14017) in 2021. Through this executive order, the U.S. has begun to investigate supply chain vulnerabilities and prepare countermeasures by mobilizing the entire federal government across 10 areas, including four key items (semiconductors, batteries, pharmaceuticals, and rare earth elements) and six major sectors (defense, health and bio, ICT, energy, and transportation). Notable legislative actions, such as the 2021 Infrastructure Investment and Jobs Act, the 2022 CHIPS and Science Act, and the Inflation Reduction Act, have subsequently formulated actionable plans supported by legislation and federal budgets based on the findings of the supply chain survey. The U.S. government has indicated that industrial policies expressed through supply chain policies will become a core component of US government industrial and trade policy

(Kim, 2021).

Among these, legislation directly linked to carbon neutrality is the Infrastructure Investment and Jobs Act (IRA), consisting of eight titles. Subtitle D, focusing on Energy Security, is a section where various incentives related to the entire eco-friendly industry are concentrated. The US is estimated to allocate a total of $737 billion from the IRA over ten years through corporate tax, excise tax adjustments, and enhanced tax collection, with $369 billion, or 50%, earmarked for investment plans in energy security and climate change.

<Table 5. IRA major Incentives>

incentive	Main Content
Clean manufacturing facility Investment tax credit ($6.3 billion)	Investment tax credits of 6 to 30% of the investment amount are paid when installing or expanding manufacturing facilities for electric vehicles, batteries, and related materials and components in the U.S. (Example) Tax credit benefits for building and expanding electric vehicle and battery production plants in the U.S.
Advanced manufacturing production tax credit ($16 billion)	A tax credit of approximately 10% of the production cost is provided for high-tech parts and key minerals such as batteries, solar power, and wind power produced and sold in the U.S.
General eco-friendly car Tax credit ($7.5 billion)	Final assembly in North America, $3,750 paid when battery parts requirements are met and $3,750 paid when mineral requirements are met for eco-friendly vehicles not equipped with batteries of foreign corporations of concern.

commercial eco-friendly vehicle Tax credit ($3.6 billion)	A tax credit of up to $7,500 or 30% of the vehicle price is provided to consumers who purchase an eco-friendly commercial vehicle.
Eco-friendly large vehicle Subsidies ($1 billion)	Subsidies are provided for additional costs incurred when replacing an existing vehicle with an eco-friendly large vehicle, and repair costs for eco-friendly large vehicle parts.
Clean power investment ($50.9 billion) · Production tax credit ($11.2 billion)	Tax credits are paid when investing in clean power generation facilities such as solar power and wind power or producing power at such facilities.
High-tech vehicle Manufacturing facility loan ($3 billion)	When installing or expanding manufacturing facilities for high-tech vehicles and parts such as electric or hydrogen vehicles in the U.S., provide low-interest loans after review by the Ministry of Energy.
Department of Energy Loan Guarantee ($4.3 billion)	Loans are guaranteed after review by the Ministry of Energy when investing in preventing greenhouse gas emissions using cutting-edge technologies such as electric vehicle production facilities.

*Source: U.S. Congressional Budget Office presentation (September 7, 2022), Ministry of Trade, Industry and Energy press release (October 19, 2022).

Key points in the Energy Security sector of IRA emphasize tax deductions related to environmentally friendly industries. The US plans to secure the entire value chain of energy production facilities, including solar, wind, batteries, and hydrogen, within the U.S., encouraging domestic production and sales.

To support domestic production for energy security, tax deductions for energy assets, including energy storage technology and biogas, tax deductions for the production of renewable power facilities, and tax deductions for domestic production and sales of solar and wind components, have been introduced. Additionally, tax deductions for clean hydrogen production facilities, tax deductions for solar power facilities, solar water heating facilities, geothermal heat pumps, fuel cells, and small-scale wind energy, as well as tax incentives for the purchase of eligible biomass fuel assets, are outlined in various parts of Subtitle D.

Looking at the eligibility criteria for tax deductions in the energy security sector, particularly for eco-friendly vehicles, solar, and wind, the following can be observed. For electric vehicles, it is stipulated that the vehicle must be finally assembled in the North American region. Moreover, a $3,750 deduction is provided if the core minerals for battery use meet the requirements, with an additional $3,750 deduction for meeting the battery component requirements. Core minerals for batteries are expected to meet 40% by 2023 and exceed 80% by 2027, mined, processed, or recycled in the U.S. or countries that have signed an FTA with the U.S. Until 2023, more than 50% of battery components for electric cars must be finally manufactured or assembled in North America, increasing by 10% each year until it reaches 100% by 2029. Additionally, the legislation specifies that subsidies are excluded for components produced by Foreign Entities of Concern (FEOC) during the procurement of core minerals.

The primary means of supporting the solar industry in terms of policy tools in the energy security sector is through tax deductions. Two main types of tax deductions provided to solar businesses are the Production Tax Credit (PTC) and Investment Tax Credit (ITC), and businesses must choose one of them. PTC calculates tax deductions based on the proportion of renewable energy production, while ITC deducts a certain percentage of the investment amount. PTC provides a tax deduction benefit of 1.5 cents per kWh for ten years when meeting wage and apprenticeship conditions, and 0.3 cents if not met. ITC offers a tax deduction benefit of 30% of the investment amount when meeting wage and apprenticeship conditions.

In the case of wind power, both the Production Tax Credit (PTC) and Investment Tax Credit (ITC) are applicable. The PTC tax deduction benefits for onshore wind power, which were initially scheduled to expire in 2021 before the enactment of the Infrastructure Investment and Jobs Act (IRA), have been extended, allowing for continued PTC application. Additionally, the ITC provides tax deduction benefits for offshore wind power until 2035. Particularly noteworthy is the requirement for the share of US-made components in other renewable energy sectors, which is set at 40%. In contrast, for offshore wind power, it is sufficient to meet a 20% or more share of US-made components (including US-made steel, iron, and manufactured components). Moreover, tax deductions are granted for additional components related to wind power, such as nacelles, blades, towers, and substructures, when produced or sold domestically in the U.S. Furthermore, a 10% tax deduction is provided for the sale of ships produced or modified for the purpose of developing, transporting, installing, operating, or maintaining offshore wind power components. Notably, the guidance for solar and wind differs from the IRA battery regulations by not explicitly excluding concerns related to FEOC, allowing for the inclusion of

Chinese products.

According to the analysis by U.S. Senators in 2022, key goals and related programs in energy security and climate change include five aspects: energy cost reduction, strengthening energy security, reducing carbon emissions across the economy, sharing clean benefits with local communities, and promoting climate change adaptation in local communities. Specifically, concerning community investments, there is a push for the green transformation of existing infrastructure in transportation and ports. The initiative involves promoting community-led projects and enhancing community capacity programs. Investments for climate change adaptation in local communities include funding for smart agriculture, forest restoration, land conservation, and clean energy development in rural communities. The U.S. Infrastructure Investment and Jobs Act simultaneously pursues policy objectives of securing the safety of the supply chain and revitalizing the U.S. domestic economy, highlighting the close integration of climate policy with economic security policy.

<Table 6. U.S. Senator Analysis Data>

Main goal	Program	Budget (unit: dollar)
Lowers energy costs for Americans	Consumer Home Energy Rebate Program: Helps low-income consumers electrify their appliances and improve energy efficiency.	9 billion
	10-year consumer tax credit: Tax credits for heat pumps, rooftop solar, electric heating and water heaters	-

	Tax credit for eco-friendly vehicles for low- and middle-income groups	Used vehicle 4,000/New vehicle 7,500
	Provide subsidies for home energy efficiency improvements	1 billion
Increases American energy security	Production tax credits to accelerate the processing of solar panels, wind turbines, batteries, and critical minerals	30 billion
	Investment tax credits for building clean technology manufacturing facilities such as electric vehicles, wind turbines, and solar panels	10 billion
	Defense Production Act (DPA) funding for heat pumps and core mineral processing	500 million
	Provide subsidies to remodel existing automobile manufacturing facilities to produce eco-friendly vehicles	2 billion
	Loan support for construction of eco-friendly vehicle manufacturing facilities	20 billion
	Support for national research institutes to accelerate advanced energy research	2 billion
Decarbonizing all sectors of the economy	Tax credits and state loan programs for clean electricity and energy storage	30 billion
	Tax credits for the adoption of clean fuels and clean commercial vehicles	-
	Subsidies and high-tech industrial facility tax credits to reduce emissions from the largest industrial sources, such as chemical, steel, and	6 billion

	cement plants	
	Purchasing U.S.-manufactured clean technologies ($9 billion) Supporting the U.S. Postal Service’s purchase of zero-emission vehicles ($3 billion)	9 billion/ 3 billion
	Supporting the deployment of carbon emissions reduction technologies in underserved areas	27 billion
	Program to reduce methane emissions from natural gas production and distribution	-
Investments into disadvantaged communities	Investing in community-led projects and community capacity-building centers to address the disproportionate harm caused by climate change.	3 billion
	Support transportation facilities or construction projects to reconnect communities separated by existing infrastructure barriers.	3 billion
	Support for the purchase and installation of carbon reduction equipment and technology at ports to reduce port air pollution	3 billion
	Support for clean medium and large vehicles such as school buses, public transportation buses, and garbage trucks	10 billion
Resilient rural communities	Smart Agriculture Support	20 billion
	forest expansion prevention, forest conservation, and urban tree planting, etc.	5 billion
	support domestic production of biofuels and build	-

	infrastructure for sustainable aviation fuel (SAF) and other biofuels	
	Grants to conserve and restore coastal habitats	2.6 billion

* Source: Senate Democrat (2022), Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022

5.2. Carbon Barrier: Clean Competition Act

The U.S. CCA aims to compel importers to pay for the difference in emissions intensity between the origin country's emissions intensity profile and the U.S. industry's average emissions intensity profile, calculated per ton of emissions. It applies to 12 sectors including fossil fuels, petroleum refining, steel, and aluminum, with a charge of $55 per ton of carbon emissions, increasing annually by 5% above inflation. It will be implemented starting in 2025, and from 2026, the scope will expand to include imported finished products containing at least 500 pounds (226 kg) of energy-intensive primary products, and by 2028, the minimum raw material threshold will be lowered to 100 pounds.

<Table 7. Main Contents of CBAM>

Application field	Fossil fuels, petroleum refining, petrochemicals, fertilizers, hydrogen, adipic acid, cement, steel, aluminum, glass, pulp and paper, ethanol
Carbon price	$55 per ton, 5% above inflation each year
Cost imposition method	Importer pays for emissions per ton equal to the difference between the emissions intensity of the country of origin and the U.S. industry average. ▪ In the absence of reliable data: the ratio of the emission

	intensity level of the country of origin economy to that of the US economy. ▪ Where reliable data are available: the ratio of the average emissions intensity of the industry in the country of origin to the emissions intensity of the corresponding industry in the United States.
Domestic industry impact	▪ U.S. producers pay for emissions above the industry average ▪ The baseline is calculated by the Ministry of Finance, and based on the baseline, the average emission capacity is calculated for Scope 1 and 2 emissions for each industry. ▪ Baseline is designed to decrease by 2.5% annually from 2025 to 2028 and by 5% thereafter.
Export rebate	Producers of raw materials in the United States subject to carbon border adjustment are eligible for export rebates (subject to compliance with WTO rules).
Implementation period	Phased introduction of applicable products starting in 2024. Starting in 2026, the scope of application will be expanded to include imported finished products containing at least 500 pounds (226 kg) of energy-intensive primary products, and the minimum raw material quantity standard will be increased to 100 pounds in 2028. downgraded to
Revenue utilization	75% of revenues to fund investments in decarbonization of affected industries 25% of revenues to fund investments in decarbonization in least developed countries
Least Developed Countries (LDCs)	Least developed countries are exempted

*Source: CSIS, (2022), 'Trade Tools for Climate: Transatlantic Carbon Border Adjustments', https://www. csis.org/analysis/trade-tools-climate-transatlantic-carbon-border-adjustments / U.S. Congress, Clean Competition Act, S. 4355, 117th Cong., 2nd sess., https://www.congress. gov/117/bills/s4355/BILLS-117s4355is.pdf

6. EU carbon neutral policy

6.1. Carbon Neutrality and the Blend of Supply Chain Policies

The NZIA (Net-Zero Industrial Act) fosters an industrial environment to facilitate the rapid expansion of carbon-neutral technologies, providing favorable conditions for crucial sectors in achieving carbon neutrality, including solar power, wind power, heat pumps, electrolyzers, and fuel cells. The bill aims to secure domestic manufacturing capacity for strategic net-zero technology up to 40% of the EU's annual consumption needs by 2030 and guarantee the free movement of carbon-neutral technologies within the EU single market.

The Carbon Neutrality Strategy Project of the NZIA bill focuses on improving investment conditions to activate the net-zero technology manufacturing project. The key components involve strategic carbon-neutral technologies, which encompass the eight major technologies: solar and solar thermal, wind power, batteries, and storage, heat pumps and geothermal energy, electrolysis and fuel cells, sustainable biogas and biomethane, carbon capture and storage, and grid technology. This list may be updated based on future technological demand and contributions. Carbon-neutral technology projects located within the EU can be selected if they meet one or more of the following conditions:

(i) Contribute to the technological and industrial resilience of the domestic energy system by expanding manufacturing capacity for components or elements overly dependent on imports from specific third countries within the carbon-neutral technology value chain.

(ii) Contribute to the competitiveness of the domestic carbon-neutral industry supply chain and create high-quality jobs, thereby positively impacting the domestic supply chain or downstream sectors.

Following the NZIA enactment, EU member countries are required to designate a 'One Stop Shop' for each national jurisdiction within three months, streamlining administrative and permitting responsibilities for projects.

The NZIA mandates considering the sustainability and resilience contributions in the auction process for public procurement and renewable energy supply. The Act outlines criteria for assessing sustainability and resilience contributions, allocating a 15-30% scoring bonus for judgment and bid criteria. When designing incentive schemes for consumers encouraging the purchase of final products of carbon-neutral technologies, considerations of sustainability and resilience contributions are required, providing consumers with financial compensation within 5% of the final cost.

To support the role of industries in the region during the adoption of carbon-neutral technologies and clean energy transition, the European Commission and member countries may collaborate with third countries. Potential collaboration areas include enhancing cooperation across carbon-neutral value chains, mutual recognition of suitability assessments, resolving non-tariff trade barriers to avoid export restrictions, and prioritizing participation in carbon-neutral industry partnerships with third countries.

On the other hand, the EU has provided a framework for assessing the importance, diversification, and research and development innovation of raw materials by announcing the Raw Materials Initiative in 2008 and the Action Plan on Critical Raw Materials in 2020. Since 2011, the EU has been designating and managing a list of Critical Raw Materials (CRM), which are essential elements for the EU's pursuit of green and digital transitions. CRMA aims to reduce external dependence on critical raw materials, promote import diversification, and strengthen the value chain. Comprising a total of 10 chapters and 47 articles and appendices, Chapter 3 focuses on the strategic projects related to strengthening the domestic raw material value chain, licensing procedures, implementation conditions, and exploration, while Chapter 5 covers topics related to circularity, certification and environmental footprint, free movement and compliance, and market supervision in relation to sustainability.

CRMA sets targets for the manufacturing cycle of strategic raw materials by 2030, including (ⅰ) Mining more than 10% of the ore, minerals, or concentrates necessary for producing over 10% of the EU's annual consumption of strategic raw materials within the EU, (ⅱ) Ensuring that the processing capacity of strategic raw materials, including all intermediate processing stages within the EU, can produce over 40% of the annual consumption of strategic raw materials, and (ⅲ) Setting a goal for the recycling capacity of strategic raw materials, including all intermediate recycling stages within the EU, to produce over 15% of the annual consumption of strategic raw materials.

The Act designates and regulates strategic projects to enhance the strategic raw material value chain, allowing for support. The criteria for recognition as a strategic project are as follows:

(ⅰ) Expected significant contribution to the supply security of strategic raw materials within the EU.

(ⅱ) Technologically feasible with estimable production quantities.

(ⅲ) Capable of implementation in a sustainable manner concerning environmental, human rights, and social aspects.

(ⅳ) For projects within the EU, providing benefits that transcend national borders in terms of project establishment, operation, or production outside the member state.

(ⅴ) For projects in third countries' emerging markets or developing countries, consideration of mutual benefits with the EU.

The Commission is obliged to establish a system promoting long-term off-take agreements for strategic projects. Through this system, the Commission must match procurers and project planners based on bids from long-term buyers indicating the quantity, quality, price, and purchase period of strategic raw materials and proposals from project planners.

To enhance the circularity of key raw materials within the EU, each member state must adopt and implement relevant national programs within three years after the CRMA's enactment. Measures that can be included in national programs are increasing the use of secondary key raw materials, research and innovation programs for mature recycling technologies and improved material efficiency, and ensuring technical expertise supporting the circularity of the key raw material value chain. In public procurement, the Act specifies preferences for the introduction of waste collection and recycling systems with high recovery potential, the reuse of products and components with high recovery potential, and the inclusion of recycled content.

CRMA emphasizes strategic partnerships with third countries, prioritizing countries based on their potential contributions to supply stability concerning storage capacity, extraction, and recycling capabilities. Factors considered include existing collaboration agreements with the EU, and whether the third-country regulations consider ESG factors and mutual benefits. Discussions around secure, economic, and sustainable supplies of critical raw materials have been central to various government forums, and initiatives like the Mineral Security Partnership and Critical Raw Materials Club complement existing collaboration systems or promote sustainable investments in critical raw material-producing countries, fostering value chain sophistication.

The industrial and trade policies presented in NZIA and CRMA reveal a close connection with climate and energy policies, indicating a characteristic pursued consistently throughout the provisions of the legislation. The EU sets sustainability and circularity as vital criteria for key value judgments across the entire framework of the legislation, aligning with the sustainability objectives pursued by the EU. In NZIA, sustainability is being carefully considered as a critical criterion in the selection of key support projects, public procurement, auction bidding, and the design of financial compensation systems for consumers (Leem, 2023). Similarly, in CRMA, considerations for circularity, such as the recycling and recirculation of critical raw materials, are emphasized throughout the entire legislation

6.2. Carbon Barrier: Carbon Border Adjustment Mechanism

The EU's CBAM aims to level the playing field between EU producers subject to the EU-ETS and foreign producers, contributing to GHG reduction while preventing the loss of competitiveness for EU industries domestically. It applies to six major sectors including steel, aluminum, cement, fertilizers, and hydrogen. Reporting entities must submit reports to the EU Commission within one month after the end of each quarter, including quarterly imported product information, specifying the total quantity of products by production facility in the origin country and the actual total embodied emissions per unit of electricity MWh or ton of product. Additionally, they must report the total indirect emissions and carbon pricing paid and reimbursement or compensation details according to the methodology of the compliance regulation. For steel, aluminum, and hydrogen, only direct emissions are calculated, while for other products, indirect emissions are included. The embodied emissions are determined based on actual emissions, using either the average emissions intensity profile for the exporting country or the sub-average emissions intensity profile for the corresponding industry within the EU-ETS, if emission data is not available. The transition period will occur from October 2023 to December 2025, with full implementation starting from January 2026, and the gradual phasing out of free allocation for EII under the EU-ETS is planned from 2026 to 2034. pounds.

<Table 8. Main Content of CCA>

Introduction period	Transition period: '23.10 ~ '25.12 Full-scale implementation: '26.1 ~

Applicable items	downstream products such as screws, bolts, and iron/steel products (evaluate whether organic chemicals, polymers, etc. are included before the end of the transition period, and cover all EU-ETS areas by 2030) (Aiming to expand to target)
Scope of domestic emissions calculation	▪ Indirect emissions are also included, but only direct emissions are calculated for steel, aluminum, and hydrogen (indirect emissions refer to the emissions of electricity consumed during the production process, and the indirect emissions calculation methodology is planned to be specified during the transition period) ▪ Embedded emissions are determined based on actual emissions, but if there is no available emissions data, the average emission intensity by the exporting country is applied as the default value or the lower average emission intensity of the relevant industry within the EU-ETS is applied.
Proposal for phasing out free allocation in EU-ETS	Gradual abolition from 2026 to 2034
Exemption conditions	Carbon costs are paid in the country of origin through taxes, fees, and emissions trading system
Reporting method and items	▪ The reporter must submit a report (CBAM report) containing information on imported products to the committee every quarter within one month after the end of the quarter (the first report submission deadline is January 31, 2024).

	▪ The total amount of products by type specified by the production site in the country of origin (expressed in MWh for electricity and tons for other products) and the actual total embodied emissions must be reported as CO2e emissions per MWh of electricity or tons of CO2e emissions per ton of product by type. In addition, the total amount of indirect emissions other than the power contained in each type of product calculated according to the methodology of the implementing law, as well as the carbon price paid in the country of origin and details of refund or compensation, etc. must be reported.

*Source: Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May; 2023 EY(2023.5.22.), https://www.ey.com/en_gl/tax-alerts/final-regulations-published-for-new-eu-carbon-border-adjustment

7. Policy comparison and recommendations for Korean policies

7.1. Comparison of Policies between the United States and Europe

7.1.1. Implications of Carbon Neutrality and Supply Chain Policies

The carbon-neutral policies and legislation of the U.S. and the EU aim to achieve sustainable supply chain stabilization in realizing carbon neutrality. The US seeks to internalize production bases related to carbon neutrality, focusing on initiatives such as the greening of existing infrastructure in transportation and ports, investments in community-led projects for job creation, and support for energy cost savings through incentives like environmentally friendly vehicle tax credits, subsidies for home energy efficiency improvements, and consumer home energy rebate programs. The EU's policies emphasize sustainability and resilience in terms of supply chain stability, environmental factors, and labor aspects. The emphasis on sustainability and resilience in the current legislation aligns with the EU's pursuit of a circular economy, indicating that these considerations are likely to continue to be influential in the future.

In the utilization of policy instruments related to achieving carbon neutrality and supply chain, there are interesting differences between the policies of the U.S. and the EU. While the US primarily employs direct and immediate measures such as tax deductions, subsidy payments, loan expansion, and guarantee support, the EU focuses on policy measures for improving investment environments and conditions, such as streamlining project approval processes, supporting public procurement and auctions, easing regulations, and enhancing international cooperation.

The domestication policies of supply chains pursued by the U.S. and the EU are still in the early stages of implementation, and the outcomes of these policies may exhibit different patterns on a global scale and in local contexts. There is a potential aspect in which the alliance of capital and energy accelerates environmentally friendly competition to reduce carbon emissions, leading to carbon neutrality through resource inputs and policy focus (Allan et al., 2021). A similar trend is observed in other countries; Japan formulated a green transition plan in 2023, and India is expanding policy implementation for domestic carbon-neutral technologies and stable industrial supply chains through production-linked incentive programs.

On the other hand, relying on global supply chains based on the flow of free trade and reciprocity to optimize cost savings and expand clean technologies can pose complex issues for the crucial global supply chain (Helveston and Nahm, 2019)67. Reshoring the supply chain to the home country may lead to a net cost to the world economy, as each country needs to achieve similar cost-saving effects achieved by competitive firms, and there may not be enough time or additional resources for such achievement (Allan et al., 2021). Therefore, reshoring policies can lead to inefficient use of resources and price inflation, potentially adversely affecting job growth worldwide.

Furthermore, influencing competitiveness through tools, including subsidies for specific sectors' production, poses a risk of harm to other countries in the global zero-sum game (OECD, 2022). Environmental industry policies can create complex conflicts between individual countries' interests and global interests, and when supply chain internalization policies are added, they may exacerbate geopolitical issues. Furthermore, supply chain control and subsidy-centered internalization policies can compel artificial intervention in international trade flows, potentially conflicting with provisions of the World Trade Organization and National Trade Acts (Allan et al., 2021).

7.1.2. Risks of Carbon Trade Barriers

The US and the EU, in introducing carbon border adjustment mechanisms, aim not only to reduce industrial carbon emissions but also to protect their domestic industries. Mattoo et al. (2013) confirmed that most policy design options under CBAM would adversely affect exports and economic welfare in developing countries, modeling the impact on numerous countries and trading partners. Monitoring, Reporting, and Verification (MRV) of carbon content demand significant statistical capacity from exporters, irrespective of whether producers certify product carbon content compared to EU averages or use a product-specific approach. Reliable data measurement and management systems for calculating carbon emissions are necessary for EU CBAM, as exporters may face unfavorable standards if actual emission data is insufficient (Jung, 2023).

Moreover, given the difficulty for EII to deviate from carbon-intensive systems and the high costs of improvement, CBAM increases the vulnerability of developing economies. Consequently, the implementation of CBAM could reduce exports from these countries, and without effective mitigation and environmental sustainability for EII, the economic impact could be substantial (Ameli et al., 2021; Mealy and Teytelboym, 2020). These countries may require support for integrating clean technologies into production processes and reducing carbon dioxide emissions (WTO, 2021). Åhman et al. (2017) argue that advanced countries must bear considerable responsibility, investing in the development and dissemination of technologies needed to transform energy-intensive industries.

If revenues from carbon border adjustment mechanisms are used for green development and technology transfer to developing countries, these economic negative impacts could be mitigated, but losses to economic welfare may remain. However, proposed revenue funds from CBAM are suggested to be retained within the EU as contributions to domestic resources, aligned with recommendations for countries transferring innovation to address EII (Åhman et al., 2017). Åhman et al. (2017) assert that carbon leakage and trade issues associated with industrial policies will be critical issues in global climate policy facing unequal climate goals and carbon prices over the next 30 to 40 years.

7.2. Improvements in Korea's carbon neutrality and supply chain policies

7.2.1. Strengthening the combination of CN and SC

Aussilloux et al. (2020) highlight three central issues that industrial policies should address in the next 10-20 years, with the first being the impact of ecological transition on industries. Among these, they identify the decarbonization of production facilities in sectors such as power, automotive, and aviation, as well as the removal of carbon emissions in the industrial sector, as key challenges. The carbon neutrality and supply chain internalization policies of the U.S. and the EU, while showing differences in approach, are designed to operate based on the combination of carbon neutrality and supply chain stability. Ensuring sustainability can lead to the stable achievement of carbon neutrality, contributing to the long-term development of industries. Mission-oriented innovations, such as climate change response, offer societal benefits inherently linked to the issues they aim to address, including national security and sustainable growth (Rodrik, 2014). Meckling (2019) argues that as green industrial policies shift towards the forefront of climate change response, climate policies have become central elements of economic and industrial policies rather than typical cases of environmental policy.

Countries can actively leverage the potential of strategic industrial development, export expansion, job creation, and growth drivers through environmentally friendly industrial policies. To achieve this, a stable backup for supply chains towards carbon neutrality becomes even more crucial. Moreover, innovation and technology diffusion are generally key means to overcome these challenges (Popp, Newell, & Jaffe, 2010), making them goals in themselves.

As of now, Korea's carbon neutrality policies and Acts do not emphasize policy elements related to the sustainability and resilience of the supply chain. As observed earlier, among Korea's major five carbon neutrality policies announced since 2018, only two policies touch upon the role of the supply chain. Both policies address securing mineral resources, establishing dedicated rare metal stockpiles, extending stockpile periods, recycling end-of-life resources, and nurturing companies possessing rare metals. However, they heavily focus on supply-side policies and remain at a declarative level. Furthermore, the special measures bill related to protecting and enhancing the competitiveness of carbon-neutral industries, proposed in the National Assembly, lacks coverage of policies related to monitoring, securing raw materials, international cooperation, and supply chain shock stability. Therefore, Korea's carbon neutrality policies need to present more organically connected policies to enable realization based on the foundations of supply chains that are resource-supply, job and demand-oriented.

< Table 9. Comparison of incentive policies in Korea, the US, and the EU >

Classification		Policy tool	Korea		U.S.	EU	
			Carbon neutral policy	Supply Chain Policy	IRA	NZIA	CRMA
Supply	Within company	Subsidy					
		Tax Incentives					
		Finance					
		License					
		Deregulation					
		Infrastructure					
		Technology Development					
		Education & Training					
	Between company	Tax Incentives					
		Priority Support Project					
Demand		Public Procurement					
		Consumer Subsidy					
Governance		International Cooperation					

No policy tools available or not found

*Based on OECD, (2022), ‘An Industrial Policy Framework for OECD Countries’ and Leem et al., (2023), ‘Comparative analysis of carbon neutral trade policy policies’, ISSUE PAPER 2023-09, pp. 132-144, the author has reorganized.

7.2.2. Supplementing sustainability and resilience elements of supply chain policy

Gasser (2022) emphasizes that energy security can have different meanings for each country due to its natural resources, political system, economic well-being, ideology, geographical location, and international relations. Strategic autonomy is increasingly considered a crucial goal in industrial policy (Ding and Dafoe, 2021), and the U.S. and the EU demonstrate divergent approaches to realizing strategic domestication industries based on values such as carbon neutrality and security. Therefore, for sustainability and resilience, Korea needs to conduct a thorough analysis of the market size, competitiveness, and supply chain differences in sectors associated with policies with the U.S. and the EU. It should unravel the complex functions related to the economic feasibility, risks, and directions for the internalization and localization of production bases.

This study argues that Korea's carbon neutrality policy will increase connectivity with supply chain policies, thereby adding emphasis to the sustainability and resilience of the supply chain. Lessons on securing sustainability and resilience can be derived from U.S. job creation and regional investment strategies, as well as the EU's matching with project planners in the public procurement process and consumer support measures. In the global context of environmental politics, it should be considered that green industrial policies, as argued by Malhotra and Schmidt (2020), can contribute to inducing behavioral changes for addressing climate change by reducing mitigation costs and generating social co-benefits.

The OECD (2022) emphasizes the increasing importance of demand policies in innovative mission-oriented industrial strategies, and Anderson et al. (2021) argue that demand policies complement supply tools in promoting innovative industrial changes. The EU policy emphasizes sustainability across environmental, social, and labor dimensions for supply chain stability and resilience. The US IRA Act balances considerations for domestic facility internalization, investments in local communities, and support for consumers. In contrast, Korea's policies, such as the Industrial Supply Chain 3050 strategy and Supply Chain Stabilization Act, mainly emphasize responsive elements to supply aspects and supply chain crises. Crisis response policies for supply risks can be efficient in absorbing shocks from complex and unpredictable supply chain variables but may struggle to ensure structural sustainability. Therefore, Korea should incorporate a balanced policy mix by referencing the US and EU policies, aligning supply policies with job creation, local investments, and demand policies to support sustainability.

Firstly, job creation needs to be considered in conjunction with policy-driven investments in local infrastructure. The OECD (2022) has identified the inclusive and equitable enhancement of regional distribution of economic activity as a ripple effect of place-based strategies. Given Korea's history of many region-based and reshoring policy cases, it can effectively utilize these approaches. Noteworthy examples include the swift processing support for permits through the designation and operation of Carbon Neutral Industrial Specialized Complexes under the Carbon Neutrality Industrial Act, the construction and operation of specialized zones under the Strategic Technology Act, and the establishment and operation of national industrial complexes and advanced specialized zones under the Basic Plan for Advanced Strategic Industries (Leem, 2023). Supporting job creation through specialized areas based on comparative advantages and technological expertise specific to certain regions can contribute significantly to achieving a just transition, a crucial aspect of the carbon neutrality process.

From a demand perspective, it is necessary to strengthen the role of public procurement. For public procurement, not only should measures be taken to address market risks, but also standards, targets, and efficiency assurance for operations need to be established and implemented. While Korean Acts obligate supply agencies to reflect resource security factors in public procurement and recommend measures for procurement, clear objectives, and implementation methods have not yet been provided. Addressing the ambiguity regarding the role of leading operators under the Supply Chain Stabilization Act (National Assembly of Korea, 2022) and paying attention to EU procurement regulations can enhance the efficient utilization of storage bases under the National Resources Security Act. The EU, through the NZIA, presents detailed public procurement standards and operates public procurement support targeting projects rather than companies. Mandating the government to match procurers with carbon strategy project planners could help secure sources of demand and mitigate uncertainties in medium to long-term operations. For impactful and urgent public procurement, considering the application of a regulatory sandbox system, checking the effectiveness of licensing procedures, and streamlining effects before improving the system could be considered.

Moreover, U.S. Acts utilize policy instruments such as Local Content Requirements (LCR), while EU legislation includes measures aimed at protecting domestic industries by setting targets for domestic installation capacity. Korea needs to analyze which policy tools, whether targeting installation capacity or employing direct tools like LCR, contribute more effectively to domestic production competitiveness and job retention. For instance, LCR can serve as a crucial policy instrument for fostering the renewable energy manufacturing sector by preventing the erosion of the domestic renewable energy market by products from specific countries (Leem, 2023).

Enhancing international cooperation for the supply of strategic resources is a critical aspect of stable public procurement. Both the US and EU aim to strengthen supply chain self-reliance while pursuing a derisking strategy through cooperation with allies or foreign countries. The US is pushing for the creation of a buyer club for securing essential mineral resources with the EU, and the US Congress proposed the 'Essential Minerals Security Act' in January 2024. This bill regulates the diversification of essential mineral supply chains, strengthening ties with allied countries, and establishing an international cooperation strategy for advanced mining technology.

Despite limitations such as a lack of minerals and natural resources, an export-oriented economic structure, and a relatively small domestic market, Korea is among the countries with the highest number of Free Trade Agreements (FTAs) and possesses competitive technological capabilities in the refining and smelting industries. Fortunately, key minerals are abundant in allied countries, providing an opportunity to establish collaborative supply chains through recent economic bloc formations. Therefore, Korea should collaborate with mineral-abundant nations, including the U.S. and the EU, to leverage the potential for securing production hubs for raw materials and components and ensuring the stability of the supply chain through technological development cooperation. Particularly, the increasing demand for key minerals in carbon-neutral industries anticipates the growth of the domestic mineral industry. To overcome challenges such as the contraction of public and private overseas resource investments and insufficient domestic processing facility infrastructure, a long-term vision is needed within the country (Leem, 2023).

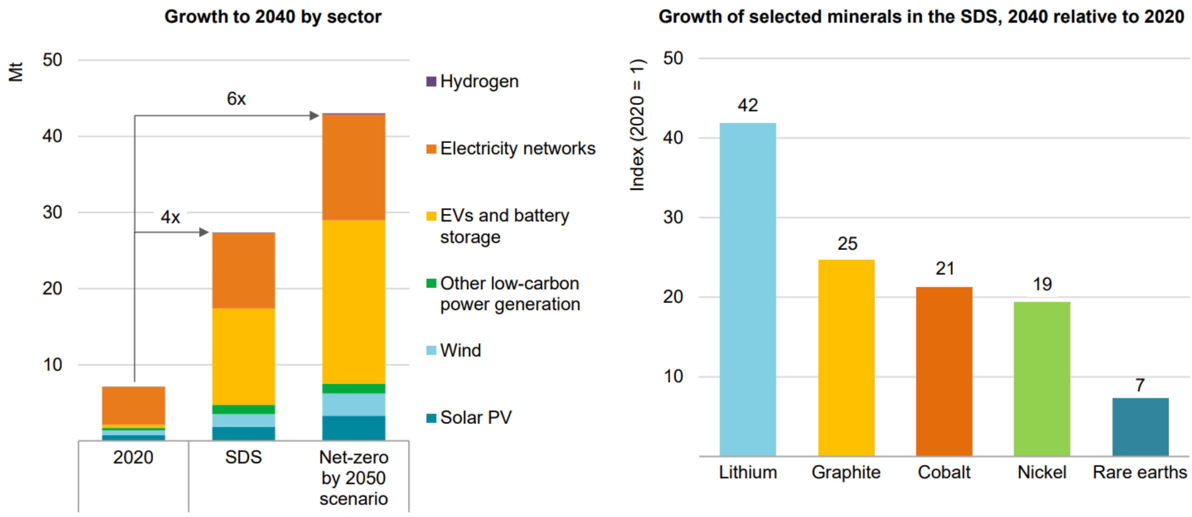

Figure 7. Clean energy mineral demand outlook (Source: IEA (2022), The Role of Critical Minerals in Clean Energy Transitions, p. 9.)

In industries where a market-based approach, raw material characteristics, logistics conditions, etc., favors localization strategies over internalization based on production-base considerations, it is not necessarily essential to adhere strictly to domestic internalization. Before advancing localization efforts, a thorough analysis of the target country's resource recycling obligations, carbon neutrality policies, and strengthening and fluctuations in carbon-neutral and supply chain policies should be essential. In the U.S., the IRA and CHIPS Act propose attractive incentives for domestication, demanding reciprocal measures. The FEOC regulations under the IRA limit the joint investment stake with Chinese companies to 25%, while the CHIPS and Science Act imposes requirements on the U.S. government for access to semiconductor facilities, profit-sharing, submission of corporate financial data, and restrictions on the expansion of Chinese factories (NIST, 2023). Adhering to these regulations implies potential risks, such as the modification of local investment strategies, deteriorating anticipated productivity and profitability, and the possibility of disclosing technology and trade secrets. Therefore, industries in Korea planning carbon-neutral strategies, including semiconductor and battery industries, should not consider subsidy benefits as the primary driver for local expansion. Instead, they should explore various methods to hedge risks, including clarifying contract conditions considering potential regulatory changes, enhancing mergers and acquisitions with local companies, and reinforcing pre-trade cooperation between the two governments.

For example, in the case of batteries, one of Europe's eight key carbon-neutral technologies, Korean companies are heavily investing in production facilities in Europe. Challenges arising from the absence of local facilities addressing safety, performance, supply chain inspections, recycling of used batteries, and management, as stipulated in the EU Battery Regulation, can be addressed through discussions on strengthening partnerships with local companies or strategies for creating used battery clusters. Additionally, for carbon-intensive industries like steel, cement, and chemicals, considerations should be given to actively responding to Europe's CBAM and the implementation of carbon regulations across borders in the U.S. under the Clean Energy Competition Act.

7.3. Designing CCfD in Response to Carbon Barriers

The implementation of carbon border adjustment mechanisms by the US and the EU is imposing significant burdens on the competitiveness of Korea's EII. While currently, the most export-intensive item among the applied products, steel, will directly suffer, it is essential to prepare medium to long-term strategies in anticipation of the expansion of the applied products in the future and the likely design of the system to favor EU domestic industry protection and competitiveness enhancement. The Korean government is currently engaging in ongoing discussions with the EU Commission and Council to enhance transparency and alleviate burdens related to CBAM implementation. Analyzing 22 press releases related to CBAM by the Korean government from July 2021 to February 2024, the Korean government is discussing and partially reconciling issues such as the prohibition of discriminatory treatment of South Korean companies under CBAM, alignment with international trade norms such as WTO and FTAs, exemption from mandatory certificate purchases considering Korea's K-ETS, and demands for climate, environmental, and energy tax recognition. Furthermore, guidelines are being prepared to facilitate smooth compliance with emission reporting obligations by companies.

As previously discussed, Korea's incentive policies related to EII encompass a diverse portfolio spanning fair transition, energy and material efficiency, technology development, CCUS, and carbon price incentives. Particularly, focusing on technology development for process transition and fuel and material conversion tailored to the characteristics of large-scale devices and facility industries in the steel, petrochemical, and cement sectors within the EII industry.

However, decarbonization remains challenging and costly in the EII, necessitating the consideration of sustainable and long-term policy interventions. The long investment cycle required in EII implies that assets installed today must comply with emission reduction targets in 2030 and 2040 (Eicke, 2021), necessitating a long-term policy strategy encompassing the entire value chain, from foundational research through market activation for growth and long-term market traction. Among these, subsidies and investments are direct and efficient means. Capital subsidies have been widely used in rapidly industrializing countries (Haley & Haley, 2013), and investment subsidies, tax exemptions, and other mechanisms to protect EII are commonly used in OECD countries.

This study proposes an in-depth review and design of CCfD considering the industrial characteristics of EII and the risks of low-carbon investment. Although the potential of CCfD has been mentioned in the 'Vision and Strategy for Carbon-Neutral Industrial Transition' and the 'National Strategy for Carbon-Neutral Green Growth and the First National Basic Plan,' specific implementation details, timing, and plans have not yet been announced.

Currently, CCfD mechanisms are being considered in Germany, Portugal, the Netherlands, France, EU member states, and the UK (Janssen, 2023). The EU Commission is considering a subsidy system for low-carbon technologies using CCfD design utilizing innovation funds across the EU, while the UK is developing CCfD for CCUS support as part of the CCUS infrastructure fund (UK Department for Business, 2022). Specifically, the federal government in Germany has promised funding for project-based pilot programs for CCfD in the steel, cement, lime, and ammonia sectors.

Private investment in EII is challenged by initial investment costs, higher operating and investment costs than existing carbon-intensive processes, and insufficient and uncertain carbon pricing due to political factors (Richstein, 2022). The goal of CCfD is to minimize the risk of regulatory policy changes and provide confidence in government climate policies to attract private investment (Chiappinelli & Neuhoff, 2020). In this process, promoting fund acquisition through project debts reduces project planners' fundraising costs (Dukan and Kitzing, 2023).

Various approaches have been considered regarding the introduction of CCfD, including whether to use Contracts for Difference (CfD), utilize the use of put options (McWilliams & Zachmann, 2021), employ specific bidding or technology-neutral approaches, and explore ways to integrate with other policies (Gerres & Linares, 2020; Sartor & Bataille, 2019).

Considerations regarding the introduction of CCfD include setting appropriate criteria for project costs and emissions, types of costs and benefits to be considered, and allocation methods. Hoogsteyn et al. (2024) have shown that the ability of tools to mitigate carbon prices varies depending on the CCfD design chosen. Lösch et al. (2022) propose the following factors to be considered in CCfD design:

- Contract prices, effective CO2 prices, and formulas for CCfD payments
- Definition of system boundaries
- Reference and project cost determination for calculating incremental costs
- CCfD payments

- Direct marketing of green products (considering potential green premiums)
- Bidding and selection processes

Contract Price (Strike Price)

The contract price is one of the most critical elements in CCfD. To establish a stable investment system and encourage efficient use of materials, a more precise price setting, including measures to prevent carbon leakage, is necessary (Richstein, 2022). Since the contract price remains fixed throughout the entire period, an increase in the contract price may limit incentives for investment in low-carbon technologies (Richstein et al., 2021).

Magacho (2024) suggests that independently evaluated contract prices related to specific project costs are desirable from an efficiency standpoint. Independent experts are necessary to derive appropriate prices for various individual technologies (Leipprand, 2021). On the other hand, price determination through auction procedures is more favorable for static efficiency since the bidder offering the lowest price becomes the beneficiary (Leipprand, 2021).

Additionally, dynamic (flexible) price adjustments can decarbonize the value chain from energy to final products (Gerres, 2020), enhancing decarbonization efficiency. Regular adjustment of contract parameters can prevent an imbalance in project funding utilization (Agora Energiewende et al., 2022). In case of unforeseen additional costs such as energy price increases, higher operating costs can be compensated through dynamic adjustments, and changes in the scale of funding due to emission reductions can also be addressed through dynamic adjustments.

Two cost factors associated with public administration are involved in CCfD utilization (Gerres, 2020). Firstly, there are costs related to hedging against carbon price risks, reducing overall societal risks by allocating price risks to the government. Secondly, it involves direct technical support, as once technologies become competitive, there is no longer a need for projects. This is because, as technologies follow learning curves, the contribution of CCfD to innovation support for new projects decreases over time (Gerres, 2020).

Payback Mode

Contracts with payback conditions are cost-effective for contract issuers as the repaid funds can be converted into CCfD financing (Chiappinelli et al., 2020). Repayment mechanisms are more efficient for contract issuers as they cover price risks borne by the issuer when the reference price exceeds the exercise price. In contrast, contracts without payback conditions pose less risk of emission reduction because companies can achieve emission reductions regardless of the price level.

Bidding

Bidding is preferred as it is the best way to address information asymmetry between governments and companies in CCfD project implementation. The selection of companies and projects through a multi-stage process involving bidding factors is positively evaluated for static efficiency since the final price determination occurs through a competitive process (McWilliams & Zachmann, 2021).

Price Volatility

Price volatility in energy and raw materials can exacerbate uncertainty about carbon abatement costs, thus amplifying the risk of investment decisions (Richstein et al., 2022). Due to such price volatility, CCfD project implementers are obliged to pay an amount proportional to the carbon price, but passing on these costs to product prices is difficult (Hoogsteyn et al., 2024). Consequently, participating companies in projects are exposed again to carbon price risks.

Misuse of the Scheme

Project participants may promote technologies with the lowest emission reduction costs rather than those with the highest abatement potential. To mitigate this possibility, consideration should be given to sectoral and technological allocations. Moreover, there is a risk that a few bidders within a sector may raise prices for cheap technologies, leading to the promotion of economically unviable technologies (EWI, 2021).

Contract Duration

Long-term contracts are expected to be more efficient for beneficiaries, as production facilities receive subsidies until they become economically viable (Esterhaus, 2020).

Rilling et al. (2022), through research on CCfD, have derived the following considerations for policymakers when introducing CCfD:

i) If the compensation procedure emphasizes static efficiency, policymakers should choose a design that encourages competition, which may reduce the diversity of project participants and dynamic efficiency.

ii) Assessment criteria for some design elements, such as geographic factors, diversity, and dynamic adjustments of price and quantity, may be ambiguous. Design options should be carefully selected considering all effects.

iii) Consideration should be given to the interdependence of design elements, such as the impact of the investment recovery mode on the contract period.

7.3. Considerations and limitations of study

7.3.1. Limitations of Research on Carbon Neutrality and Supply Chain Policies

Securing a sustainable supply chain is gaining attention as a critical policy essential for achieving carbon neutrality and responding to unforeseen crises with direct implications for national security. Strengthening policy tools on the demand side within the current Korean framework is necessary to ensure sustainability and resilience. Future national resources should contribute to job creation and social safety nets, requiring policy enhancements and long-term strategies. The proposed strengthening of public procurement, expansion of international cooperation, and linkage with job creation in this study are just some of the various means to enhance sustainability. In addition to exploring policy tools from other demand perspectives, a balanced approach with supply-side policies is necessary.

It is crucial not to overlook the criticism that national support policies may lead to supporting inefficient or failing companies, perpetuating the survival of zombie firms, delaying productivity improvement, and reducing the level playing field of fair competition (OECD, 2022). Public procurement systems for internalizing the supply chain may demand continuous government budget allocations due to the absence of operational strategies, rising labor costs, and market mechanism failures. Flexible adjustments and feedback mechanisms for execution plans focused on long-term operational strategies and efficiency in public procurement, job creation through local policies, and the supply of operational personnel are vital. Considering the inevitable impact of carbon neutrality and supply chain security policies of various countries, continuous monitoring and analysis are necessary. In the future, research is needed on the interaction between international politics, economics, and the appropriate policy tool mix for supply-demand, including carbon neutrality and supply chain security.

7.3.2. Limitations of Research on CCfD Policy Design

Before advancing policies related to CCfD design, it is essential to fully recognize the possibility of unintended consequences. Firstly, CCfD is considered an interim policy tool that supports climate-friendly production processes in the market until they can competitively land against existing emission-intensive processes (Lösch et al., 2022). If the supply chain decarbonizes before CCfD expires, project participants have a financial obligation to repay an amount proportional to the carbon price. However, there are limitations to passing on these costs to product prices.

Furthermore, there are differing views on the risk of CCfD undermining the efficiency of emissions trading systems. Due to the cap on emissions, policies like CCfD may be criticized for potentially circumventing emission reductions rather than achieving them if the cap is not appropriately adjusted (Hoogsteyn, 2022). Conversely, Lösch et al. (2022) argue that concerns about CCfD weakening the EU ETS are unfounded, as CCfD could complement rather than undermine the EU ETS. Instead, CCfD could be viewed as a policy tool to address market failures that hinder the diffusion of technologies and as a risk mitigation tool to expand new technologies necessary for efficient transition pathways.

8. Conclusion

This addressed the study of the relationship between Korea's carbon neutrality and the supply chain, identifying areas for improvement in Korean policies through a comparison with the U.S. and the EU. The ongoing disruption and localization of supply chains triggered by global conflicts and the power struggle between the US and China are challenging to resolve in the short term and are likely to deepen. This trend directly or indirectly influences Korea's carbon neutrality policy and industrial supply chain, emphasizing the need to consider it as a crucial factor in economic and military security aspects.

The current carbon neutrality and supply chain policies in Korea have a weak interconnection between the two, with the supply chain policy primarily focusing on crisis response-centered supply strengthening. Enhancing the link between carbon neutrality and supply chain policies, and incorporating policy tools that enable sustainable supply chains, are lessons from the policies of the U.S. and the EU. These lessons should be utilized to improve Korea's institutional framework. Mission-oriented missions like carbon neutrality require a balance between supply and demand policy tools to ensure sustainability and resilience.

A strategic review based on current trends in international politics and economics and efforts to secure sustainability should not stop. Instead, current crisis response and supply-centric policies should be complemented with a social and labor perspective. Sectors and areas requiring supply chain internalization need institutional improvements, including the redesign of public procurement systems and investment and operational approaches that can be linked to job creation. Considering the limitations of domestic resources and a small domestic market, diversifying the supply chain through international cooperation, along with the development of the domestic mineral industry, is necessary for job creation and regional development effects. A balanced combination of supply and demand policies ensures the sustainability and resilience of the supply chain, forming the basis for achieving long-term carbon neutrality.

Furthermore, the necessity of introducing CCfD as an incentive policy for energy-intensive industries and the factors to be considered in its design have been proposed. The CCfD system is a policy tool aimed at dispersing carbon price risks and incentivizing private investment in long-term technological integration, taking into account the characteristics of EII. The success of the CCfD policy depends on careful consideration of various factors such as exercise price, duration, bidding participation, payback mode, and contract scope. Analyzing case studies from advanced countries, modeling contracts, and coordinating between governments and businesses are essential efforts to ensure the successful implementation of policy measures.

Reference

Agora Energiewende; FutureCamp; Ecologic Institut; Wuppertal Institut (2022). Klimaschutzver-träge für die Industrietransformation. Kurzfristige Schritte auf dem Pfad zur Klima-neutra-lität der deutschen Grundstoffindustrie. [Online]. Available: https://static.agoraenergiewende.de/fileadmin/Projekte/2021/2021_10_DE_KIT/AEW_249_Klimaschutzvertraege-IndustrietransformationStudie_WEB.pdf

Åhman, Max., Nilsson J. Lars., Johansson, Bengt., (2017), Global climate policy and deep decarbonization of energy-intensive industries, Climate Policy, 17:5, 634-649, DOI:10.1080/14693062.2016.1167009

Akbari, M., & Hopkins, J. L., (2022). Digital Technologies as enablers of supply chain sustainability in an emerging economy. Operations Management Research, 1–22. https://doi.org/10.1007/ s12063-021-00226-8

Allan, Bentley., Lewis, Joanna I., Oatley, Thomas. (2021). Green Industrial Policy and the Global Transformation of Climate Politics. 3-14.

Ameli, N., Dessens, O., Winning, M., Cronin, J., Chenet, H., Drummond, P., Calzadilla, A., Anandarajah, G., & Grubb, M. (2021). Higher cost of finance exacerbates a climate investment trap in developing economies. Nature Communications, 12(1), 1–12. https://doi.org/10.1038/s41467-021-24305-3

Anderson, B. et al. (2021), “Policies for a climate-neutral industry: Lessons from the Netherlands”, OECD Science, Technology and Industry Policy Papers, No. 108, OECD Publishing, Paris, https://dx.doi.org/10.1787/a3a1f953-en

Aussilloux, V., Frocrain, R., Lallement, R. (2020). Les politiques industrielles en France: Evolutions et comparaisons internationales, France Stratégie, p.12.

Bassi, A.M., Yudken, J.S., Ruth, M., (2009). Climate policy impacts the competitiveness of energy-intensive manufacturing sectors. Energy Policy 37 (8), 3052–3060.

Beard, T. R., Ford, G. S., Koutsky, T. M., & Spiwak, L. J. (2009). A valley of death in the innovation sequence: an economic investigation. Research Evaluation, 18, 343–556. doi:10

Bechtsis, D., Tsolakis, N., Vlachos, D., & Iakovou, E., (2017). Sustainable supply Chain Management in the Digitalisation era: The impact of automated guided Vehicles. Journal of Cleaner Production, 142, 3970–3984. https://doi.org/10.1016/j.jclepro.2016.10.057.

Bechtsis, D., Tsolakis, N., Vlachos, D., & Srai, J. S., (2018). Intelligent Autonomous Vehicles in digital supply chains: A Framework for integrating innovations towards sustainable value networks. Journal of Cleaner Production, 181, 60–71. https://doi.org/10.1016/j.jclepro.2018.01.173.

Bocken, N. M. P., Olivetti, E. A., Cullen, J. M., Potting, J., & Lifset, R. (2017). Taking the circularity to the next level: A special issue on the circular economy.Journal of Industrial Ecology, 21(3), 476–482.Retrieved from https://doi.org/10.1111/jiec.12606

Böhringer, C.; Balistreri, E.; Rutherford, T., (2012) The role of border carbon adjustment in unilateral climate policy: Overview of an energy Modeling Forum study (EMF 29). Energy Econ. 2012, 34, S97–S110.

Bolsher, H., Graichen, V., Graham, H., Healy, S., Lenstra, J., Meindert, L., ... Timmons-Smakman, F. (2013). Carbon leakage evidence project – fact sheet for selected sectors. Rotterdam: ECORYS.

Brook, B. B., Edney, K., Hillerbrand, R., Karlsson, R., & Symons, J., (2015). Energy research within the UNFCCC: a proposal to guard against ongoing climate deadlock. Climate Policy. Advanced online publication. doi:10.1080/14693062.2015.1037820.

Carbone, J.; Rivers, N., (2017). The Impacts of Unilateral Climate Policy on Competitiveness: Evidence from Computable GeneralEquilibrium Models. Rev. Environ. Econ. Policy 2017, 11, 24–42.

CBO.(2022).EstimatedBudgetaryEffectsofPublicLaw117-169, Sept. 7.

Chiappinelli, O., Erdmann, K., Gerres, T., Haussner, M., Juergend, I., K. Neuhoff et al. (2020). Industrial Innovation: Pathways to deep decarbonization of Industry. Part 3: Policy Implications. [Online]. Available: https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/industrial_innovation_part_3_en.pdf

Chiappinelli, O., K. Neuhoff (2020). Time-consistent carbon pricing: The role of carbon contracts for differences. DIW Discussion Papers Nº 185

Climatewatch, (2020). Historical GHG emissions. https://www.climatewatchdata.org/ghg-emissions.

Critical Minerals Security Act of 2024, https://www.congress.gov/bill/118th-congress/senate-bill/3631/text

CSIS, (2022), 'Trade Tools for Climate: Transatlantic Carbon Border Adjustments', https://www. csis.org/analysis/trade-tools-climate-transatlantic-carbon-border-adjustments

Department Of Energy, (2023). 10 CFR Chapter III, Interpretation of Foreign Entity of Concern, Federal Register / Vol. 88, No. 231 / Monday, December 4, 2023 / Proposed Rules, https://www.govinfo.gov/content/pkg/FR-2023-12-04/pdf/2023-26479.pdf

Ding, J., Dafoe, A., (2021). The Logic of Strategic Assets: From Oil to AI, Security Studies, Vol. 30/2, pp. 182-212, https://doi.org/10.1080/09636412.2021.1915583

Dukan, M., Kitzing, L., (2023). A bigger bang for the buck: The impact of risk reduction on renewable energy support payments in Europe. Energy Policy 173, 113395. URL: https://www.sciencedirect.com/science/article/pii/S0301421522006140, doi:10.1016/j.enpol.2022.113395

Eicke, Laima.,Weko, Silvia., Maria Apergi a, Marian, Adela., (2021). Pulling up the carbon ladder? Decarbonization, dependence, and third-country risks from the European carbon border adjustment mechanism, Energy Research & Social Science 80(2021) 102240.

Eltayeb, T. K., Zailani, S., & Ramayah, T., (2011). Green Supply Chain initiatives among certified companies in Malaysia and environmental sustainability: Investigating the outcomes. Resources Conservation and Recycling, 55(5), 495–506. https://doi.org/10.1016/j.resconrec.2010.09.003.

Esterhaus, I., (2020). VCI-Position zu Carbon Contracts for Difference. [Online]. Available: https://www.vci.de/langfassungen/langfassungenpdf/2020-09-30-vci-positionspapier-carbon-contracts-for-difference.pdf

Cho, Eungyo, (2023). ‘Supply chain strategies of high-tech industries seen through China’s export controls and our response: Focusing on the semiconductor and battery industries’ p19.

European Commission (2021). Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757 Available from: https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf

European Commission, (2021c). Summary report: Public consultation on the carbon border adjustment mechanism (CBAM). URL https://ec.europa.eu/info/law/betterregulation/have-your-say/initiatives/12228-EU-Green-Deal-carbon-borderadjustment-mechanism-/public-consultation_en

European Commission, (2023a), Proposal for a regulation of the European Parliament and of the Council on establishing a framework for ensuring a secure and sustainable supply of critical raw materials, COM(2023) 160 final.

European Commission, (2023b), Proposal for a regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe’s net-zero technology products manufacturing ecosystem (Net-Zero Industry Act), COM(2023) 161 final.

European Commission. (2018). A clean planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Retrieved from https://ec.europa.eu/clima/policies/strategies/2050_en

EWI, (2021). Wann lohnen sich Carbon Contracts for Differences? Die Effekte unsicherer CO2- Preise und Kosten sowie deren Implikationen auf die Ausgestaltung. [Online]. Available: https://www.ewi.unikoeln.de/cms/wp-content/uploads/2021/11/Wann-lohnen-sich-CarbonContracts-for-Differences_PolicyBrief_20211130.pd

Favier, A., De Wolf, C., Scrivener, K., & Habert, G. (2018). A sustainable future for the European cement and concrete industry: Technology assessment for full decarbonization of the industry by 2050. Retrieved from https://doi.org/10.3929/ethz-b-000301843

Fischedick, M., Joyashree, R., Acquaye, A., Allwood, J., Ceron, J.-P., Geng, Y., ... Tanaka, K. (2014). Industry In:(Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University P

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y.,Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C.,Tanaka, K., (2014). Industry. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y.,Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P.,Kriemann, B., Savolainen, J., Schlomer, S., von Stechow, C., Zwickel, T., Minx, J.C. €(Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and NewYork, NY, USA, pp. 739e810.

Ford, S., & Despeisse, M., (2016). Additive Manufacturing and sustainability: An exploratory study of the advantages and challenges. Journal of Cleaner Production, 137, 1573–1587. https://doi.org/10.1016/j. jclepro.2016.04.150.

Fragkos, P.. (2020) Global Energy System Transformations to 1.5 ◦C: The Impact of Revised Intergovernmental Panel on Climate ChangeCarbon Budgets. Energy Technol. 2020, 8, 2000395.

Fragkos, Panagioti., Fragkiadakis, Kostas., Paroussos, Leonidas., (2021). Reducing the Decarbonisation Cost Burden for EUEnergy-Intensive Industries, Energies 2021, 14, 236. https://doi.org/10.3390/en14010236.

Gasser, P. A., (2020). Review on Energy Security Indices to Compare Country Performances. Energy Policy, 139, 111339.

Gerres, Timo., Linares, Pedro., (2020). Carbon Contracts for Differences: their role in European industrial decarbonization, Climate Friendly Materials

Platform

Haley, U., & Haley, G. (2013). Subsidies to Chinese industry – State capitalism, business strategy, and trade policy. Oxford: Oxford University Press.

Hart, D., (2017). Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects. Information Technology and Innovation Foundation.Available at: http://www2.itif.org/2017-second-valley-of-death.pdf.

He, G., Mallapragada, D. S., Bose, A., Heuberger-Austin, C. F., & Gençer, E. (2021). Sector coupling via hydrogen to lower the cost of energy system decarbonization. Energy & Environmental Science, 14(9), 4635–4646. https://doi.org/10.1039/d1ee00627d.

Helm D. and C. Hepburn (2005), "Carbon contracts and energy policy: An outline proposal". Oxford University Department of Economics Discussion Paper.

Helveston, John, Nahm, Jonas. (2019). China's Key Role in Scaling Low-Carbon Energy Technologies. Science 366 (6467): 794–796. https://doi.org/10.1126/science .aaz1014, PubMed: 31727813

Hernandez, H., Grassano, N., Tübke, A., Potters, L., Gkotsis, P., Vezzani, A., (2018). The 2018 EU Industrial R&D Investment Scoreboard. Luxembourg: PublicationsOffice of the European Union. Available at: http://iri.jrc.ec.europa.eu/scoreboard18.html.

Hertwich, E. G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Wolfram, P. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environmental Research Letters, 14(4), 043004. Retrieved from https://doi.org/10.1088/1748-9326/ab0fe3

Hoogsteyn, Alexander., Bruninx, Kenneth., Delarue, Erik., (2024). Carbon Contracts for Difference Design: Implications for EnergyMarkets and Carbon Pricing Mechanisms. Climate Policy.

IEA. (2015). Energy Technology Perspectives 2015. Paris: IEA /OECD.

IEA, (2022). The Role of Critical Minerals in Clean Energy Transitions, p.9.

Janssen, D., (2023). Exploitatiesteun en (Carbon) Contracts for Difference (CCfD). Technical Report. Waterstof Industrie Cluster. URL: https://www.waterstofnet.eu/nl/waterstof-industrie-cluster/ledenportaal/downloads/wic-policy-recommendations.

Jung, Hoon., (2023). Introduction of the carbon border adjustment mechanism confirmed, a response strategy for the era of climate diplomacy, National Assembly Futures Institute, Futures Brief, 23-08

Kayikci, Y., (2018). Sustainability impact of digitization in logistics. Procedia Manufacturing, 21, 782–789.

Kazancoglu, Y., Kazancoglu, I., & Sagnak, M., (2018). A new holistic conceptual framework for Green Supply Chain Management Performance Assessment based on Circular Economy. Journal of Cleaner Production, 195, 1282–1299. https://doi.org/10.1016/j.jclepro.2018.06.015

Kechichian, E., Pantelias, A., Reeves, A., Henley, G., Liu, J., 2016. A Greener Path to Competitiveness: Policies for Climate Action in Industries and Products. WorldBank Group, Washington, DC. Retrieved from. http://documents.worldbank.org/curated/en/835691472028683380/A-greener-path-to-competitiveness-policies-for-climate-action-in-industries-and-products.

Kim, Eunmi., Lee, Seonghee., (2022). Carbon neutrality promotion trends and response directions in the international community in the industrial sector: Focusing on small and medium-sized enterprises, p.21.

Kim, Gye-hwan,, Sa, gongmok., Kang, Jihyun., Jeong, Seong-in., Kim. Bau., Kim, Yunsoo., Lee, Moonhyung., (2021), Industrial and trade strategy for strategic autonomy in the era of economic hegemony competition, Korea Institute for Industrial Economics and Trade. Research Report 2021-15.

Knox-Hayes, J.; Brown, M.A.; Sovacool, B.K.; Wang, Y., (2013) Understanding Attitudes toward Energy Security: Results of a CrossNational Survey. Glob. Environ. Chang. 23, 609–622

Korea International Trade Association, (2020), Paradigm change in the global value chain and the future of Korean trade

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. Ecological Economics, 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Krishnan, S., Gupta, S., Kaliyan, M., Kumar, V., & Garza-Reyes, J. A., (2021). Assessing the key enablers for industry 4.0 adoption using Micmac Analysis: A case study. International Journal of Productivity and Performance Management, 70(5), 1049–1071. https://doi.org/10.1108/ijppm-02-2020-0053.

Lee, Jun., (2022). Changes in external conditions surrounding the global supply chain and response measures, KIET industrial economy, p22.

Leem, Soyoung., Kim, Gyehwan., Cho, Eungyo., (2023). Comparative analysis of carbon neutral trade policy policies, ISSUE PAPER 2023-09, pp.132-144

Leipprand, A., Schaefer, T., Walther, M., (2021). Carbon Contracts for Difference for an Accelerated Industrial Transformation. [Online]. Available: https://www.energy4climate.nrw/fileadmin/Service/Publikationen/Ergebnisse_IN4climate.NRW/2021/in4climatenrw-positionspapierklimaschutzvertraege-de-web-2021-

Lösch, Oliver., Friedrichsen, Nele., Eckstein, Johannes., Richstein, Jörn C., (2022). Carbon Contracts for Difference as an essential instrument to decarbonize basic materials industries.

Magacho, Guilherme. Espagne, Etienne.,Godin, Antoine., (2024). Impacts of the CBAM on EU trade partners: consequences for developing countries, CLIMATE POLICY2024, VOL. 24, NO. 2, 243–259https://doi.org/10.1080/14693062.2023.2200758

Malhotra, Abhishek., Schmidt, Tobias S., (2020). Accelerating Low-Carbon Innovation. Joule 4 (11): 2259–2267. https://doi.org/10.1016/j.joule.2020.09.004

Material Economics (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry. Available from: https://materialeconomics.com/publications/industrial-transformation-2050

Material Economics, (2019). Industrial Transformation 2050 e Pathways to Net-Zero Emissions from EU Heavy Industry. Available at:

https://materialeconomics.co m/publications/industrial-transformation-2050.

Material Economics. (2019). Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry. Stockholm: Material Economics.

Mattoo, A., Subramanian, A., van der Mensbrugghe, D., He, J., (2013). Trade effects of alternative carbon border-tax schemes, Review of World Economics 149 (3) 587–609, https://doi.org/10.1007/s10290-013-0159-0.

May, Nils; Neuhoff, Karsten (2017), Financing power: Impacts of energy policies in changing regulatory environments, DIW Discussion Papers, No. 1684, Deutsches Institut für Wirtschaftsforschung (DIW), Berlin

McWilliams, B., & Zachmann, G. (2021). Commercialization contracts: European support for low-carbon technology deployment (No. 15/2021; Policy Contribution). Bruegel.

McWilliams, B., Zachmann, G., (2021): Commercialisation contracts: European support for low-carbon technology deployment. In: Policy Contribution (15/21).

Mealy, P., Teytelboym, A. (2020). Economic complexity and the green economy. Research Policy, 103948.

Meckling, Jonas, Nahm, Jonas. (2019). The Politics of Technology Bans: Industrial Policy Competition and Green Goals for the Auto Industry. Energy Policy 126 (March): 470–479. https://doi.org/10.1016/j.enpol.2018.11.031

Ministry of Trade, Industry and Energy, (2022). Held a briefing session on utilizing major U.S. IRA incentives, https://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_seq_n=166187&bbs_cd_n=81

Ministry of Trade, Industry and Energy, (2023). Annual and December 2022 export and import trends; p.1.

Ministry of Trade, Industry and Energy, (2024), December 2023 and annual import and export trends; press release, p.11.

Neuhoff, K., Acworth, W., Barret, S., Owen, A., Fisher, C., Munnings, C., ... Roth, S. (2015). Inclusion of consumption of carbon-intensive commodities in carbon pricing mechanisms. Retrieved from http://www.diw.de/documents/dokumentenarchiv/17/diw_01.c.523297.de/policy-brief-ioc.pdf.

NIST, (2023), Funding Opportunity – Commercial Fabrication Facilities FACT SHEET: CHIPS Program Office Launches Notice of Funding Opportunity https://www.nist.gov/system/files/documents/2023/02/28/CHIPS_NOFO-1_Fact_Sheet_0.pdf

Oberthür, Sebastian., Khandekar, Gauri, Wyns, Wyns, Tomas., (2021). Global governance for the decarbonization of energy-intensive industries: Great potential underexploited

Oberthür, Sebastian., Khandekar, Gauri., Wyns, Tomas., (2021). Global governance for the decarbonization of energy-intensive industries: Great potential underexploited, Earth System Governance

OECD, (2022). An Industrial Policy Framework for OECD Countries

Pamenter, Sarah., Myers, J. Rupert., (2021). Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts, Journal of Industrial Ecology 2021;25:359–376.

Papadis, E., & Tsatsaronis, G., (2020). Challenges in the decarbonization of the Energy Sector. Energy, 205, 118025. https://doi.org/10.1016/j.energy.2020.118025.

Park, A., & Li, H., (2021). The effect of blockchain technology on supply chain sustainability performances. Sustainability, 13(4), 1726. https://doi.org/10.3390/su13041726.

Paroussos, L.; Fragkos, P.; Capros, P.; Fragkiadakis, K., (2014). Assessment of carbon leakage through the industry channel: The EU perspective. Technol. Forecast. Soc. Chang. 2014, 90, 204–219. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0040162514000602

Pee, Arnout., Pinner, Dickon., Roelofsen, Occo., Somers, Ken., Speelman, Eveline., Witteveen, Maaike., (2018). Decarbonization of industrial sectors: the next frontier, McKinsey&Company

Perdana, Sigit., Vielle, Marc., (2022). Making the EU Carbon Border Adjustment Mechanism acceptable and climate-friendly for least-developed countries. Energy Policy, https://doi.org/10.1016/j.enpol.2022.113245

Popp, D., Newell, R., Jaffe. A., (2010). Energy, the Environment, and Technological Change, in Handbook of the Economics of Innovation, Volume 2, Handbook of the Economics of Innovation, Elsevier, https://doi.org/10.1016/s0169-7218(10)02005-8.

Puica, E., (2020). Cloud computing in Supply Chain Management and economic, environmental, and social impact analysis. Informatica Economica, 24(4/2020), 41–54. https://doi.org/10.24818/ issn14531305/24.4.2020.04.

Quere, C. L., (2015). Towards a culture of low-carbon research for the 21st Century. Tyndall Centre for Climate Change Research.

Rabbi, Mohammad Fazle., Popp, József., Máté, Domicián., Kovács, Sándor., (2022).

Raj Kumar, N., (2016). Cloud Computing for Green Supply Chain Management. Global Research and Development Journal for Engineering

Regulation (EU) 2023/957 of the European Parliament and of the Council of 10 May; 2023 EY(2023), https://www.ey.com/en_gl/tax-alerts/final-regulations-published-for-new-eu-carbon-border-adjustment

Richstein, J.C., 2017. Project-Based Carbon Contracts: A Way to Finance Innovative Low-Carbon Investments. URL: https://papers.ssrn.com/abstract=3109302, doi:10.2139/ssrn.3109302

Richstein, J.C., Kröger, M., Neuhoff, K., Chiappinelli, O., & Lettow, F. (2021). Carbon Contracts for Difference – An assessment of selected socio-economic impacts for Germany. Report for Project CFM TRACTION

Richstein, Jörn C., Neuhoff, Karsten., (2022). Carbon contracts-for-difference: How to de-risk innovative investments for a low-carbon industry? iScience 25, 104700, https://doi.org/10.1016/j.isci.2022.104700

Rilling, Anabel., Anatolitis, Vasilios., Zheng, Lin., (2022). How to design Carbon Contracts for Difference – A systematic literature review and evaluation of design proposals.

Rodrik, D. (2014). Green industrial policy, Oxford Review of Economic Policy, Vol. 30/3, pp. 469- 491, https://doi.org/10.1093/oxrep/gru025.

Sartor, O., and C. Bataille (2019). Decarbonising Basic Materials in Europe: How Carbon Contracts-for-Difference Could Help Bring Breakthrough Technologies to Market. IDDRI Study, no. 6

Senate Democrat, (2022). Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022.

Serra, P., & Fancello, G., (2020). Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for Decarbonizing international shipping. Sustainability, 12(8), 3220. https://doi.org/10.3390/su12083220.

Shanks, W., Dunant, C. F., Drewniok, M. P., Lupton, R. C., Serrano, A., & Allwood, J. M. (2019). How much cement can we do without? Lessons from cement material flows in the UK. Resources, Conservation and Recycling, 141, 441–454. https://doi.org/10.1016/j.resconrec.2018.11.002

Shee, H., Miah, S. J., Fairfield, L., & Pujawan, N., (2018). The impact of cloud-enabled process integration on supply chain performance and firm sustainability: The moderating role of Top Management. Supply Chain Management: An International Journal, 23(6), 500–517. https://doi.org/10.1108/ scm-09-2017-0309

Shen, Shiran Victoria., (2021). Accelerating Decarbonization in China and the United States and Promoting Bilateral Collaboration on Climate Change. Stanford University

Shibin, K. T., Gunasekaran, A., Papadopoulos, T., Dubey, R., Singh, M., & Wamba, S. F., (2016). Enablers and barriers of flexible green supply chain management: A total interpretive structural modeling Approach. Global Journal of Flexible Systems Management, 17(2), 171–188. https://doi.org/10.1007/ s40171-015-0109-x.

Simola, H., et al., (2021). CBAM!–Assessing potential costs of the EU carbon border adjustment mechanism for emerging economies. BOFIT Policy Brief 10.

Sindhwani, Rahul., Hasteer, Nitasha,. Behl, Abhishek., Chatterjee, Chinmayee., Hamzi, Lotfi., (2022), Analysis of sustainable supply chain and industry 4.0 enablers: a step towards decarbonization of supply chains, pp. 2-3.

Skjærseth JB, Eikeland PO, Christensen AR, Gulbrandsen LH, Underdal A,Wettestad J., (2013) Coporate responses to EU Emissions Trading, Comparative analysis.

Sovacool, B.K.; Rafey, W. Snakes in the Grass., (2011), The Energy Security Implications of Medupi. Electr. J. 24, 92–100.

Spaargaren G, Oosterveer P, Loeber A., (2013) Food practices in transition: changing food consumption, retail and production in the age of reflexive modernity. London: Routledge.

SPIRE, (2013). SPIRE roadmap. Brussels

Sriyogi, K., (2016). Sustainable supply Chain Management Practices: An environmental perspective in Indian Manufacturing companies. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2753437.

Stroumpoulis, A., & Kopanaki, E. (2022). Theoretical perspectives on sustainable supply Chain Management and Digital Transformation: A literature review and a conceptual framework. Sustainability, 14(8), 4862. https://doi.org/10.3390/su14084862.

Truby, J., (2018). Decarbonizing Bitcoin: Law and policy choices for reducing the energy consumption of blockchain technologies and digital currencies. Energy Research & Social Science, 44, 399–410. https://doi.org/10.1016/j.erss.2018.06.009.

U.S. Congress, Clean Competition Act, S. 4355, 117th Cong., 2nd sess., https://www.congress. gov/117/bills/s4355/BILLS-117s4355is.pdf

UK Department for Business, E..I.S., (2022). The Carbon Capture and Storage InfrastructureFund: an update on its design (accessible webpage). URL: https://www.gov.uk/government/publications/design-of-the-carbon-capture-and-storage-ccs-infrastructure-fund/the-carbon-capture-and-storage-infrastructure-fund-an-update-on-its-design-accessible-webpage.

Unruh, G.C., (2000). Understanding carbon lock-in, Energy Policy 28 (12) 817–830, https://doi.org/10.1016/S0301-4215(00)00070-7.

Wells, P,, Nieuwenhuis, P., (2012). Transition failure: understanding continuity in the automotive industry. Technol Forecast Soc Change 2012;79:1681–92. http://dx.doi.org/10.1016/j.techfore.2012.06.008.

Wesselinga, J.H., Lechtenböhmer, S., Åhmanc, M., Nilssonc, L.J., Worrelld, E., Coenen, L., (2017). The transition of energy-intensive processing industries towards deep decarbonization: Characteristics and implications for future research, Renewable and Sustainable Energy Reviews 79(2017). 1303-1313.

Weyant, J.P. (1999.) The Costs of the Kyoto Protocol: A Multi-Model Evaluation; The Energy Journal (Special Issue); Cleveland, OH, USA; pp. 1–398. Available online: https://web.stanford.edu/group/emf-research/docs/emf16/CostKyoto.pdf

Wong, E. Y., Lau, H. Y., & Chong, J. S., (2013). Supply chain decarbonization in shipping and Logistics Transportation. Journal of Traffic and Logistics Engineering, 1(2), 233–237. https://doi.org/10.12720/ jtle.1.2.233-237

World Bank, (2022). https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

World Economic Forum, Ellen MacArthur Foundation, & McKinsey & Company. (2016). The new plastics economy—rethinking the future of plastics. Retrieved from https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics.

World Economic Forum., (2021). Net-Zero Challenge: The supply chain opportunity. Insight Report. 9-34.

Worrell, E., Bernstein, L., Roy, J., Price, L., & Harnish, J. (2009). Industrial energy efficiency and climate mitigation. Energy Efficiency, 2, 109–123

Worrell, Ernst., Biermans, Gijs., (2005). Move over! Stock turnover, retrofit, and industrial energy efficiency. Energy Policy 2005;33:949–62. http://dx.doi.org/10.1016/j.enpol.2003.10.017

Wyns, T., Khandekar, G., Robson, I., (2018). Industrial Value Chain: A Bridge towards a Carbon Neutral Europe. Europe's Energy Intensive Industries Contribution to the EU Strategy for Long-Term EU Greenhouse Gas Emissions Reductions. Vrije Universiteit Brussel, Institute for European Studies. Available at: https://www.ies.be/files/Industrial_Value_Chain_25sept_0.pdf