

Development of a Framework for Sharing the Cost of Carbon Footprint Reduction in Products

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**Development of a Framework for Sharing the Cost of Carbon
Footprint Reduction in Products**

A Dissertation Submitted in Partial Fulfillment
of the Requirement for the Degree of Ph.D. in Economics

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Chapter 1. Introduction

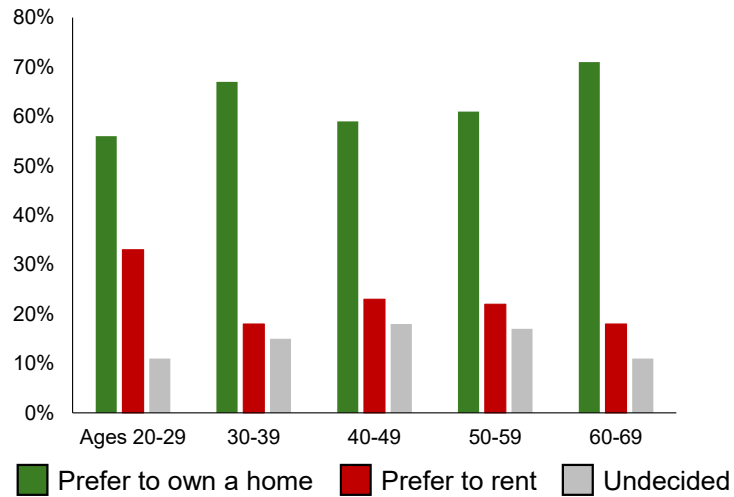
1.1. Global warming and the urgency of CO₂ mitigation

Since the Industrial Revolution, global warming has become more serious due to the increase in greenhouse gas emissions such as CO₂. In fact, the global average temperature, relative to the 1850–1900 baseline, increased by approximately 1.1°C between 2011 and 2020 (IPCC, 2023), clearly indicating the progression of climate change. According to the IPCC report, even if global warming is limited to 1.5°C, the global mean sea level is projected to rise by approximately 2–3 meters over the next 2,000 years, and by about 2–6 meters if warming is limited to 2°C. Accordingly, there are concerns about the increasing damage to coastal ecosystems, settlements, infrastructure, and economic losses (IPCC, 2023). Furthermore, the IPCC has specified the remaining carbon budget required to limit global warming to particular temperature thresholds. If annual CO₂ emissions remain at 2019 levels, cumulative emissions from 2020 to 2030 are projected to almost deplete the 1.5°C budget and use up more than one-third of the 2°C budget. Based on these backgrounds, the decrease of CO₂ emissions is global issue. Similarly, Japan set a goal for achieve carbon neutral by 2050. In this context, the reduction of CO₂ emissions has become an urgent global challenge, and Japan has declared its commitment to achieving carbon neutrality by 2050.

1.2. Roles of the steel and construction sectors in Japan's carbon neutrality and the significance of wooden housing

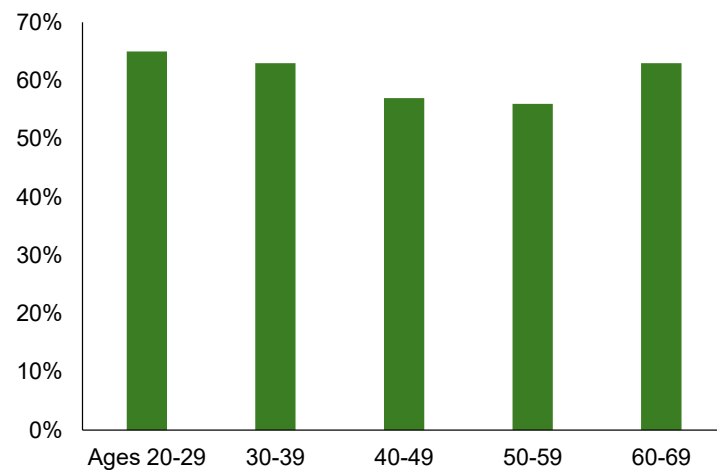
The iron and steel industry, as well as the civil engineering and building construction sectors, play a crucial role in achieving carbon neutrality in Japan. As of 2023, the iron and steel industry

accounted for approximately 14% of total domestic CO₂ emissions, while the civil engineering and building construction sectors accounted for about 0.7% (National Institute for Environmental Studies, 2025). Furthermore, approximately 22% of steel products are supplied to the civil engineering and building construction sectors, a proportion almost equivalent to that of the automobile industry (23%) (Ministry of Economy, Trade and Industry, 2024). In addition, the iron and steel industry accounts for 6.4% of CO₂ emissions based on energy consumption in civil engineering and building construction (MLIT, 2020). These figures indicate that the two sectors are closely interconnected through their supply chains, highlighting the necessity of coordinated efforts toward decarbonization. 90% of 4 stair houses are non-wooden houses, meanwhile, 80% of the lower houses (1-3 stair) are wooden-houses. According to the Building Starts Statistics (MLIT, 2022), more than 90% of houses with four or more stories are non-wooden, while approximately 80% of lower houses (one to three stories) are wooden. In terms of total floor area, wooden low-rise houses account for about 2.5 times that of non-wooden ones. The widespread use of wooden houses can be attributed not only to their lower construction costs but also to the environmental benefits of wood, such as its carbon storage capacity. Furthermore, a survey by the Ministry of Land, Infrastructure, Transport and Tourism (2019) found that more than half of all generations wish to own a house, and many of them prefer newly built detached houses (Figures 1-1 and 1-2). Therefore, there is consistent demand for wooden houses, making them an important target for emission reduction in the residential sector. Since over 90% of CO₂ emissions during construction originate from the supply chain (Huang *et al.*, 2018), achieving decarbonization in housing requires emission reductions throughout the entire supply chain.



Source: Author's compilation based on the Monitor Survey (MLIT, 2019)

Figure 1-1. Housing ownership preferences by age group



Source: Author's compilation based on the Monitor Survey (MLIT, 2019)

Figure 1-2. Proportion of respondents who wish to own a newly built detached house by age group

1.3. Decarbonization challenges in the steel sector and supply chain burden sharing

While the previous section examined the civil engineering and building construction sectors as downstream industries, this section turns to the iron and steel sector, an upstream industry that plays a major role in CO₂ emissions associated with construction activities. The reduction of direct CO₂ emissions from the iron and steel sector serves as a crucial strategy for lowering the environmental impact of other sectors across the entire supply chain. However, achieving decarbonization in this sector entails considerable costs. It is estimated that research and development, along with capital investment, will require roughly 10 trillion yen by 2050 (Cabinet Office, 2024). Furthermore, the marginal abatement cost of implementing hydrogen-based direct reduction ironmaking technology is projected to be approximately 500 USD per ton of CO₂ (IEA, 2018; IPCC, 2022; EWI, 2022). This cost is significantly higher than the marginal abatement costs in the cement, construction, and transportation sectors, which are estimated at 20–80 USD per ton of CO₂ through measures such as material substitution, enhanced insulation and energy-efficient equipment, and the use of biofuels. Such a high-cost structure puts financial pressure on iron and steel companies, making it difficult for them to address decarbonization on their own. Therefore, it is essential to establish a mechanism for fairly sharing decarbonization costs across the entire supply chain. Among the potential measures, the carbon inset—an approach in which companies invest in emission-reduction activities within their own supply chains—has attracted growing attention. For instance, direct investments in regenerative agriculture at raw material sourcing sites represent a typical example of such initiatives. Applying this framework to the iron and steel industry and supporting the decarbonization of upstream sectors are key to achieving carbon management across the entire supply chain. To realize this, it is essential to quantitatively assess the emission responsibility of each sector for CO₂ emissions originating from steel production.

1.4. Structure of this thesis

This thesis consists of five chapters (Figure 1-3). Chapter 2 provides a comprehensive review of the development and applications of environmentally extended input–output analysis (EEIOA) and studies on emission responsibility. In addition, it clarifies the contributions and limitations of previous research and describes the novelty and objectives of this thesis.

Chapter 3 identifies emission hotspots within the supply chain of wooden houses in Japan by combining EEIOA, using the total floor area of houses as the functional unit, with a clustering approach. As a result, clusters related to iron and cement were identified as major sources of emissions, demonstrating that promoting the reuse of building foundations and implementing renovation policies are effective mitigation measures.

Chapter 4 applies an EEIOA based on a shared-responsibility emission accounting framework to decompose the CO₂ emission responsibilities of the iron and steel sector into upstream and downstream components and proposes a scheme for fair cost allocation. As a result, the shared-responsibility emission approach redistributed emission responsibility, significantly reducing the burden on the final goods production sectors. In particular, the cost burden of the automobile sector was reduced to approximately one-seventeenth of that under the consumption-based emission approach, highlighting the importance of equitable responsibility sharing.

Chapter 5 summarizes the findings obtained in Chapters 3 and 4 and presents the overall conclusions of this thesis.

The contents of Chapters 3, 4, and 5 of this thesis have been published in the following peer-reviewed academic journals.

Chapter 3:

Imada, S., Maeno, K., Kagawa, S. (2024) CO₂ emission hotspots analysis on supply chains for wooden houses in Japan, *Journal of Environmental Management*, 353, 120151.

Chapter 4:

Imada, S. (2025) Sharing CO₂ abatement costs in the iron and steel sector: A shared responsibility input-output approach, *Ecological Economics*, 230, 108504.

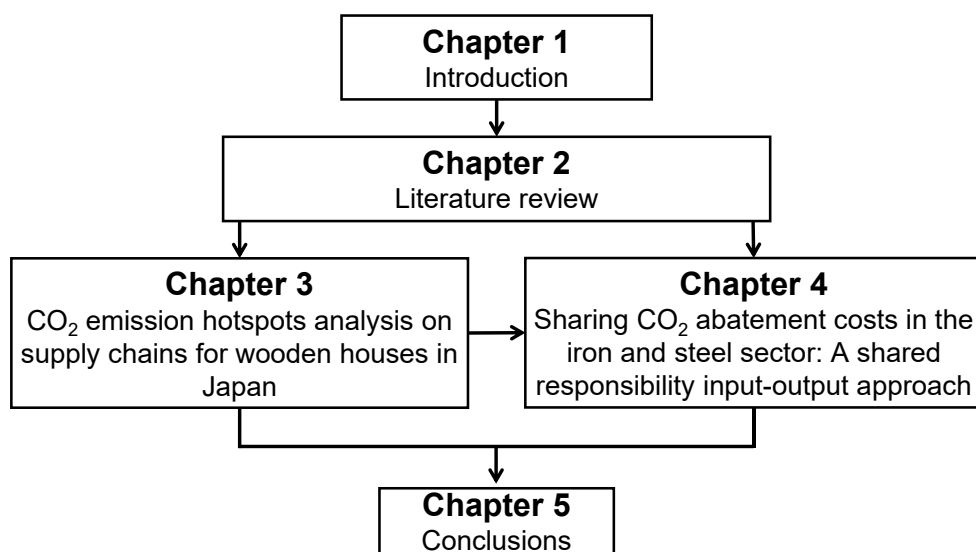


Figure 1.3. Structure of this thesis

Chapter 2. Literature review

2.1. *Life-cycle assessment (LCA)*

In recent years, governments and companies have been intensifying their efforts to reduce material consumption and environmental impact. In particular, growing attention has been directed toward estimating and reporting CO₂ emissions across the entire product life cycle—from resource extraction and raw material production to product manufacturing, distribution and consumption, and finally disposal or recycling (Whiteman *et al.*, 2013; Bjørn *et al.*, 2017). In this context, Life Cycle Assessment (LCA) has been widely used across research, industry, and policy fields as an environmental assessment method for evaluating the life cycles of products and services (Guinée *et al.*, 2011; McManus & Taylor, 2015; Moutik *et al.*, 2023). In 1997, the International Organization for Standardization (ISO) standardized Life Cycle Assessment (LCA) as part of the ISO 14000 series of international standards for environmental management, under ISO 14040 (Klüppel, 1998). In 2006, ISO 14040:2006 and ISO 14044:2006 were published, providing the principles, framework, and guidelines for conducting Life Cycle Assessment (LCA) and establishing its overall conceptual structure (Klöppfer, 2012).

2.2. *Process-based (Bottom-up) LCA: Characteristics and limitations*

There are two main approaches to Life Cycle Assessment (LCA): bottom-up LCA and top-down LCA. Bottom-up LCA quantitatively evaluates the environmental impacts of products and processes across their entire life cycle — from resource extraction and raw material acquisition to manufacturing, use, and end-of-life disposal or recycling, often described as a “cradle-to-grave”

approach (Hendrickson et al., 1998). One of the key characteristics of the bottom-up LCA approach is its ability to conduct detailed analyses for specific products, enabling companies to identify the main environmental impact drivers across their entire life cycle (Heijungs, 1994; Carlsson Reich, 2005; Hellweg & Canals, 2014). The bottom-up LCA approach has been widely applied in previous studies focusing on various products and services (e.g., Scharlemann & Laurance, 2008; Christensen *et al.*, 2009; Koehler & Wildbolz, 2009; Milà i Canals *et al.*, 2011; Yokokawa *et al.*, 2019). Scharlemann and Laurance (2008) focused on the environmental impacts of biofuels and revealed that, when agricultural crops are used as feedstocks, biofuels can cause greater environmental burdens than conventional fuels depending on production conditions. In the field of architecture as well, numerous LCA studies have been conducted, some of which evaluate entire building systems while considering all stages of the life cycle (e.g., Arpke & Hutzler, 2006; Norman *et al.*, 2006; Ramesh *et al.*, 2010; Pauliuk *et al.*, 2013; Saner *et al.*, 2013; Cabeza *et al.*, 2014; Abd Rashid & Yusoff, 2015; Lee *et al.*, 2017; Kayo *et al.*, 2018; Nakano *et al.*, 2024). In particular, Kayo *et al.* (2018) focused on the Japanese construction sector. They estimated the environmental burdens associated with wood consumption and demonstrated that increasing the proportion of wooden buildings and the use of wood in energy applications contributes to reducing GHG emissions.

On the other hand, several limitations of the bottom-up LCA approach have been identified. Since the system boundaries can be arbitrarily defined, it is not possible to account for all CO₂ emissions from indirect suppliers, which leads to an underestimation of total life-cycle CO₂ emissions (Lenzen, 2000; Raynolds *et al.*, 2000; Suh *et al.*, 2004; Hondo, 2008; Zhang & Wang, 2016a). In addition, it has been pointed out that previous studies not only employ different methodologies but also exhibit considerable variation in the data and assumptions used (e.g., product system boundaries) (Suh, 2009; Nässén *et al.*, 2007). With regard to data, collecting process-level information requires enormous time and cost; therefore, analyses are often limited to processes considered to have

significant environmental impacts. Consequently, truncation errors have been identified as a limitation of this approach (Lave *et al.*, 1995; Lenzen, 2000; Suh & Kagawa, 2005; Wiedmann, 2009a).

2.3. Development and applications of environmentally-extended input-output analysis (EEIOA)

To address these limitations of the bottom-up LCA approach, the use of input–output table (IOT) has been increasingly promoted. Originally, the IOT was developed by Leontief (1936, 1941) for economic analysis. Subsequently, it has been applied to studies of pollution, waste management, energy use, and environmental analysis (e.g., Daly, 1968; Isard *et al.*, 1968; Ayres & Kneese, 1969; Leontief, 1970; Leontief & Ford, 1972; Victor, 1972; Leontief, 1973; Herendeen, 1973; Wright, 1974; Rose & Miernyk, 1989; Duchin, 1990; Duchin, 1992; Wier *et al.*, 2001). Leontief (1970) and Leontief and Ford (1972) analyzed the relationship between economic activity and environmental pollution by incorporating emissions of waste and environmentally harmful substances with no market value into the input–output framework. During the 1970s, when the oil crisis occurred, Herendeen (1973) and Wright (1974) estimated the energy consumption throughout the life cycles of products and technologies using input–output tables.

In the 1980s, Defourny and Thorbecke (1984) and Crama *et al.* (1984) proposed Structural Path Analysis (SPA), a method that quantifies the contribution of each supply chain path within a network to overall environmental impacts. This approach has since been applied to both economic and environmental analyses (e.g., Sonis *et al.*, 1997; Treloar, 1997; Treloar *et al.*, 2001; Lenzen, 2002; Lenzen *et al.*, 2003; Wood & Lenzen, 2003; Peters & Hertwich, 2006a; Lenzen, 2007; Minx *et al.*, 2009; Lenzen & Murray, 2010; Llop & Ponce-Alifonso, 2015; Nagashima *et al.*, 2017; Gunluk-Senesen *et al.*, 2018; Mitoma *et al.*, 2021; Chen *et al.*, 2022). Treloar (1997) applied SPA to identify the structural paths of energy flows and revealed that the cement sector appeared twice among the top

nine paths in the Australian residential construction sector. Peters and Hertwich (2006a) conducted a detailed analysis of the environmental impact structures of the consumption, government, and export sectors in the Norwegian economy using structural path analysis (SPA). They revealed that, in households, major emissions originated from daily-life-related activities such as transportation and food; in the government sector, from indirect emissions associated with construction and public expenditures; and in exports, from pollution-intensive industries such as shipping, oil, and metals. Gunluk-Senesen *et al.* (2018) applied structural path analysis (SPA) to examine the ripple effects of the expansion of Turkey's construction sector in the 2000s on employment and imports. The results revealed that public construction policies during that period promoted intermediate goods imports rather than employment growth.

From the 1990s onward, EEIOA was applied to investigate the effects of international trade on energy consumption and CO₂ emissions, as well as the CO₂ emissions associated with industrial production activities (e.g., Common and Salma, 1992; Gay and Proops, 1993; Wyckoff and Roop, 1994; Lenzen, 1998; Wier, 1998; Wier and Hasler, 1999; Munksgaard *et al.*, 2000; Machado *et al.*, 2001; Sánchez-Chóliz and Duarte, 2004; Peters and Hertwich, 2006b). Wyckoff and Roop (1994) conducted an EEIOA using bilateral international trade flow data and input–output tables for Canada, France, Germany, Japan, the United Kingdom, and the United States. They revealed that the direct and indirect CO₂ emissions embodied in the manufactured goods imported by these six countries accounted for approximately 13% of their total CO₂ emissions. Lenzen (1998) employed EEIOA using Australia's IOT and revealed that indirect emissions embodied in household consumption accounted for approximately 70% of total domestic emissions. In contrast, more than 50% of the energy embodied in exports was concentrated in primary industries such as agriculture, mining, and metals. Machado *et al.* (2001) employed an EEIOA with hybrid units (combining physical and monetary data) using Brazil's 1995 IOT and energy statistics. They revealed that Brazil's exports of non-energy goods

embodied about 40% more energy and 56% more carbon than its imports.

From the 2000s onward, many studies have utilized advanced environmentally extended input–output analysis (EEIOA) to identify the most CO₂ emission–intensive transactions within supply chains, that is, CO₂ emission hotspots (e.g., Lenzen, 2003; Kagawa *et al.*, 2009; Acquaye *et al.*, 2011; Kagawa *et al.*, 2013a; Kagawa *et al.*, 2013b; Kagawa *et al.*, 2015; Maeno *et al.*, 2022; Maeno, 2023). Lenzen (2003) identified environmentally significant sectors in the Australian economy by using coefficients of variation that account for forward and backward linkage indices and the variability of matrix elements. Kagawa *et al.* (2013a, 2013b) combined spectral clustering with input–output analysis to identify CO₂ emission hotspots within supply chain networks. Maeno *et al.* (2022) and Maeno (2023) employed the Scenario-based Extraction Method (SEM) and the Hypothetical Extraction Method (HEM) to identify CO₂ emission hotspots in the Japanese automobile supply chain based on a global multi-regional input–output table (MRIOT).

To summarize the discussion so far, the following conclusion can be drawn. Because EEIOA can consider a more comprehensive system boundary than bottom-up LCA, it addresses one of the major weaknesses of the bottom-up approach, namely, the arbitrariness in defining system boundaries. Additionally, because it utilizes existing data such as input–output tables, CO₂ emission hotspots can be estimated with relatively low cost and time (Suh, 2009; Man *et al.*, 2017; Hung *et al.*, 2019).

2.4. Environmentally extended input–output analysis (EEIOA) focusing on the construction sector

Building on the advantages of input–output tables summarized in Section 2.3, numerous studies have focused on assessing the environmental impacts of the construction sector, which is characterized by complex supply chains (Hong *et al.*, 2016; Zhang and Wang, 2016a; Zhang and Wang,

2016b; Chen *et al.*, 2017; Huang *et al.*, 2018; Onat and Kucukvar, 2020; Hou *et al.*, 2021; Chen *et al.*, 2022; Su *et al.*, 2022). Hong *et al.* (2016) estimated the direct and indirect energy consumption associated with construction activities in China by using a multi-regional input–output table. They revealed that coal accounted for the largest share of primary energy use across all provinces in China. This result is attributed to the fact that the construction sector consumes a large amount of iron and steel, and coal is used as a major energy source in the production of those materials. Based on these results, Hong *et al.* (2016) presented several discussions and policy recommendations to reduce energy consumption in China’s construction sector. They pointed out that the iron and steel industry, which lies upstream of construction activities, is highly energy-intensive. Therefore, expanding the use of environmentally friendly materials with lower energy consumption is an effective means of reducing total energy use in construction. They further suggested that the iron and steel industry should promote the development of energy-efficient technologies and high value-added products with lower energy intensity.

Chen *et al.* (2017) used a multi-regional input–output table to estimate CO₂ emissions from China’s construction sector between 1995 and 2011. They found that total CO₂ emissions increased from 621 Mt in 1995 to 3,035 Mt in 2011, with indirect emissions accounting for 95–99% of the total. They also revealed that the basic metals and fabricated metal products sectors together contributed about 11% of total emissions from 1995 to 2009. Based on these findings, Chen *et al.* (2017) presented several discussions and policy recommendations for reducing CO₂ emissions in China’s construction sector. They argued that the increase in CO₂ emissions was mainly driven by rapid urbanization and the resulting surge in demand for construction products such as buildings, roads, and railways. Therefore, emission reduction policies should also focus on indirect CO₂ emissions, which constitute the majority of the sector’s total emissions. They emphasized the importance of promoting the use of low-carbon materials supplied by upstream sectors such as basic and fabricated metals, as well as

reducing material use within the construction sector itself.

2.5. Conceptual frameworks for emission responsibility: production-based emissions, consumption-based emissions, and shared responsibility-based approaches

The previous studies discussed in Sections 2.3 and 2.4 have estimated the environmental burdens of goods and services using input–output tables. The fact that CO₂ emissions are embodied in goods traded through supply chains leads to a fundamental question: Who should bear responsibility for CO₂ emissions? Moreover, should emission responsibility be evaluated based on production-based emissions or consumption-based emissions? (Kondo *et al.*, 1998; Munksgaard and Pedersen 2001; Ferng, 2003; Hoekstra and Janssen, 2006; Wiedmann, 2009b)

Production-based emissions are a fundamental principle adopted in global climate policies such as the Kyoto Protocol and the Paris Agreement. Under this principle, producers are regarded as being responsible for environmental burdens, including CO₂ emissions, that arise from the production of energy, goods, and services. However, this principle has certain limitations. All CO₂ emissions associated with the production of export goods are attributed to the producing country. Therefore, it becomes difficult for emerging exporting countries, such as China, to achieve their emission reduction targets (Munksgaard and Pedersen, 2001; Pan *et al.*, 2008). Such a situation has been pointed out to exacerbate the problem in which emission reductions in developed countries are offset by increases in other countries, resulting in the transfer of emissions from developed to developing countries (i.e., carbon leakage) (Peters *et al.*, 2011). In fact, this tendency has been reported in countries such as Brazil and Japan (Schaeffer & Leal de Sá, 1996; Kondo *et al.*, 1998).

Many previous studies have discussed consumption-based emissions as an alternative

approach to address the limitations of production-based emissions, particularly the problem of carbon leakage. Under the consumption-based emissions approach, consumers, the final users of energy, goods, and services, are regarded as responsible for the associated environmental burdens, including CO₂ emissions. Consequently, this approach allows the issue of carbon leakage to be re-examined and helps to elucidate how the transfer of embodied emissions is linked to the relocation of production (Peters, 2008). On the other hand, since each country must make decisions regarding economic activities that occur abroad, it has been pointed out that governments find it difficult to manage GHG emissions generated outside their own territories (Peters, 2008). It has also been pointed out that assigning emission responsibility solely to consumers may undermine producers' incentives to reduce emissions during the production process (Bastianoni *et al.*, 2004; Kander *et al.*, 2015).

To overcome the extreme polarization between production-based and consumption-based emission responsibilities, the concept of shared responsibility has been proposed, in which the responsibility for emissions is distributed between producers and downstream consumers including both industrial users and final households (e.g., Ferng, 2003; Gallego and Lenzen, 2005; Rodrigues *et al.*, 2006; Lenzen *et al.*, 2007; Andrew and Forgie, 2008; Peters, 2008; Piñero *et al.*, 2019; Airebule *et al.*, 2023). Gallego and Lenzen (2005) argue that a politically feasible consensus lies somewhere between production-based and consumption-based emissions. In other words, the responsibility for the environmental burden associated with transactions within the supply chain should be allocated in some form between producers and downstream consumers. In the shared responsibility framework proposed by Gallego and Lenzen (2005), emission responsibility is equally divided between producers and downstream consumers, with each bearing 50%. This framework helps avoid the extreme situations observed in production-based or consumption-based accounting, where all emission responsibility is assigned solely to either the producer or the downstream consumer.

However, the framework did not define the percentage of emission responsibility based on specific indicators. Rodrigues *et al.* (2006) argued that it is desirable to derive such indicators from theoretical properties. Indeed, Lenzen *et al.* (2007) pointed out a limitation of the 50–50 shared responsibility. Consider two supply chains: (1) sand mining → glass → glass containers → food manufacturer → final consumer, and (2) sand mining → glass → glass containers → food manufacturer → retailer → final consumer. Assuming that the retailer sells the products from the food manufacturer without any further processing, the emission responsibility assigned to the final consumer in the second supply chain becomes twice as large as that in the first. This discrepancy arises because the model fixes the shares of emission responsibility at 50% for both producers and downstream consumers (see Lenzen *et al.*, 2007). In other words, under the framework proposed by Gallego and Lenzen (2005), when a supply chain is arbitrarily subdivided, the impact at each stage is halved. As a result, in a more finely disaggregated supply chain, the final impact inevitably becomes smaller than that in an aggregated supply chain. To address this limitation, Lenzen *et al.* (2007) employed value added as an indicator independent of industry classification. Because the total value added remains unchanged regardless of how finely the supply chain is disaggregated, using it as a basis enables a consistent allocation of responsibility.

Andrew and Forgie (2008) estimated New Zealand's greenhouse gas emissions in 2001 using three different accounting approaches: the production-based, consumption-based, and value-added-based shared-responsibility frameworks. As a result, under the production-based approach, emitters were held responsible for their own emissions, with no responsibility assigned to foreign countries. From the consumer perspective, however, 52% of domestic emissions were attributed to overseas entities through exports, while households accounted for 43%. Under the shared-responsibility approach based on value added, New Zealand as a whole was found to bear approximately 74% of the total emission responsibility. Airebule *et al.* (2023) estimated CO₂ emissions for China, the United

States, India, Japan, and Russia from 2002 to 2014 using three different accounting approaches: the production-based, consumption-based, and value-added-based shared-responsibility frameworks. As a result, they found that during this period, emissions based on the shared-responsibility approach increased by 157% in China and 116% in India.

Studies that have estimated emission responsibilities using such shared-responsibility frameworks consistently emphasize that establishing appropriate responsibility criteria for the fair allocation of emissions is essential to achieving global emission reduction targets under international climate policies (Andrew and Forgie, 2008; Piñero *et al.*, 2019; Airebule *et al.*, 2023).

2.6. Contributions of this thesis

Previous studies have utilized EEIOA to quantitatively identify both the direct and indirect CO₂ emissions, as well as emission hotspots, associated with the final demand for the construction sector. These studies have helped overcome the limitations of bottom-up Life Cycle Assessment (LCA). In parallel, discussions on emission responsibility—specifically, “who should be held accountable for emissions” and “how emission responsibilities should be shared”—have also advanced. Such analyses have made significant contributions to understanding the overall environmental impacts of the construction sector. However, many previous studies have aggregated civil engineering works (e.g., dam and road construction) and residential building projects into a single “construction sector,” thereby limiting their findings to identifying emission hotspots for the sector as a whole. Furthermore, much of the prior research has focused on energy-intensive upstream industries such as the iron and steel sector, highlighting the introduction of energy-efficient technologies and the expanded use of low-carbon materials as effective strategies for decarbonizing the entire construction sector. Yet, quantitative discussions on who should bear the costs of research, development, and implementation

of such technologies and to what extent remain insufficient.

To address these research gaps, this thesis makes two main contributions. First, Chapter 3 focuses on Japan's wooden housing sector from a consumption-based perspective, identifying CO₂ emission hotspots within its supply chain. Second, Chapter 4 examines the issue of cost allocation for the research and development of decarbonization technologies in the iron and steel sector. Based on the shared-responsibility emission framework, the chapter explores how these costs should be equitably distributed across the entire supply chain.

Chapter 3. CO₂ emission hotspots analysis on supply chains for wooden houses in Japan

3.1. Introduction

Global CO₂ emissions from the buildings and construction sector accounted for 27% of the total energy-related CO₂ emissions (IEA, 2023a). Specifically, global CO₂ emissions resulting from building activity and energy usage in the buildings sector accounted for approximately 16% of the total CO₂ emissions within the buildings and construction sector (IEA, 2023a). Considering the circumstances, it is crucial to mitigate the CO₂ emissions from the construction sector to tackle climate change.

While national policies have primarily focused on reducing CO₂ emissions during the energy consumption phase in buildings, an increasing number of recent studies have emphasized the importance of addressing CO₂ emissions during the building phase (Hernandez and Kenny, 2010; Ibn-Mohammed *et al.*, 2013; Man *et al.*, 2017; Röck *et al.*, 2020). For example, the EU taxonomy is considering mandatory disclosure of information regarding the embodied carbon of materials used in the construction of new buildings (European Commission, 2021). Additionally, some countries and regions emphasize the importance of focusing on the 'carbon footprint' due to varying national conditions across the EU (European Commission, 2021). Finland has established criteria for green public procurement of low-carbon buildings, which include a requirement that a minimum of 10% of the weight of construction materials be made of renewable or recycled materials (Ministry of Economic Affairs and Employment 2016; Kuittinen and Häkkinen, 2020). However, in Japan, there is currently no policy specifically targeting the reduction of CO₂ emissions during the building phase. The Japanese Government has implemented a subsidy policy to financially support individuals who

build their homes with higher thermal insulators (e.g., exterior walls, roof, windows) and those who install photovoltaic power generation systems at home (Ministry of the Environment, 2020). The subsidy policy aims to reduce a households' annual energy consumption balance to zero (Ministry of the Environment, 2020). However, it is important to note that policies with a focus of construction supply chains do not currently exist.

Previous studies estimated CO₂ emissions from the supply chains for manufacturing products necessary for construction activity (i.e., indirect CO₂ emissions associated with construction activity) (Huang *et al.*, 2018; Nuri and Murat 2020; Chen *et al.*, 2022). Huang *et al.* (2018) showed that CO₂ emissions from the construction sector were 5.7 billion t-CO₂ worldwide, representing 23% of global CO₂ emissions in 2009. They further indicated that the indirect CO₂ emissions from the construction sector accounted for 94% of the construction emissions. Therefore, to mitigate the CO₂ emissions from the construction sector, an effective policy to reduce the CO₂ emissions from the construction supply chains is needed. To establish an effective policy, it is imperative to identify CO₂ emission hotspots in the construction supply chains (Wiebe, 2018).

Two primary types of studies regarding CO₂ emissions from the construction supply chain are commonly employed: bottom-up, process-based Life Cycle Assessment (LCA) and top-down LCA utilizing input-output table. Process-based Life Cycle Assessment (LCA) can assess CO₂ emissions produced from construction phase by considering information about the building, such as the quantity of materials used during the construction phase (Su and Zhang, 2016; Bahramian and Yetilmezsoy, 2020; Hossain and Ng, 2020). Su and Zhang (2016) conducted a process-based Life Cycle Assessment (LCA) analysis of three steel-framed houses (apartments) in China. They revealed that the CO₂ emissions per m² ranged from 385 kg-CO_{2e}/m² to 525 kg-CO_{2e}/m². Hossain and Ng (2020) conducted a process-based Life Cycle Assessment (LCA) analysis of a 40-story reinforced concrete public

housing building in Hong Kong. They revealed that the CO₂ emissions per m² were 691 kg-CO_{2e}/m². However, process-based LCA not only employs different methods across various studies but also exhibits substantial variation in the data and assumptions (e.g., product system boundary) it incorporates (Suh, 2009). The methodological question such as system boundaries, completeness, comprehensiveness, units and robustness of the footprint indicators was also discussed (Wiedmann and Minx, 2008). Hence, it is difficult to compare the results of studies, even those concentrating on the domestic construction sector (Dixit *et al.*, 2013). Additionally, process-based LCA might underestimate the direct and indirect CO₂ emissions from the construction supply chain (Zhang *et al.*, 2016a). Given these considerations, Input-Output analysis considering the ‘complete’ product system boundary is commonly employed to assess the direct and indirect CO₂ emissions from the construction supply chain (Suh, 2009; Man *et al.*, 2017; Hung *et al.*, 2019). Previous studies employing Input-Output analysis to identify the CO₂ hotspots within the construction supply chain network (Zhang *et al.*, 2016a; Zhang *et al.*, 2016b; Huang *et al.*, 2018; Nuri and Murat, 2020; Hou *et al.*, 2021; Chen *et al.*, 2022; Su *et al.*, 2022). Nuri and Murat (2020) estimated the global carbon footprint induced by construction activity in five countries (Canada, China, India, Japan, and USA) and identified hotspot sectors in each country employing multiple global MRIO databases such as, WIOD, Exiobase 2.3, Exiobase 3.4, Eora26 and GTAP. They found that CO₂ emissions from the construction sector in the five countries in 2012 ranged from 343 Mt-CO_{2e} to 1818 Mt-CO_{2e}. Chen *et al.* (2022) used Structural Path Analysis to estimate global carbon footprint induced by construction activity in five countries (China, India, Japan, Russia, and USA) and identified CO₂ hotspot supply chain paths in construction supply chain network of each country. Chen *et al.* (2022) further demonstrated that the major contributors to the construction emissions in the five countries (China, India, Japan, Russia, and USA) were electricity, gas, and water supply, petroleum, chemicals, and non-metallic mineral products, and transportation. In addition to these two methods, several previous studies have employed a hybrid approach, combining process-based methods with input-output methods (Zhang *et al.*, 2016a; Hong *et al.*

al., 2016). Zhang *et al.* (2016a) utilized the environmentally-extended Chinese input-output tables with 17-139 sectors for the years 1997, 2000, 2002, 2005, 2007, 2010, 2012, and employed the hybrid approach to assess life-cycle CO₂ emissions in the Chinese building sector. They found that Scope 3 emissions through the building supply chain, involving building materials preparation and transportation, accounted for the largest share of life-cycle CO₂ emissions at approximately 70% (Zhang *et al.*, 2016a). Based on the hybrid approach, Hong *et al.* (2016) utilized the environmentally-extended Chinese input-output table with 41 sectors for the year 2010 and employed the hybrid approach to assess life-cycle energy consumption in the Chinese building sector. They focused on the supply chain of prefabricated building components such as staircase, balcony, etc., in the Chinese building sector and estimated life-cycle energy consumption during the manufacturing phase of the prefabricated building components as approximately 77 GJ/m³. It is important to note that the LCA results based on the hybrid approach largely depend on the sector resolution in the input-output table employed in the study (Suh, 2009).

Although previous studies employing Input-Output analysis identified CO₂ hotspots within construction supply chains, they considered a highly aggregated construction sector, encompassing a wide variety of construction activities such as roads, dams, and house construction. It should be noted that the functional unit for roads can be the total road length, whereas for houses, it can be the total floor area. Thus, the functional units of buildings significantly differ. The functional unit serves as the standard to which all inputs and outputs are related. In this regard, the determination of the functional unit is very important (Mattila *et al.*, 2012; Bahramian and Yetilmezsoy, 2020). Policymakers should establish effective policies to reduce supply chain emissions of specific buildings (i.e., houses) with the same functional unit. According to Bahramian and Yetilmezsoy (2020), in 61% of previous studies on the Life Cycle Assessment (LCA) of buildings, the ‘m²’ (square meter) was defined as the functional unit. Therefore, in this study, the functional unit of a house is defined as ‘m²’ (square meter), following

many previous studies. This study focused on a wooden house as a specific building and deepened the understanding regarding construction supply chain analysis by considering a functional unit.

This study identified CO₂ hotspots within the construction supply chains of wooden houses, which accounted for approximately 90% of the total housing stock, including attached houses, in Japan in 2021. (Ministry of Agriculture, Forestry and Fisheries, 2022). Firstly, we utilized Environmentally-Extended Input-Output Analysis (EEIOA) to estimate CO₂ emissions from the supply chains involved in constructing an ‘average’ wooden house in Japan in 2015. Secondly, we employed the Unit Structure Model, an application of input-output analysis (Ozaki, 1980, 1990; Kagawa *et al.*, 2013a; Maeno *et al.*, 2022), to formulate the supply chain structure (network) of an average wooden house. The unit structure model allows visualization and estimation of the supply chain structure of intermediate goods directly and indirectly required during the construction of wooden houses, which cannot be estimated by basic EEIOA. Thirdly, we proposed a weighted adjacency matrix based on the estimated supply chain structure of an average wooden house. The adjacency matrix was weighted by CO₂ emissions embodied in direct and indirect inter-industry transactions induced by house construction. Finally, we applied Industrial Cluster Analysis (Kagawa *et al.*, 2013a, 2015; Maeno *et al.*, 2022) to the weighted adjacency matrix to identify CO₂ emission-intensive inter-industry transactions (i.e., CO₂ emission hotspots) in the construction supply chains of an average wooden house.

3.2. Methodology

3.2.1. Carbon footprint calculation

The gross output vector $\mathbf{x} = (x_i)(i = 1, \dots, n)$ in the input-output table consisting of n sector can be formulated as follows:

$$\begin{aligned}\mathbf{x} &= \mathbf{Z}\mathbf{i} + \mathbf{f} \\ &= \mathbf{A}\mathbf{x} + \mathbf{f}\end{aligned}\tag{1}$$

where $\mathbf{Z} = \{z_{ij}\}$ represents the intermediate input matrix showing intermediate inputs from sector i to sector j , $\mathbf{i}$ shows the summation vector whose elements are all 1, $\mathbf{f}$ denotes the final demand vector (domestic final demand plus exports). $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} = (z_{ij}/x_j) = (a_{ij})$ represents the input coefficient matrix showing the intermediate input from sector i required per unit of production in sector j . Rearranging equation (1), we obtain the following equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f}\tag{2}$$

where $\mathbf{I}$ represents the unit matrix and $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L} = (l_{ij})$ represents the Leontief inverse matrix (Leontief, 1953). l_{ij} represents the output in sector i directly and indirectly required per unit of final demand in sector j .

We used Equation (3) to estimate consumption-based CO₂ emissions:

$$\mathbf{q} = \hat{\mathbf{e}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \hat{\mathbf{e}}\mathbf{L}\mathbf{f}\tag{3}$$

where $\hat{\mathbf{e}}$ represents the diagonal matrix whose diagonal elements are direct CO₂ emission intensities (i.e., direct CO₂ emissions per unit of production in sector i) shown as e_i . It should be noted that the hat denotes the diagonalization of a vector.

3.2.2. Unit structure analysis

The Unit Structure Model using an input-output table (Ozaki, 1980, 1990; Kagawa *et al.*, 2013a; Maeno *et al.*, 2022) determines the supply chain structure of intermediate goods needed directly and indirectly to meet the final demand of one unit for a particular sector j . We estimated the supply chain structure of intermediate goods directly and indirectly needed to meet the final demand of an average wooden house (i.e., j = wooden house). We also used a Unit Structure Model that was extended for environmental analysis following Kagawa *et al.* (2015). This is represented by Equation (4):

$$\begin{aligned}
 \mathbf{Q} = \hat{\mathbf{e}}\mathbf{A}\mathbf{L}\hat{\mathbf{f}}_j &= \begin{bmatrix} e_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e_n \end{bmatrix} \begin{bmatrix} a_{11} & \cdots & a_{1k} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ik} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nk} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} l_{1j}f_j & \cdots & 0 & \cdots & 0 \\ \vdots & & \vdots & & \vdots \\ 0 & \cdots & l_{kj}f_j & \cdots & 0 \\ \vdots & & \vdots & & \vdots \\ 0 & \cdots & 0 & \cdots & l_{nj}f_j \end{bmatrix} \\
 &= \begin{bmatrix} e_1 & \cdots & 0 & \cdots & 0 \\ \vdots & & \vdots & & \vdots \\ 0 & \cdots & e_k & \cdots & 0 \\ \vdots & & \vdots & & \vdots \\ 0 & \cdots & 0 & \cdots & e_n \end{bmatrix} \begin{bmatrix} a_{11}l_{1j}f_j & \cdots & a_{1k}l_{kj}f_j & \cdots & a_{1n}l_{nj}f_j \\ \vdots & & \vdots & & \vdots \\ a_{k1}l_{1j}f_j & \cdots & a_{ik}l_{kj}f_j & \cdots & a_{in}l_{nj}f_j \\ \vdots & & \vdots & & \vdots \\ a_{n1}l_{1j}f_j & \cdots & a_{nk}l_{kj}f_j & \cdots & a_{nn}l_{nj}f_j \end{bmatrix} \\
 &= \begin{bmatrix} e_1a_{11}l_{1j}f_j & \cdots & e_1a_{1k}l_{kj}f_j & \cdots & e_1a_{1n}l_{nj}f_j \\ \vdots & & \vdots & & \vdots \\ e_ka_{k1}l_{1j}f_j & \cdots & e_ka_{ik}l_{kj}f_j & \cdots & e_ka_{in}l_{nj}f_j \\ \vdots & & \vdots & & \vdots \\ e_na_{n1}l_{1j}f_j & \cdots & e_na_{nk}l_{kj}f_j & \cdots & e_na_{nn}l_{nj}f_j \end{bmatrix} \tag{4}
 \end{aligned}$$

where $\mathbf{f}_j$ denotes the final demand vector whose only j^{th} element has a figure and otherwise zeros,

and $\widehat{\mathbf{L}}\mathbf{f}_j$ represents the diagonal matrix of $\mathbf{L}\mathbf{f}_j$. $l_{kj}f_j$ represents the amount of the intermediate good of sector k needed directly and indirectly to meet the final demand for a specific sector j . $a_{ik}l_{kj}f_j$ represents the amount of the intermediate good of sector i needed to product intermediate input goods in the sector k . Therefore, the matrix element of $\mathbf{Q}$, $e_i a_{ik} l_{kj} f_j$, represents the CO₂ emissions induced by the intermediate inputs from sector i to sector k needed directly and indirectly to meet the final demand in sector j (i.e., the unit structure of sector j).

3.2.3. Supply chain cluster analysis

We used Equation (4) for the CO₂ emission of the supply chain structure in the wooden housing sector (i.e., the unit structure of the wooden housing sector) and created the adjacency matrix $\mathbf{G}$ based on the unit structure matrix as follows.

$$\mathbf{G} = \begin{cases} g_{ij} = q_{ij} + q_{ji} (i \neq j) \\ g_{ij} = 0 (i = j) \end{cases}$$

We applied a cluster analysis of the supply chain to the adjacency matrix $\mathbf{G}$. This enables us to solve the modularity maximization problem regarding the adjacency matrix $\mathbf{G}$ (Newman and Girvan, 2004; Newman, 2006). Following Newman (2006), the modularity maximization problem was transformed into an eigenvalue decomposition problem of the modularity matrix defined as $\mathbf{B} = \mathbf{G} - \mathbf{P}$ where $\mathbf{P} = (p_{ij}) = \left(\frac{k_i \times k_j}{\sum_i k_i} \right)$ and k_i denote the degree of the sector i .

Following Newman and Girvan (2004) and Newman (2006), modularity Q is formulated as the sum of $\frac{1}{\sum_i k_i} \left(g_{ij} - \frac{k_i \times k_j}{\sum_i k_i} \right)$ over all pairs of sectors i and j belonging to the same cluster, where g_{ij} denotes the ‘actual’ CO₂ emissions of inter-industry transactions between sector i and j , and

$\frac{k_i \times k_j}{\sum_i k_i}$ represents the ‘expected’ CO₂ emissions of inter-industry transactions between them.

Mathematically, we can rewrite modularity Q as $\frac{1}{2\sum_i k_i} \left(g_{ij} - \frac{k_i \times k_j}{\sum_i k_i} \right) (s_i s_j + 1)$, where $s_i = 1$ if sector i belongs to cluster #1 and $s_j = -1$ if it belongs to cluster #2 (Newman, 2006). It is important to note that we assume a supply chain network is divided into two clusters. The modularity in matrix form can be further formulated as $Q = \frac{1}{2\sum_i k_i} \mathbf{s}^T \mathbf{B} \mathbf{s}$ (Newman, 2006). Notably, a strong cluster structure yields a higher modularity value between 0 and 1. Newman (2006) suggested transforming the modularity maximization problem into a heuristic problem by solving the eigenvalue decomposition of the modularity matrix (see Newman (2006) for detailed mathematical formulations of the bipartition algorithm used in this study).

One idea for the modularity clustering is that a supply chain network can be partitioned into two subnetworks (i.e., clusters) by looking at positive and negative sign of elements of the eigenvector corresponding to the largest eigenvalue for the modularity matrix. The recursive bipartition algorithm can be used in this study. The m industrial clusters identified in this study are represented as $\{C_1, C_2, \dots, C_m\}$.

3.2.4. Data

We used the direct sectoral CO₂ emission intensity estimated by the National Institute for Environmental Studies, Japan (Nansai, 2019; Nansai *et al.*, 2020). Further, we used the 2015 input-output table¹ with the highest sector resolution of 496 row sectors $\times$ 380 column sectors published by the Ministry of Internal Affairs and Communications (Ministry of Internal Affairs and

¹ We converted the rectangular input-output table into a square input-output table with 367 row sectors and 367 column sectors. It is important to note that this study utilized data from 2015, which is nearly 10 years old. Hence, this data limitation should be considered when interpreting the study's findings, as 2015 is the latest year for the Japanese Input-Output Table.

Communications, 2019). We converted the rectangular input-output table into a square input-output table with 367 row sectors $\times$ 367 column sectors.

The report published by the Ministry of Land, Infrastructure, Transport, and Tourism (2022a) provides the grand total floor area of detached houses constructed between 2018 and 2021, including both wooden and non-wooden houses. We estimated the average total floor area per newly-constructed home by dividing the grand total floor area by the number of wooden and non-wooden houses constructed between 2018 and 2021. It is important to note that since wooden houses accounted for approximately 90% of the total housing stock in Japan in 2021 (Ministry of Agriculture, Forestry and Fisheries, 2022), we consider the functional unit of the average wooden house to be a total floor area of 119 square meters.

By dividing 42 million square meters of the gross total floor area of wooden houses built in 2015 by 119 square meters of the average total floor area of a house, we estimated the number of average wooden houses constructed in 2015 as a total of 352,941 houses (Ministry of Land, Infrastructure, Transport and Tourism, 2022b). To estimate the construction cost per an average wooden house, we divided 8.8 trillion JPY of the gross output of the wooden housing sector² in 2015 by 352,941 houses of the number of the average wooden houses built in 2015. As a result, we estimated the construction cost per house as 25,142,857 JPY. In this study, the wooden residential construction sector in the final demand vector had a figure of the construction cost of an average wooden house and other final demand sectors had zero values.

It is important to note that the average floor area used in this study does not account for regional differences in land area (e.g., in urban areas, residential floor space typically tends to be

² The government has already surveyed the gross output of the wooden housing sector in 2015, and its value is documented in the original input-output table.

smaller, whereas in rural areas, the opposite trend is observed). This average represents the floor area of new single-family homes across Japan from 2018 to 2021. The larger residential floor space in rural areas results in a larger carbon footprint for a house, whereas the smaller floor space in urban areas leads to a smaller carbon footprint for a house. Different functional units for houses can be considered in regional carbon footprint analyses, making regional carbon footprint analysis an important area for further study.

3.3. Results

3.3.1. Production-based CO₂ emissions

In 2015, the wooden residential construction sector of Japan had a gross output of approximately 8.8 trillion JPY, which constituted 0.8% of the total of gross outputs of sectors in Japan in 2015. Based on the Embodied Energy and Emission Intensity Data (3EID) for Japan Using Input-Output Tables published by the National Institute for Environmental Studies (Nansai, 2019; Nansai *et al.*, 2020), the direct (on-site) CO₂ emissions from the wooden residential construction sector was approximately 139 kt-CO₂ in 2015. The production-based emissions of the wooden residential construction sector accounted for only 0.2% of the total CO₂ emissions from domestic industrial activities which were minimal compared with other industrial sectors.

3.3.2. Consumption-based CO₂ emissions

We used the EEIOA formulated as Eq. (3) and estimated the direct and indirect CO₂ emissions (i.e., consumption-based CO₂ emissions) associated with final demand for the wooden residential construction sector. Although the direct CO₂ emissions of the wooden residential construction sector

were marginal, the direct and indirect CO₂ emissions were approximately 13,412 kt-CO_{2e} and thus they were 96 times larger than the direct emissions. The direct and indirect CO₂ emissions of the wooden residential construction accounted for 3.6% of CO₂ emissions from manufacturing sector in Japan in 2015 (Ministry of the Environment, 2023). In other words, this result indicates that wooden houses were a significant contributor to the CO₂ emissions throughout the entire construction supply chains.

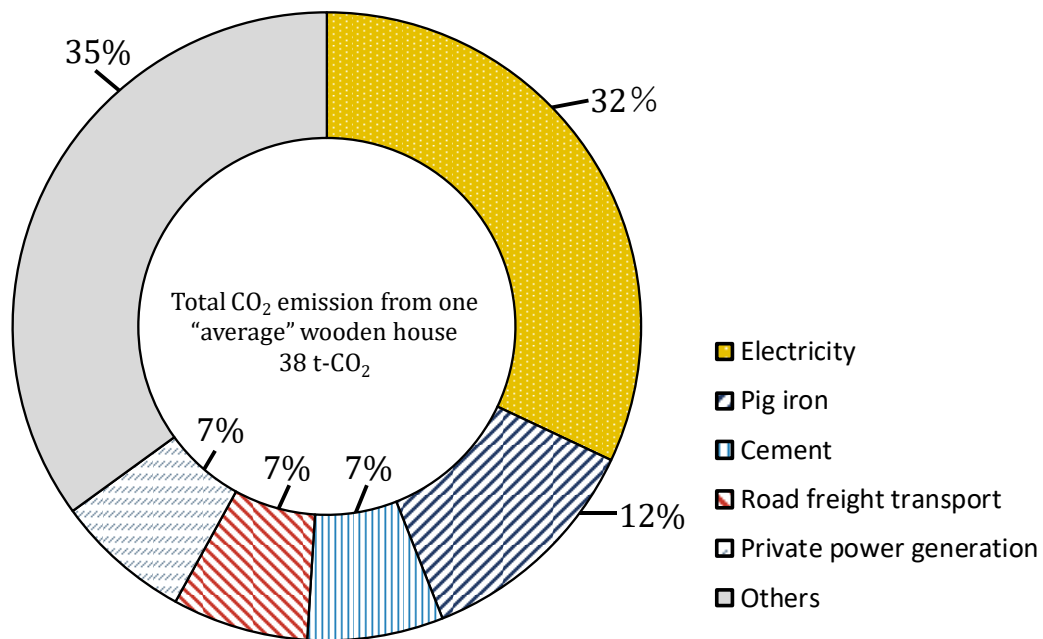


Figure 3-1. Direct and indirect CO₂ emissions embodied in the construction of an average wooden house (i.e., carbon footprint of an average wooden house) and top five sectors largely contributing to the emissions

Dividing the direct and indirect CO₂ emissions associated with final demand for the wooden residential construction sector in 2015 by the number of the average wooden houses built in 2015 yielded the direct and indirect CO₂ emissions of an average wooden house with a functional unit of 119 square meters (i.e., carbon footprint of an average wooden house) as 13,412 (kt-CO₂)÷352,941

(houses)=38 (t-CO_{2e} per house) (Figure 3-1). We estimated the direct and indirect CO₂ emissions of an average 'non-wooden' house, considering a functional unit of 119 square meters, to facilitate a comparison with the emissions from an average 'wooden' house. To achieve this, we initially determined the market share of non-wooden houses in the non-wooden residential construction sector for the year 2015. This involved dividing the total gross floor area of non-wooden houses by the overall gross floor area of non-wooden residential buildings (including houses and apartments) newly constructed in 2015. The resulting calculation showed a market share of 0.23. Next, we estimated the number of average non-wooden houses constructed in 2015 by dividing the gross total floor area of non-wooden houses built that year by the average total floor area of a house (119 square meters). This calculation yielded a total of 51,314 houses. To determine the direct and indirect CO₂ emissions associated with the final demand for the non-wooden residential construction sector in 2015, we divided the emissions by the number of average non-wooden houses built in that year. This allowed us to calculate the direct and indirect CO₂ emissions of an average non-wooden house with a functional unit of 119 square meters (i.e., the carbon footprint of an average non-wooden house) as 4,204,118 (kt-CO_{2e}) divided by 51,314 (houses), resulting in 81.9 (t-CO_{2e} per house). This finding indicates that the environmental impact from one non-wooden house is equivalent to that of two or more wooden houses. Furthermore, the top five sectors that largely contributed to the CO₂ emissions from the construction supply chains were electricity, pig iron, cement, road freight transport, and private power generation (Figure 3-1). Figure 1 shows that the emissions from these five sectors accounted for 65% of the total of the supply chain emissions.

3.3.3. Unit structure analysis of constructing a wooden house

We used the Unit Structure Model in Eq. (4) to estimate the supply chain structure of an average wooden house. Table 1 represents the top 10 CO₂-intensive inter-industry transactions with higher

emissions of q_{ij} in the unit structure matrix and its CO₂ emissions caused by the transactions. Steel products are mainly used as important materials to strengthen the foundation of a house. Consequently, the foundation work greatly contributed to the carbon footprint of a wooden house via an environmentally important supply chain path from pig iron (#139) to crude steel (converters) (#141) with a contribution of 4.52 t-CO_{2e}, accounting for 12% of the carbon footprint (Table 3-1). In particular, the construction technology should be innovated for reducing the CO₂-intensive steel products in downstream side and simultaneously the CO₂-intensive iron production should be decarbonized upstream side. It is also important to note that the top 10 transactions with higher emissions listed in Table 1 were responsible for almost half of the direct indirect CO₂ emissions.

Table 3-1. Top 10 CO₂-intensive inter-industry transactions in the supply chain structure of an average wooden house and its CO₂ emissions

Rank	Code	Supplier		Code	Purchaser	CO ₂ emissions (t-CO _{2e})
1	139	Pig iron	→	141	Crude steel (converters)	4.52
2	261	Electricity	→	249	Wooden residential construction	2.06
3	130	Cement	→	131	Ready-mixed concrete	1.83
4	283	Road freight transport	→	249	Wooden residential construction	1.71
5	261	Electricity	→	77	Miscellaneous Wooden Products	0.94
6	262	On-site power generation	→	261	Electricity	0.83
7	261	Electricity	→	26	Coal, crude oil, natural gas	0.78
8	130	Cement	→	249	Wooden residential construction	0.54
9	133	Pottery, china and earthenware	→	249	Wooden residential construction	0.52
10	261	Electricity	→	261	Electricity	0.51
Sub total						14.3

3.3.4. Supply chain cluster analysis

We used the supply chain cluster analysis to identify CO₂ emission-intensive clusters (i.e., CO₂ emission hotspots) from the construction supply chain network. Table 2 represents the top 10

clusters with higher CO₂ emissions within the supply chain structure of a wooden house and the CO₂ emissions from these clusters. We determined that Cluster #1 (cluster code: C1) had the largest CO₂ emissions at 5.68 t-CO_{2e}, followed by Cluster #4 (cluster code: C4) at 2.81 t-CO_{2e}, and Cluster #2 (cluster code: C2) at 2.27 t-CO_{2e}. These cluster accounted for approximately 28% of carbon footprint of a wooden house (Table 3-2). Table 3-3 represents sectors that belongs to the specific cluster identified in Table 2. For instance, Cluster #1 consists of sectors involved in iron production, such as the pig iron and crude steel (converters) sectors (Table 3-3). Cluster #2 also consists of sectors involved in cement, such as the cement and ready-mixed concrete sectors (Table 3-3). Thus, important materials such as crude steel and cement necessary for wooden house construction were identified as a well-separated CO₂-intensive cluster, whereas this current study found that construction work for the exterior of a house contributed significantly to CO₂ emissions via the second largest emission cluster including flowers and plants, pottery, china and earthenware, miscellaneous structural clay products, and wooden residential construction (see C6 in Table 3-3), accounting for 7.4% of the carbon footprint (Table 3-2). The pottery sector encompasses tiles and clay roof tiles. Consequently, both pottery and wooden houses are categorized within the same cluster, as tiles can be utilized for the exterior walls of wooden houses. Furthermore, the plant sector could be considered part of the same cluster as wooden houses, given that plants and potted plants are cultivated for aesthetic purposes within residential settings.

Figure 3-2 visualizes the supply chain network diagram of Cluster #1 with the highest emissions. The arrow in Figure 3-2 represents the inter-industry delivery between sectors necessary for constructing a wooden house and the circle denotes a logarithmic scale of the direct CO₂ emission intensity in t-CO₂/million JPY (i.e., direct CO₂ emissions per unit of output) of a specific sector. Cluster #1 (C2) has a feature such that the CO₂ emissions resulting from the inter-industry delivery from the pig iron to crude steel sectors induced the emissions of 4,750 kg-CO₂ and accounted for 97% of the

total emissions of Cluster #1 (Figure 3-2). This result is due to the fact that the pig iron sector is not only a hub of that cluster but also has a relatively high direct emission intensity of 36 t-CO₂/million JPY (Figure 3-2).

Table 3-2. Top 10 CO₂-intensive inter-industry clusters in the supply chain structure of an average wooden house and its CO₂ emissions

Rank	Cluster code	CO ₂ emissions (t-CO ₂ e)	Percentage of CO ₂ emissions within a cluster to the carbon footprint of an average wooden house
1	C1	5.68	14.9%
2	C4	2.81	7.4%
3	C2	2.27	6.0%
4	C7	1.54	4.1%
5	C5	0.88	2.3%
6	C3	0.51	1.3%
7	C6	0.38	1.0%
8	C18	0.14	0.4%
9	C17	0.10	0.3%
10	C16	0.10	0.3%

Table 3-3. Industries belonging to CO₂-intensive inter-industry clusters in the supply chain structure of an average wooden house

Rank	Cluster code	Sector code	Sector name
1	C1	#120	Coal products
		#139	Pig iron
		#140	Ferro alloys
		#141	Crude steel (converters)
		#142	Crude steel (electric furnaces)
		#143	Hot rolled steel
		#148	Cast iron pipes and tubes
		#149	Cast and forged materials
2	C4	#233	Repair of ships
		#11	Flowers and plants
		#86	Coated paper and construction paper
		#133	Pottery, china and earthenware
		#135	Miscellaneous structural clay products
		#144	Steel pipes and tubes
		#249	Wooden residential construction
		#283	Road freight transport
3	C2	#27	Gravel and quarrying
		#28	Crushed stones
		#130	Cement
		#131	Ready mixed concrete
		#132	Cement products
4	C7	#22	Special forest production, except growing of mushrooms
		#70	Miscellaneous wearing apparel and clothing accessories
		#75	Plywood, glued laminated timber
		#76	Sawmilling and planing of wood
		#77	Miscellaneous manufacture of wood products, including bamboo and rattan
		#78	Wooden furniture
		#167	Manufacture of tanks, reservoirs, and containers of metal
		#246	"Tatami" (straw matting) and straw products
		#261	Electricity
		#284	Water transport
5	C5	#82	Pulp
		#83	Paper
		#84	Paperboard
		#88	Miscellaneous paper containers
		#89	Manufacture of corrugated paper and paperboard and of containers of paper and paperboard
		#90	Manufacture of other articles of paper and paperboard
		#91	Printing, plate making, bookbinding
		#262	Private power generation
		#308	Publishing of newspapers, journals, and periodicals
		#309	Book publishing

6	C3	#21	Silviculture • Logs
		#74	Timber
		#286	Harbor transport service
7	C6	#98	Petrochemical basic products
		#100	Aliphatic intermediates
		#103	Methane derivatives
		#107	Thermoplastics resins
8	C18	#248	Other manufactured industrial products
		#270	Wholesale trade
		#287	Air transport
		#295	Activities of head offices (public management)
		#296	Activities of head offices
		#301	Services incidental to telecommunications
		#344	Engineering and architectural services
9	C17	#44	Manufacture of starches and starch products
		#99	Petrochemical aromatic products
		#105	Miscellaneous industrial organic chemicals
		#110	Medicines
		#113	Paint and varnishes
		#114	Manufacture of paints, varnishes and similar coatings, printing ink and mastics
		#118	Manufacture of other chemical products n.e.c.
10	C16	#92	Manufacture of fertilizers and nitrogen compounds
		#101	Manufacture of basic chemicals
		#104	Plasticizer
		#106	Thermosetting Resins
		#108	Other synthetic resins
		#111	Oil and fat processed products, surfactants
		#116	Gelatin and adhesives

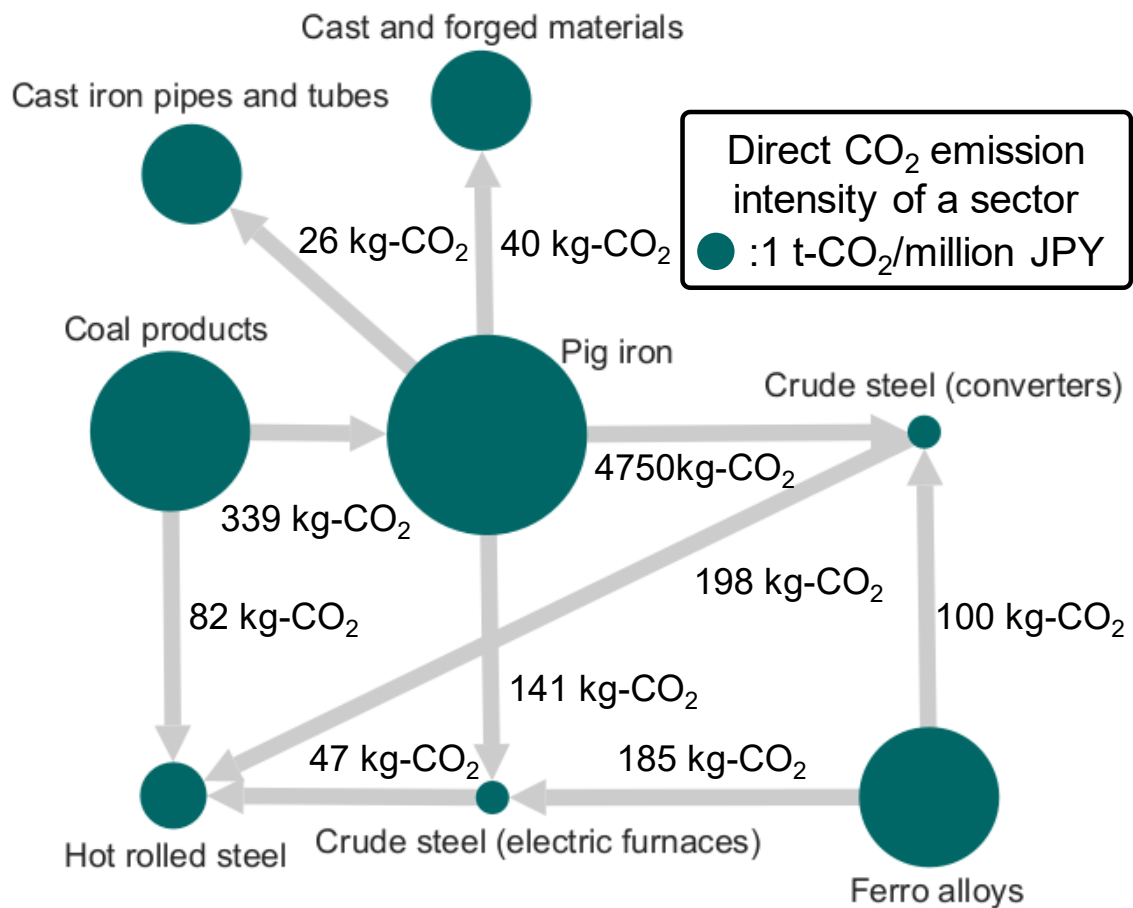


Figure 3-2. Supply chain network diagram of Cluster #1

3.4. Discussion

Some previous studies, as well as the results of this study, have noted the significant contribution of the electricity, non-metallic products (including the cement sector), and steel sectors to the overall CO₂ emissions of the construction sector. For example, Man *et al.* (2017) noted that cement, concrete, and bricks accounted for 32.9% of CO₂ emissions from the construction sector in Australia in 2013, while steel accounted for 9.3%. Su *et al.* (2022) found that the electricity and heat supply sector accounted for about 50% of China's construction sector-derived CO₂ emissions in 2017, with the metals sector accounting for 25%. These findings suggest that the composition of the key sectors that contribute significantly to CO₂ emissions in both the wooden residential construction sector and the construction sector has remained relatively consistent. CO₂ emissions per m² for wooden houses, as determined in this study, were 320 kg-CO_{2e}/m². In Sweden, the CO₂ emissions per m² for the materials production, transportation phase, and construction phase of a two-story wooden house were 195.3 kg/m² (Petrovic *et al.*, 2019). It is important to note that Petrovic *et al.* (2019) employed a process-based LCA, whereas this study used an input-output-based LCA. The variation in emissions per floor between Petrovic *et al.* (2019) and this study is attributed to the distinction in the LCA system boundary setting employed in each study. In comparison, the emissions per m² for commercial (concrete frame), residential (apartments with a shear-wall structure), and overall construction (shear-wall structure) in China were 400.95 kg-CO_{2e}/m², 415.92 kg-CO_{2e}/m², and 499.85 kg-CO_{2e}/m², respectively (Zhang and Wang, 2016b). It should be noted that this may lead to an overestimation of CO₂ emissions from the residential sector if the analysis is performed without separating residential construction and civil engineering construction (e.g., dams). Conversely, it is also possible to underestimate CO₂ emissions from civil construction.

It has become evident that the carbon footprint during construction is smaller for wooden houses compared to non-wooden ones. In addition to this advantage, wooden houses are also

recognized for their carbon storage benefits compared to other building methods (Amiri *et al.*, 2020; Churkina *et al.*, 2020; Andersen *et al.*, 2022). The estimated carbon storage per average wooden house was found to be 16 t-CO₂ (see Supplementary Information for data and formulations). This value represents a similar percentage of CO₂ emissions derived from the electricity and pig iron sectors (Figure 3-1). This indicates that wooden houses can mitigate the environmental impact of the building sector both in the short and long term. However, it is important to note that since only carbon storage is estimated, it does not account for the impact of deforestation at the end of its useful life when released or due to construction.

Based on the results of this study, we provide policy recommendations for reducing environmental impact during the construction of wooden houses. To reduce the CO₂ emissions from the higher priority CO₂ emission hotspots, CO₂ emission reduction measures are needed from both the supply and demand aspects.

Based on the results in Figure 3-2, mitigating cluster-wise emissions is crucial, necessitating a reduction in the direct CO₂ emissions from pig iron production. Regarding the supply side policy, the introduction of the hydrogen (H₂)-based ironmaking process, in which hydrogen is used as a reductant for iron ore, is expected. Although H₂-based iron making process attracts attentions for its environmentally friendly aspect globally, research and development (R&D) for such innovations would be more expensive than existing ironmaking processes. In order to diminish supply chain emissions associated with house building materials, construction companies as an important stakeholder are obligated to offer financial support for R&D conducted by steelmakers, as well as the implementation of new steelmaking methods. Specifically, construction companies, housing developers, and building material manufacturers can purchase government-issued GX Economic Transition Bonds as part of their ESG investment portfolios (Ministry of Economy, Trade and Industry,

2025). By doing so, the government can allocate a portion of the GX bond revenues to support the development and implementation of decarbonization technologies in the steel industry (e.g., hydrogen-based direct reduction ironmaking and electric furnace conversion). At the same time, the construction industry can indirectly contribute to the decarbonization of its own supply chain while visualizing the outcomes of its ESG investments.

To effectively mitigate the construction supply chain emissions, we further suggest that the government should mandate construction companies to report carbon footprint of their product (i.e., a newly-constructed home) and disclose the carbon footprint to buyers. By taking this action, the construction companies can evaluate whether or not the practical carbon footprint of the new house constructed by a company exceeds the benchmark footprint provided in this study. In addition, we suggest that construction companies reveal portions of environmentally important cluster-wise emissions in their carbon footprint labeling. For example, we propose the following carbon footprint labeling for the new house (Figure 3-3).

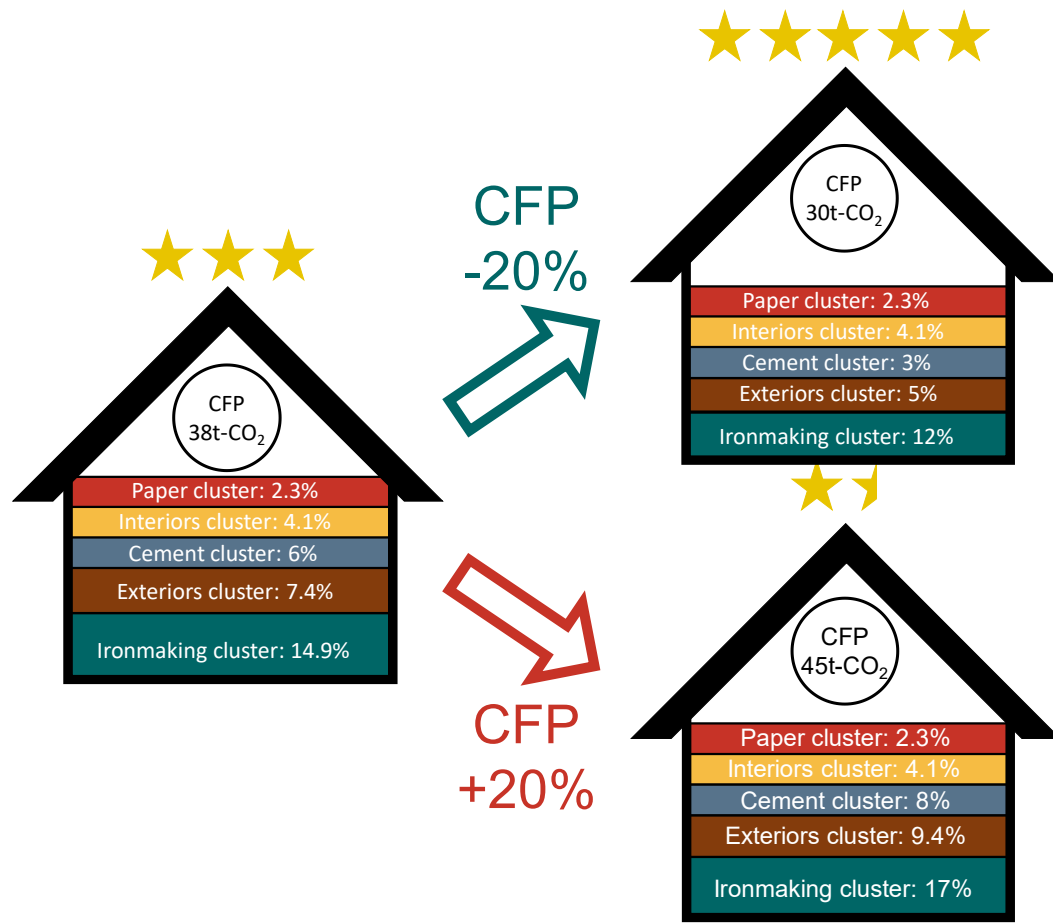


Figure 3-3. The carbon footprint labeling for the new house

CO₂ emission reduction measures in the short-term could include CO₂ emission reduction through the demand-side policy. For instance, we can reduce the demand for materials with higher CO₂ emissions by reusing existing housing through renovation and remodeling. In the past 30 years between 1988 and 2018, the number of vacant houses in other housing types (wooden detached houses, non-timber detached houses, row houses, wooden apartment houses, and non-timber apartment houses) increased 1.9 times (approximately 3.2 million units). In particular, wooden houses accounted for the largest share (28.3%) of all other housing types. Furthermore, policies exist in Japan to promote the use of vacant houses. These circumstances suggest that there are enough vacant houses for renovation and remodeling of wooden houses. Many of the steel and cement products in the clusters with particularly high CO₂ emissions (C1 and C2) are used in the foundations of homes. Therefore, by

renovating and remodeling vacant houses and other buildings that are no longer in use and reusing the foundations, CO₂ emissions that would have originally been generated during foundation construction (i.e., emissions from the top two clusters) can be significantly reduced.

3.5. Conclusion

We used the EEIOA to estimate the CO₂ emissions from the entire supply chain for the construction of one “average” wooden house. In addition, we used the Unit Structure Model to estimate the supply chain structure of an average wooden house and identified CO₂ hotspots through cluster analysis. Through these analyses, we determined that the top 10 clusters accounted for approximately 40% of the direct and indirect CO₂ emissions from one average wooden house. In particular, CO₂ emissions from the highest three clusters (C1, C4 and C2) accounted for 75% of the total CO₂ emissions from the clusters, therefore, it would be significant to reduce CO₂ emissions from these clusters.

Two aspects are important for reducing CO₂ emissions from clusters: supply side and demand-side measures. It is vital for the supply side to promote the introduction of green procurement, EV trucks and conduct R&D to reduce CO₂ emissions from the production of goods and services such as the pig iron sector. Consequently, the government must request financial support from stakeholder construction companies for technological development and implementation.

One key measure for mitigating CO₂ emissions from the demand-side is to utilize the large number of vacant wooden houses that exist in Japan. Steel and cement products with high CO₂ emissions are used in the foundations of wooden houses. By renovating and remodeling vacant houses and reusing the foundations, construction companies can significantly reduce the CO₂ emissions that would otherwise be generated in the foundation process.

Chapter 4. Sharing CO₂ abatement costs in the iron and steel sector: A shared responsibility input-output approach

4.1. Introduction

The iron and steel sector is essential for human life, as it provides crucial material necessary for constructing buildings, such as houses, schools, and hospitals, as well as for manufacturing durable goods, such as cars and bicycles. The demand in this sector is expected to increase by 25% between 2024 and 2050 (SMS Group, 2024). Thus, the iron and steel sector plays a significant role in national economies worldwide; however, the direct CO₂ emissions from this sector were 2.6 billion t-CO₂ in 2020, representing 7% of global CO₂ emissions and reflecting its categorization as an emission-intensive sector (IEA, 2020; Lei *et al.*, 2023). In addition, the global average CO₂ emission intensity for the production of crude steel is 1.91 t-CO₂ per ton (IEA, 2020). This emission intensity is higher than that of other sectors; for example, it is 3.2 times greater than the CO₂ emission intensity of the cement sector (0.6 t-CO₂ per ton) (IEA, 2023b). According to an IEA report, direct CO₂ emissions need to be reduced by 25% and CO₂ emission intensity by 3% annually by 2030 to achieve net-zero emissions by the middle of the century (IEA, 2023c). Further, some studies have clarified that the manufacturing of iron and steel products exerts environmental pressure on other sectors through the supply chain (Wu *et al.*, 2020; Shmelev and Brook, 2021). Shmelev and Brook (2021) further clarified that the iron and steel product sector (e.g., the manufacture of basic iron and steel) is strongly linked to the Austrian economy-wide supply chain in terms of CO₂ emissions compared with other Austrian sectors.

CO₂ emissions from Japan's iron and steel sector accounted for 14.2% of the total CO₂ emissions in 2023 (National Institute for Environmental Studies, 2025). This sector contributes to the

supply chains of many durable goods-producing sectors, such as the passenger motor car and construction sectors. Therefore, the iron and steel sector has a significant impact on other sectors through each supply chain. For example, Kagawa *et al.* (2013a) utilized cluster analysis and clarified energy-intensive industry clusters in the Japanese automobile supply chain and found that the industry cluster including the crude steel, hot-rolled steel, and motor vehicle bodies sectors was the third-largest consumer of energy among 27 clusters. Imada *et al.* (2024) utilized the Japanese Input–Output (IO) table and revealed that the pig iron sector accounted for 12% of the carbon footprint of a single wooden house in Japan. These results indicate that mitigating CO₂ emissions from the iron and steel sector would significantly contribute to decarbonization at the supply chain level, which has become increasingly important in recent years (UNFCCC, 2015).

Accordingly, Japan's iron and steel sector has set a goal of mitigating CO₂ emissions by more than 30% by 2030 compared with 2013 (The Japan Iron and Steel Federation, 2023). In Japan, blast furnaces are mainstream, and Japan's iron and steel sector accounts for 3.9% of the global crude steel blast furnace production (Lei *et al.*, 2023; Zhang *et al.*, 2023). Introducing hydrogen technology and expanding the use of electric furnaces powered by renewable energy are important for mitigating the CO₂ emissions from the iron and steel sector (An *et al.*, 2018; Karakaya *et al.*, 2018; Conejo *et al.*, 2020; Ren *et al.*, 2021). For example, the greenhouse gas (GHG) emission intensity of crude steel ranges from 1.1 to 1.4 t-CO₂ eq per ton in a Blast Furnace - Basic Oxygen Furnace (BF-BOF). However, GHG emission intensity could be mitigated to 0.72 t-CO₂ eq per ton by introducing Direct Reduced Iron Electric Furnaces (Yao *et al.*, 2024).

The innovative technologies required for the decarbonization of the iron and steel sector entail significant costs (Ren *et al.*, 2021; Kim *et al.*, 2022). For example, from 2015 to 2020 the average cost for a BF-BOF was approximately 490 US dollars per ton, whereas the average cost for direct hydrogen

reduction iron was approximately 650 US dollars per ton, making it approximately 25% more expensive than BF-BOF (IEA, 2023c). Currently, the government and the iron and steel sector bear the costs of research and development (R&D) and the introduction of these innovative technologies. Since the iron and steel sector plays a core role in each sector's supply chain, the entire supply chain (i.e., sectors that trade directly and indirectly with the iron and steel sector) should bear the cost of decarbonizing the steel sector, not just the government. When distributing R&D costs and introducing decarbonization technologies in the steel sector throughout the supply chain, each sector's responsibility for CO₂ emissions needs to be assessed.

Scopes 1, 2, and 3 are the recommended standards for calculating GHG emissions, including CO₂ emissions. Scope 1 refers to the GHG emissions that a company directly emits through fuel combustion or product manufacturing. Scope 2 refers to the GHG emissions that a company indirectly emits such as by using electricity and heat supplied by other companies. Scope 3 refers to the upstream and downstream GHG emissions in the supply chain emitted after raw material purchases and sales. An alternative approach to assessing CO₂ emissions from the supply chain, other than Scopes 1, 2, and 3, is consumption-based emissions. This concept, which holds that the industry consuming the goods ultimately bears responsibility for the CO₂ emissions from production activities, is utilized in process-based and top-down life cycle assessment (LCA) as an environmentally extended input-output (EEIO) analysis.

Previous studies based on LCA (Liang *et al.*, 2020; Duan *et al.*, 2022), have quantified the environmental burden of each life cycle stage in the iron and steel sector. Liang *et al.* (2020) utilized LCA, in focusing on the production of one ton of hot-rolled steel as the final product of ironworks and found that blast furnaces accounted for 69% of the total CO₂ emissions from the production process. Duan *et al.* (2022) utilized LCA to analyze steel and iron production and found that material processing

accounted for more than 80% of CO₂ emissions throughout the life cycle stages (including raw material acquisition, material processing, manufacturing, and recycling). Therefore, the environmental burden of material processing is important to reduce.

Some previous studies utilizing EEIO analysis (Kagawa *et al.*, 2013a; Onat and Kucukvar, 2020; Chen *et al.*, 2022; Imada *et al.*, 2024) have identified the iron and steel sector as a primary contributor to CO₂ emissions within the supply chains of the passenger motor car and construction sectors. Several studies have focused on the supply chains of the final demand sectors, such as the passenger motor car and construction sectors. However, few studies have focused on the supply chains of the upstream iron and steel sectors. Peng *et al.* (2018) are among the few previous researchers to analyze how final demand, both domestic and foreign, contributes to CO₂ emissions from the iron and steel sector in China through the supply chain. They found that China's fixed capital demand has the greatest effect on CO₂ emissions along numerous supply chain paths, accounting for 15.5% of the CO₂ emissions from the iron and steel sectors in China. Additionally, CO₂ emissions induced by global household demand and fixed capital demand accounted for 3.4% and 3.0%, respectively.

However, some issues remain regarding Scope 1, 2, and 3 emissions based on LCA analysis. Scope 1 alone does not assess CO₂ emissions from the product supply chain but estimates “direct” GHG emissions from the fossil fuel consumption necessary for a company’s production activities. For example, “direct” GHG emissions from goods transported by a transportation company may be estimated as Scope 1. However, the same emissions from the transportation company may be considered Scope 3 for a manufacturing company that requires goods transport in the product supply chain. This situation leads to a double-counting problem of GHG emissions calculated by Scopes 1 and 3. Another issue is that process-based LCA analysis may underestimate direct and indirect CO₂ emissions (i.e., consumption-based CO₂ emissions) from the supply chain compared to EEIO analysis

(Zhang et al., 2016a).

The concept of consumption-based emissions, based on EEIO, is that all responsibility for CO₂ emissions from the supply chain belongs to the production sector of the final goods (e.g., automobiles) or the final consumers (e.g., households) (Suh, 2009). Therefore, the responsibility for CO₂ emissions is impossible to quantify for the production sectors of intermediate goods (e.g., steel products) upstream in the relevant supply chain.

The conventional idea of responsibility for CO₂ emissions discussed above makes it difficult to determine how the costs of decarbonization in a specific “upstream” production sector should be shared in the context of supply chain complexity. Furthermore, this approach does not consider the responsibility of the intermediate goods production sectors, potentially leading to an overestimation of the responsibility attributed to the final goods production sectors. Consequently, determining the cost burden based on responsibility for CO₂ emissions is ultimately unfair to the polluter (i.e., the final goods production sectors). Cordier *et al.* (2019) simulated the allocation of repair costs for the restoration of estuarine ecosystems among stakeholders who directly or indirectly utilized port services and found that cost allocation is relatively unaffordable for polluters under the polluter pays principle. Regarding sharing CO₂ emissions responsibilities throughout the supply chain, Gallego and Lenzen (2005) and Lenzen *et al.* (2007) developed methods to quantitatively determine shared responsibility. This method divides the emissions responsibility between the production sectors of intermediate and final goods.

Peng *et al.* (2018) clarified that innovative ironmaking methods are necessary to mitigate CO₂ emissions from China’s iron and steel sector. However, no discussion has taken place on “which sector” should specifically bear “how much” of the costs of developing and introducing such technologies.

The two major ironmaking methods are blast furnace and electric furnace methods, which utilize different raw materials (blast furnace method: iron ore; electric furnace method: steel scrap), fuels (blast furnace method: coke; electric furnace method: electricity), and applications (e.g., blast furnace method: automobiles; electric furnace method: construction materials), leading to different supply chain structures. Peng *et al.* (2018) addressed “the iron and steel sector,” in which steelmaking methods are aggregated. However, the analysis failed to reflect supply chain differences and could not provide specific policy recommendations for CO₂ emission reduction technologies suitable for each steelmaking method or their respective R&D and implementation costs.

To address these issues, this study adds novelty to the existing literature in three ways. First, this crucial empirical study focuses on the iron and steel sector, which is the most CO₂-intensive sector in Japan and estimates the CO₂ emission responsibility ratios induced by the demand for final goods by steelmaking technology using the Japanese IO table. In this IO table, the iron and steel sector is subdivided according to the use of two technologies: the blast furnace and electric furnace sectors. This study also applies shared responsibility based on the value-added ratio proposed by Lenzen *et al.* (2007). Second, Lenzen *et al.* (2007) did not decompose CO₂ emission responsibility ratios at the supply chain path level. Thus, this study develops an analytical framework that utilizes the concept of shared responsibility for structural path analysis (SPA), allowing for the decomposition of CO₂ emission responsibility ratios at the supply chain path level. Third, this study develops a “practical” cost allocation framework and suggests a strategy to support decarbonization innovations in the ironmaking process throughout the supply chain.

4.2. Three approaches for estimating CO₂ emissions responsibility in supply chains

There are three approaches to estimating CO₂ emissions responsibility in supply chains:

production-based emissions, consumption-based emissions, and shared responsibility-based emissions. The production-based emissions approach estimates the carbon footprint based on the domestic consumption of fossil fuels and other resources (Franzen and Mader, 2018). For example, the iron and steel sector manufacture steel products to meet the demand from the downstream sectors (such as the passenger motor car and construction sectors), with all CO₂ emissions from the process attributed to the steel sector responsible for producing the goods. This approach is used to set emission reduction targets for countries, such as the Paris Agreement and the Kyoto Protocol. However, this approach has some limitations, such as carbon leakage (Peters and Hertwich, 2008; Li *et al.*, 2022).

The consumption-based emissions approach estimates the carbon footprint based on the domestic consumption of goods and services. This approach is effective in reducing carbon leakage as it decreases the incentive to import carbon-intensive goods and services (Pan *et al.*, 2008; Wieadmann, 2009). Based on this approach, the responsibility for CO₂ emissions from steel production is attributed to the consumption sectors (such as passenger motor cars, construction, and building sectors).

The shared responsibility-based emissions approach divides responsibility for CO₂ emissions in the supply chain between the intermediate and final goods production sectors. CO₂ emissions responsibility ratios vary by study; however, some studies have estimated these ratios based on the value added by each sector in the supply chain (Lenzen *et al.*, 2007; Piñero *et al.*, 2019; Airebule *et al.*, 2023). This approach can estimate the CO₂ emissions responsibility for steel production in the passenger motor car supply chain by dividing it between the intermediate goods production sector (i.e., the steel sector) and the final goods production sector (i.e., the passenger motor car sector) based on each sector's value-added ratio.

The remainder of this chapter is organized as follows: Section 2 formulates the study's

methodology, Section 3 describes the data used, Section 4 presents the results and discussion, and Section 5 concludes the paper.

4.3. Methodology

4.3.1. Carbon footprint estimation based on shared responsibility

To decompose responsibility for CO₂ emissions associated with final demand into the intermediate goods production (e.g., crude steel and steel production) and final goods production (e.g., construction and automobiles) sectors, this study utilized the shared responsibility approach (Gallego and Lenzen, 2005; Lenzen *et al.*, 2007) to estimate the sharing ratio based on the value-added ratio of each sector. Lenzen *et al.* (2007) explained final goods production sector responsibility using the variable $\alpha = (\alpha_{ij})$ ($0 \leq \alpha_{ij} \leq 1$) and intermediate goods production sector responsibility using the variable $1 - \alpha = (1 - \alpha_{ij})$ regarding the ratio of responsibility among sectors; $\mathbf{1}$ indicates the matrix in which all elements are 1. Each variable can be obtained using equations (1) and (2) as follows:

$$\alpha_{ij} = 1 - \frac{v_i}{x_i - z_{ii}} \quad (1)$$

$$1 - \alpha_{ij} = \frac{v_i}{x_i - z_{ii}} \quad (2)$$

where x_i , v_i , and z_{ii} represent the output, value-added, and intra-industry transactions of sector i , respectively. $x_i - z_{ii}$ represents the output of sector i minus intra-industry transactions (i.e., net output). Therefore, equation (1) represents the intermediate input rate for sector i , and equation (2) represents the value-added rate for sector i . The direct and indirect CO₂ emissions associated with

final demand can be allocated to the intermediate goods and the final goods production sectors of responsibility by applying these variables to EEIOA, as shown in equation (3) as follows:

$$\begin{aligned}
\mathbf{x} &= \mathbf{Ax} + \mathbf{y} = \boldsymbol{\alpha} \circ \mathbf{Ax} + (\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Ax} + \mathbf{y} \\
&\rightarrow (\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})\mathbf{x} = (\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Ax} + \mathbf{y} \\
&\rightarrow \mathbf{x} = (\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Ax} + (\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}\mathbf{y} \\
&\rightarrow Q = \mathbf{ex} = \mathbf{e} (\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}[(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Z}]\mathbf{i} + \mathbf{e}(\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}\mathbf{y} \tag{3}
\end{aligned}$$

where $\mathbf{A} = (a_{ij})$ represents the intermediate input coefficient matrix, indicating the intermediate input required by sector i per unit of production in sector j . $\mathbf{x} = (x_i)(i = 1, \dots, n)$ represents the column vector of the direct CO₂ emission intensity composed of sector n in the IO table. $\mathbf{e} = (e_j)$ represents the row vector of direct CO₂ emission intensity, indicating CO₂ emissions per unit production of sector j . $\mathbf{Z} = \mathbf{Ax}$ represents the column vector composed of elements that are the sum of the sector's intermediate inputs. $\mathbf{i}$ represents the column vector of ones. $\mathbf{y}$ represents the column vector of the final demand. $\mathbf{I}$ represents the unit matrix. $\circ$ represents an operation that multiplies the elements of a matrix pairwise. $\mathbf{e} (\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}[(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Z}]\mathbf{i}$ represents CO₂ emissions associated with intermediate goods production and $\mathbf{e}(\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1}\mathbf{y}$ represents CO₂ emissions associated with final goods production. Because this study only estimates the ratio of responsibility among industries, the variable β , which represents the ratio of responsibility between industries and final consumers (e.g., government and households) as proposed by Lenzen et al. (2007), is not considered.

4.3.2. Structural path analysis based on the shared responsibility model

The direct and indirect CO₂ emissions associated with the final demand of each sector can be decomposed, as obtained from equation (3), to identify the contribution of each supply chain that

connects production and consumption. Expanding the series $(\mathbf{I} - \alpha \circ \mathbf{A})^{-1}$ in equation (3) provides $(\mathbf{I} - \alpha \circ \mathbf{A})^{-1} = \mathbf{I} + \alpha \circ \mathbf{A} + (\alpha \circ \mathbf{A})^2 + (\alpha \circ \mathbf{A})^3 + \dots$; thus, the direct and indirect CO₂ emissions as Q can be decomposed to equation (4) as follows:

$$Q = \mathbf{e}[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}] + \mathbf{e}(\alpha \circ \mathbf{A})[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}] + \mathbf{e}(\alpha \circ \mathbf{A})^2[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}] + \mathbf{e}(\alpha \circ \mathbf{A})^3[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}] + \dots \quad (4)$$

For example, when the final demand for a certain product occurs, a sector emits CO₂ equivalent to $\mathbf{e}[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}]$ during the production of that product. Additionally, it requires inputs of intermediate goods equivalent to $(\alpha \circ \mathbf{A})[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}]$ to produce that product, and a sector emits CO₂ equivalent to $\mathbf{e}(\alpha \circ \mathbf{A})[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}]$ during the production of those intermediate goods. These emission processes continue infinitely through the expansion of the series $(\mathbf{I} - \alpha \circ \mathbf{A})^{-1}$. To substitute $[\mathbf{y} + \{(\mathbf{I} - \alpha) \circ \mathbf{Z}\}\mathbf{i}] = \mathbf{f}$, CO₂ emissions from sector i represented as q_i can be shown as the sum of supply chain-level emissions as follows:

$$q_i = e_i f_i + \sum_j^N e_i(\alpha_{ij} \circ a_{ij})f_j + \sum_j^N \sum_k^N e_i(\alpha_{ij} \circ a_{ij})(\alpha_{jk} \circ a_{jk})f_k + \sum_j^N \sum_k^N \sum_l^N e_i(\alpha_{ij} \circ a_{ij})(\alpha_{jk} \circ a_{jk})(\alpha_{kl} \circ a_{kl})f_l \quad (5)$$

where i, j, k, l represent the sector index, respectively. The first term on the right side of equation (5), $e_i f_i$, represents CO₂ emissions based on shared responsibility from sector i induced by the final demand of sector i (i.e., direct CO₂ emissions). The second term, $e_i(\alpha_{ij} \circ a_{ij})f_j$, represents CO₂ emissions based on shared responsibility from sector i induced by the production of intermediate goods required by sector j to fulfill its final demand (i.e., the indirect CO₂ emissions from primary spillover supply chain paths). The third term, $e_i(\alpha_{ij} \circ a_{ij})(\alpha_{jk} \circ a_{jk})f_k$, represents CO₂ emissions

based on shared responsibility from the secondary spillover supply chain paths represented as follows:

“final demand of sector l ” $\rightarrow$ “intermediate input of sector k ” $\rightarrow$ “intermediate input of sector j ”
 $\rightarrow$ “production activity of sector i .”

4.3.3. Shared responsibility of CO₂ emissions from iron and steel sector

This study focused on shared-responsibility-based emissions resulting from the production activities of the iron and steel sectors (blast and electric furnace). By substituting $(\mathbf{I} - \boldsymbol{\alpha} \circ \mathbf{A})^{-1} = \bar{\mathbf{L}} = (\bar{\mathbf{L}}_{ij})$, CO₂ emissions from the iron and steel sector (blast and electric furnace), represented as Q_b and Q_c , are shown as in equations (6) and (7).

$$Q_b = \mathbf{e}_b \bar{\mathbf{L}}[\{(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Z}_{bk}\}\mathbf{i}] + \mathbf{e}_b \bar{\mathbf{L}}\mathbf{y}_k \quad (6)$$

$$Q_c = \mathbf{e}_c \bar{\mathbf{L}}[\{(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Z}_{ck}\}\mathbf{i}] + \mathbf{e}_c \bar{\mathbf{L}}\mathbf{y}_k \quad (7)$$

where b and c represent the sector indices of the blast furnace and electric furnace sectors, respectively, and $\mathbf{e}_b$ and $\mathbf{e}_c$ represent row vectors of CO₂ emission intensity, with all values set to 0, except for those corresponding to the blast and electric furnace. $\mathbf{Z}_{bk}$ represents the intermediate input matrix, where the element corresponding to an input from the iron and steel sector b (i.e., the blast furnace sector) to a specific downstream sector k (e.g., the passenger motor car sector) has a value, whereas all other elements in the matrix are zero. Similarly, $\mathbf{Z}_{ck}$ represents the intermediate input matrix, where the element corresponding to an input from the iron and steel sector c (i.e., electric furnace sector) to a specific downstream sector k has a value, whereas all other elements in the matrix are zero. $\mathbf{e}_b \bar{\mathbf{L}}[\{(\mathbf{1} - \boldsymbol{\alpha}) \circ \mathbf{Z}_{bk}\}\mathbf{i}]$ represents CO₂ emissions from the iron and steel sector (blast furnace) associated with intermediate goods production and $\mathbf{e}_b \bar{\mathbf{L}}\mathbf{y}_k$ represents CO₂ emissions from

the iron and steel sector (blast furnace) associated with final goods production. Similarly, $\mathbf{e}_c \bar{\mathbf{L}}[\{(\mathbf{1} - \alpha) \circ \mathbf{Z}_{ck}\} \mathbf{i}]$ represents CO₂ emissions from the iron and steel sector (electric furnace) associated with intermediate goods production and $\mathbf{e}_c \bar{\mathbf{L}} \mathbf{y}_k$ represents CO₂ emissions from the iron and steel sector (electric furnace) associated with final goods production. In addition, this study decomposes shared responsibility-based emissions q_b and q_c to the supply chain path level, as shown in Equations (8) and (9):

$$\begin{aligned}
q_b &= e_b(y_b + \{(1 - \alpha) \circ Z_{bb}\}) \\
&+ \sum_k^N e_b(\alpha_{bk} \circ a_{bk})(y_k + \{(1 - \alpha) \circ Z_{bk}\}) \\
&+ \sum_j^N \sum_k^N e_b(\alpha_{bj} \circ a_{bj})(\alpha_{jk} \circ a_{jk})(y_k + \{(1 - \alpha) \circ Z_{bk}\}) \\
&+ \sum_j^N \sum_k^N \sum_l^N e_b(\alpha_{bj} \circ a_{bj})(\alpha_{jk} \circ a_{jk})(\alpha_{kl} \circ a_{kl})(y_l + \{(1 - \alpha) \circ Z_{bl}\}) \quad (8)
\end{aligned}$$

$$\begin{aligned}
q_c &= e_c(y_c + \{(1 - \alpha) \circ Z_{cc}\}) \\
&+ \sum_k^N e_c(\alpha_{ck} \circ a_{ck})(y_k + \{(1 - \alpha) \circ Z_{ck}\}) \\
&+ \sum_j^N \sum_k^N e_c(\alpha_{cj} \circ a_{cj})(\alpha_{jk} \circ a_{jk})(y_k + \{(1 - \alpha) \circ Z_{ck}\}) \\
&+ \sum_j^N \sum_k^N \sum_l^N e_c(\alpha_{cj} \circ a_{cj})(\alpha_{jk} \circ a_{jk})(\alpha_{kl} \circ a_{kl})(y_l + \{(1 - \alpha) \circ Z_{cl}\}) \quad (9)
\end{aligned}$$

The first terms on the right side of equations (8) and (9), $e_b(y_b + \{(1 - \alpha) \circ Z_{bb}\})$ and $e_c(y_c + \{(1 - \alpha) \circ Z_{cc}\})$, represent CO₂ emissions based on shared responsibility from the blast

furnace and electric furnace sectors induced by the final demand of these sectors (i.e., direct CO₂ emissions), respectively. The second terms of equations (8) and (9), $e_b(\alpha_{bk} \circ a_{bk})(y_k + \{(1 - \alpha) \circ Z_{bk}\})$ and $e_c(\alpha_{ck} \circ a_{ck})(y_k + \{(1 - \alpha) \circ Z_{ck}\})$, represent CO₂ emissions based on shared responsibility from the blast and electric furnace sectors induced by the production of intermediate goods required by sector k to fulfill its final demand (i.e., the indirect CO₂ emissions from primary spillover supply chain paths). The third terms of equations (8) and (9), $e_b(\alpha_{bj} \circ a_{bj})(\alpha_{jk} \circ a_{jk})(y_k + \{(1 - \alpha) \circ Z_{bk}\})$ and $e_c(\alpha_{cj} \circ a_{ej})(\alpha_{jk} \circ a_{jk})(y_k + \{(1 - \alpha) \circ Z_{ck}\})$, represent CO₂ emissions based on shared responsibility from the secondary spillover supply chain paths. These can be described as follows: “final demand of sector k ” → “intermediate input of sector j ” → “intermediate input of sector j ” → “production activity of sector b and c (i.e., blast and electric furnace sectors), respectively.

4.4. Data

This study utilized data on direct sectoral CO₂ emission intensity estimated and published by the National Institute for Environmental Studies, Japan (Nansai, 2019; Nansai *et al.*, 2020). Additionally, this study utilized the 2015 IO table by dividing the ironmaking method into blast furnaces and electric furnaces, as published by the Ministry of Internal Affairs and Communications (Ministry of Internal Affairs and Communications, 2019). Since this IO table consists of 496 rows and 380 columns, sector aggregation was performed based on Matsushima *et al.* (2024) to create a 367-by-367 square matrix. To determine the cost burden associated with low-carbon and decarbonization technologies for each ironmaking method, this study focused on four technologies and the costs outlined in the roadmap for the decarbonization of the iron and steel sector published by the government (Ministry of Economy, Trade and Industry, 2021).

The following summarizes each project and its costs. The first project aims to implement technologies such as hydrogen reduction technology in blast furnaces, utilization of hydrogen in plants, and carbon capture and storage to mitigate CO₂ emissions from the ironmaking process by more than 30% by 2030. The cost of this project is approximately 35.3 billion Japanese yen (JPY), with approximately 14.0 billion JPY in support from the government (hereinafter referred to as Technology 1). The second project aims to develop technologies such as low-carbon technology utilizing external hydrogen and CO₂ contained in blast furnace exhaust gas in a medium-scale test blast furnace to mitigate CO₂ emissions from the ironmaking process by more than 50% by 2030. The cost of this project is approximately 291.3 billion JPY, with approximately 121.2 billion JPY in support from the government (hereinafter referred to as Technology 2). The third project aims to implement technologies such as the direct reduction of low-grade iron ore with hydrogen to mitigate CO₂ emissions by more than 50% compared to conventional blast furnaces in a medium-scale direct reduction furnace by 2030. The cost of this project is approximately 72.4 billion JPY, with approximately 34.5 billion JPY in support from the government (hereinafter referred to as Technology 3). The fourth project aims to implement a technology to control the concentration of impurities at the same level as in the blast furnace method in a large-scale electric furnace integrated process for manufacturing high-grade steel that can be used for exterior automobile panels by 2030. The cost of this project is approximately 36.8 billion JPY, with approximately 23.6 billion JPY in support from the government (hereinafter referred to as Technology 4).

4.5. Results and discussion

4.5.1. Comparison of consumption-based and shared-responsibility-based CO₂ emissions

This study utilized conventional EEIO and EEIO based on shared responsibility to estimate

CO₂ emissions from the pig iron (blast furnace³) and crude steel (electric furnace) sectors through consumption-based and shared-responsibility emissions.

Figure 4-1 shows the contributions of the top three sectors that contribute significantly to CO₂ emissions from the pig iron sector, based on production-based emissions, consumption-based emissions, and shared responsibility. This study found that the pig iron sector, as the crude steel (blast furnace) production sector, accounted for 100% (111,164 kt-CO₂) of CO₂ emissions from the pig iron sector under production-based emissions. In comparison, under consumption-based emissions, the hot rolled steel, passenger motor car, and nonresidential construction sectors accounted for 18% (20,410 kt-CO₂), 11% (11,846 kt-CO₂), and 7% (7,374 kt-CO₂) of CO₂ emissions from the pig iron sector, respectively. These results indicate that the pig iron sector is not responsible for the CO₂ emissions associated with the final demand in Japan. However, the contribution of the downstream sectors, such as passenger motor cars and non-residential construction sectors, to consumption-based emissions was significant (see the consumption-based emissions in Figure 4-1). Additionally, under the shared responsibility-based emissions approach, the pig iron, hot rolled steel, and crude steel (converter) sectors accounted for 33% (36,523 kt CO₂), 16% (17,823 kt CO₂), and 15% (16,563 kt-CO₂) of CO₂ emissions resulting from the production activities of the pig iron sector, respectively. These results indicate a 67% decrease in CO₂ emissions contribution of the pig iron sector under shared responsibility-based emissions. In contrast, CO₂ emissions contribution from other intermediate goods-producing sectors, such as hot-rolled steel and crude steel (converters), was significant.

Figure 4-2 shows the contributions of the top ten sectors that have significantly added to CO₂ emissions from the pig iron sector based on shared responsibility, by consumption-based emissions and shared responsibility. The vertical axis represents CO₂ emissions (kt-CO₂) based on consumption-

³ The iron and steel sector using blast furnaces is included in the pig iron sector; thus, the pig iron sector in the following sentences refers to the blast furnace method in the Japanese IO table.

based emissions, whereas the horizontal axis represents CO₂ emissions (kt-CO₂) based on shared responsibility. In addition, the blue triangles represent the sectors in which the contribution to CO₂ emissions from the pig iron sector is larger under shared responsibility than consumption-based emissions, whereas the red squares represent the sectors in which the contribution to CO₂ emissions from the pig iron sector is larger under consumption-based emissions than shared responsibility. This study found that the CO₂ emissions of the hot-rolled steel sector are 20,410 kt-CO₂ and 17,823 kt-CO₂ based on consumption-based emissions and shared responsibility, respectively. These values accounted for the largest proportions: 18% and 16% of CO₂ emissions from the pig iron sector, respectively. This is attributed to the hot-rolled steel sector being part of the processing industry. Consequently, under consumption-based emissions, emission liabilities arise from the purchase of pig iron from the pig iron sector. In contrast, under shared responsibility, emission liabilities arise from the production and sale of certain goods to downstream sectors, such as the passenger motor car sector. Therefore, the responsibility of the hot-rolled steel sector for CO₂ emissions is high under both consumption-based emissions and shared responsibility. Furthermore, this figure shows that sectors such as passenger motor cars, non-residential construction (non-wooden), residential construction (non-wooden), and steel ships, which emitted significant CO₂ under consumption-based emissions, decreased by more than 70%. However, CO₂ emissions from the pig iron and crude steel sectors increased by 36,000 kt-CO₂ and 16,000 kt-CO₂, respectively, compared with consumption-based emissions.

Figure 4-3 shows the contributions of the top three sectors that significantly contribute to CO₂ emissions from the crude steel (electric furnace) sector, based on production-based emissions, consumption-based emissions, and shared responsibility. This study found that the crude steel (electric furnace) sector accounted for 100% (978 kt-CO₂) of CO₂ emissions from the crude steel (electric furnace) sector under the production-based emissions. In comparison, under the consumption-based emissions, the hot rolled steel, passenger motor cars, and non-residential construction sectors

accounted for 20% (193 kt-CO₂), 10% (94 kt-CO₂), and 7% (66 kt-CO₂) of CO₂ emissions from the crude steel (electric furnace) sector, respectively. These results indicate that the crude steel (electric furnace) sector was not responsible for CO₂ emissions under consumption-based emissions, similar to the findings shown in Figure 4-1. However, the CO₂ emissions contribution from downstream sectors, such as passenger motor cars and nonresidential construction, was significant. Additionally, under the shared responsibility-based emissions approach, the crude steel (electric furnace), hot-rolled steel, and cold-finished sectors accounted for 36% (349 kt-CO₂), 23% (221 kt-CO₂), and 4% (39 kt-CO₂) of CO₂ emissions from the crude steel (electric furnace) sector, respectively. These results indicate a 64% decrease in CO₂ emissions contribution of the crude steel (electric furnace) sector under shared responsibility-based emissions. In contrast, the CO₂ emissions contribution from other intermediate goods-producing sectors, such as hot-rolled and cold-finished steel, was significant.

Figure 4-4 shows the top ten sectors that have significantly contributed to CO₂ emissions from the crude steel (electricity) sector, based on shared responsibility. This study found that the CO₂ emissions of the hot-rolled steel sector were 193 kt-CO₂ and 221 kt-CO₂ based on consumption-based emissions and shared responsibility, respectively. These values accounted for the largest proportions: 10% and 11% of CO₂ emissions from the pig iron sector, respectively. This figure shows that sectors such as passenger motor cars, non-residential construction (non-wooden), residential construction (non-wooden), and steel ships, which emitted significant CO₂ under consumption-based emissions, decreased by more than 55%. However, CO₂ emissions from the crude steel (electric furnace) sector increased by 300 kt-CO₂ compared to under consumption-based emissions.

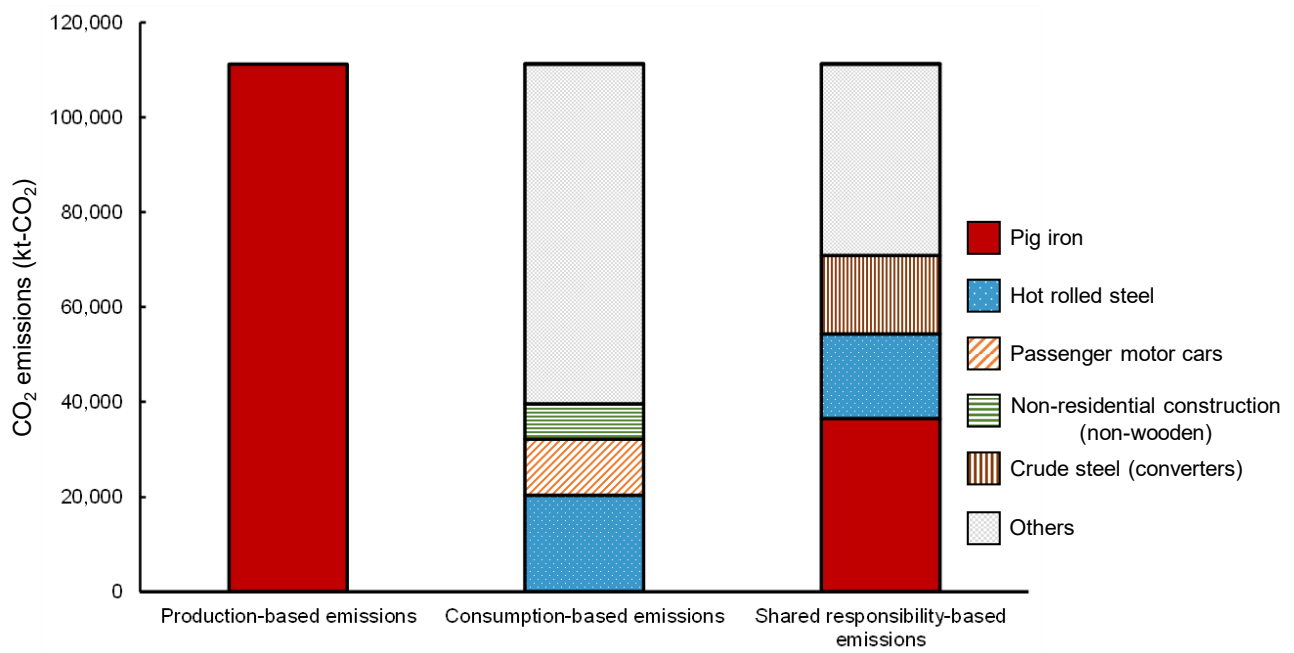


Figure 4-1. The top three sectors largely contributing to the CO₂ emissions from pig iron sector by production-based emissions, consumption-based emissions, and shared responsibility-based emissions.

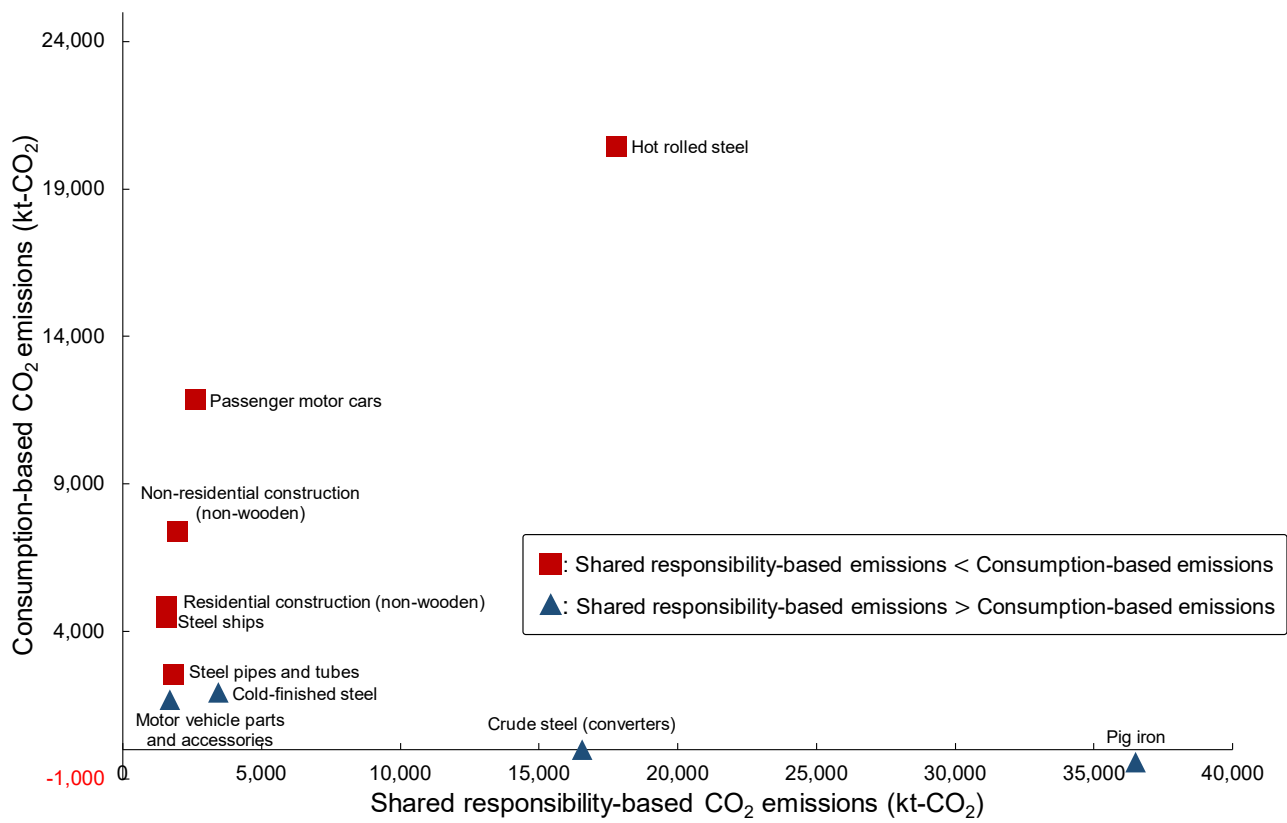


Figure 4-2. The contribution of each sector to CO₂ emissions from the pig iron sector based on consumption-based emissions and shared responsibility-based emissions

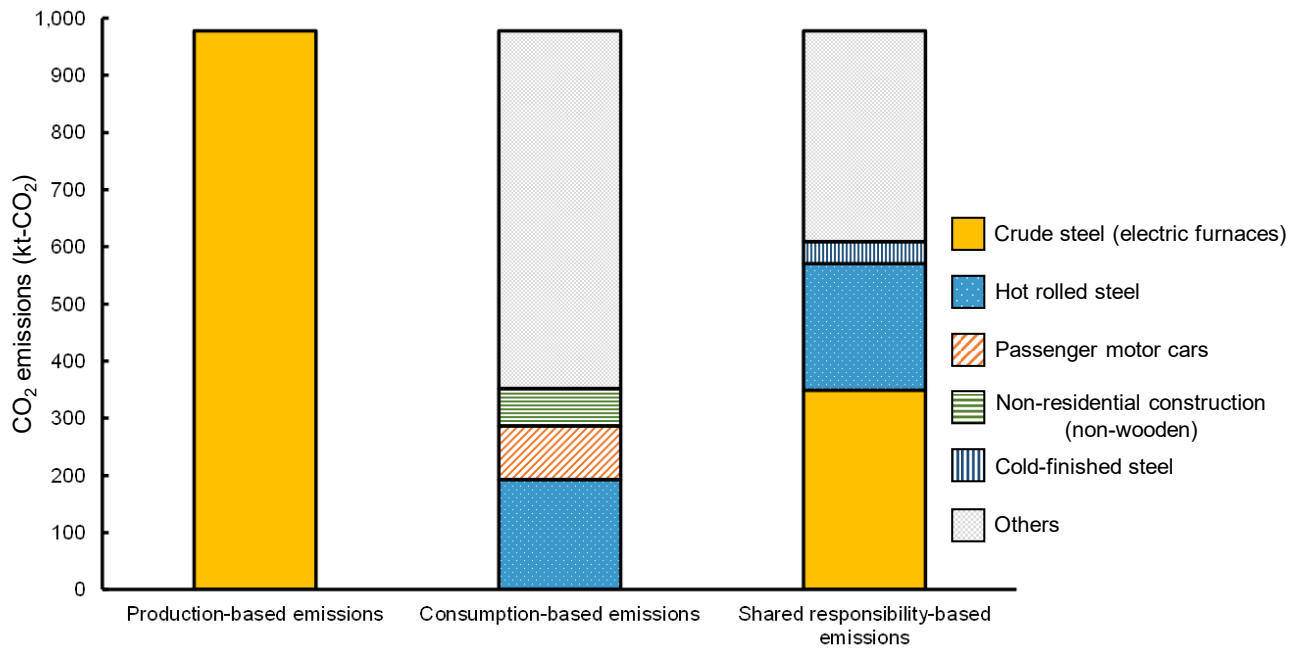


Figure 4-3. The top three sectors largely contributing to the CO₂ emissions from crude steel (electric furnaces) sector by production-based emissions, consumption-based emissions, and shared responsibility-based emissions.

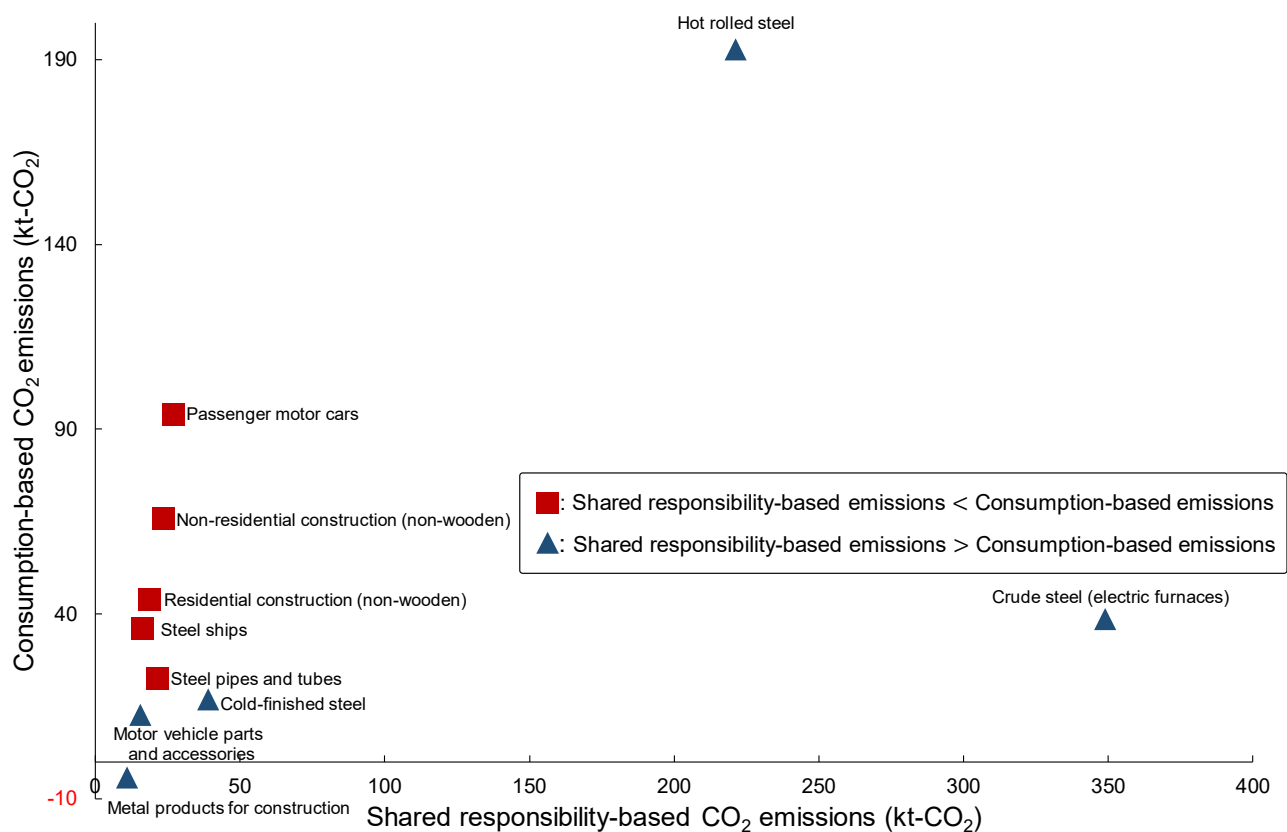


Figure 4-4. The contribution of each sector to CO₂ emissions from the crude steel (electric furnaces) sector based on consumption-based emissions and shared responsibility-based emissions

The results in Figures 4-1 and 4-2 show that the responsibility for CO₂ emissions is concentrated in the final goods production sectors, such as passenger motor cars and non-residential construction (non-wooden), under consumption-based emissions. Conversely, responsibility is distributed to intermediate goods production sectors, such as the pig iron, crude steel (converter), and crude steel (electric furnace) sectors, under shared responsibility.

4.5.2. Decomposition of CO₂ emissions into upstream and downstream sectors based on shared responsibility

This study decomposed the CO₂ emissions associated with the final demand (Figure 4-2) of each sector into the responsibility of the pig iron and steel sector as the intermediate goods production sector and the responsibility of the final goods production sectors. The responsibility of the hot-rolled steel sector (i.e., responsibility of the final goods production sector) is 10,306 kt-CO₂ out of the CO₂ emissions associated with the final demand of the hot-rolled steel sector (Figure 4-5). This accounted for approximately 60% of the CO₂ emissions from the relevant supply chain. The responsibility of the pig iron sector (i.e., intermediate goods production sector) is 7,517 kt-CO₂. As shown in Figure 4-5, the most notable finding is that the responsibility of the pig iron sector is zero for the CO₂ emissions associated with the final demands of the passenger motor car, non-residential construction, residential construction, and steel ships sectors. Thus, the final goods production sectors bear all the responsibility for CO₂ emissions.

This study also decomposed the CO₂ emissions associated with the final demand (Figure 4-3) of each sector into the responsibility of the crude steel (electric furnaces) sector as the intermediate goods production sector and the responsibility of the final goods production sectors. Similar to the results in Figure 4-5, the responsibility of the crude steel (electric furnaces) sector is zero out of the CO₂ emissions associated with the final demands of the passenger motor car, non-residential construction, residential construction, and steel ships sectors (Figure 4-6). Thus, the final goods production sectors bear all the responsibility for CO₂ emissions.

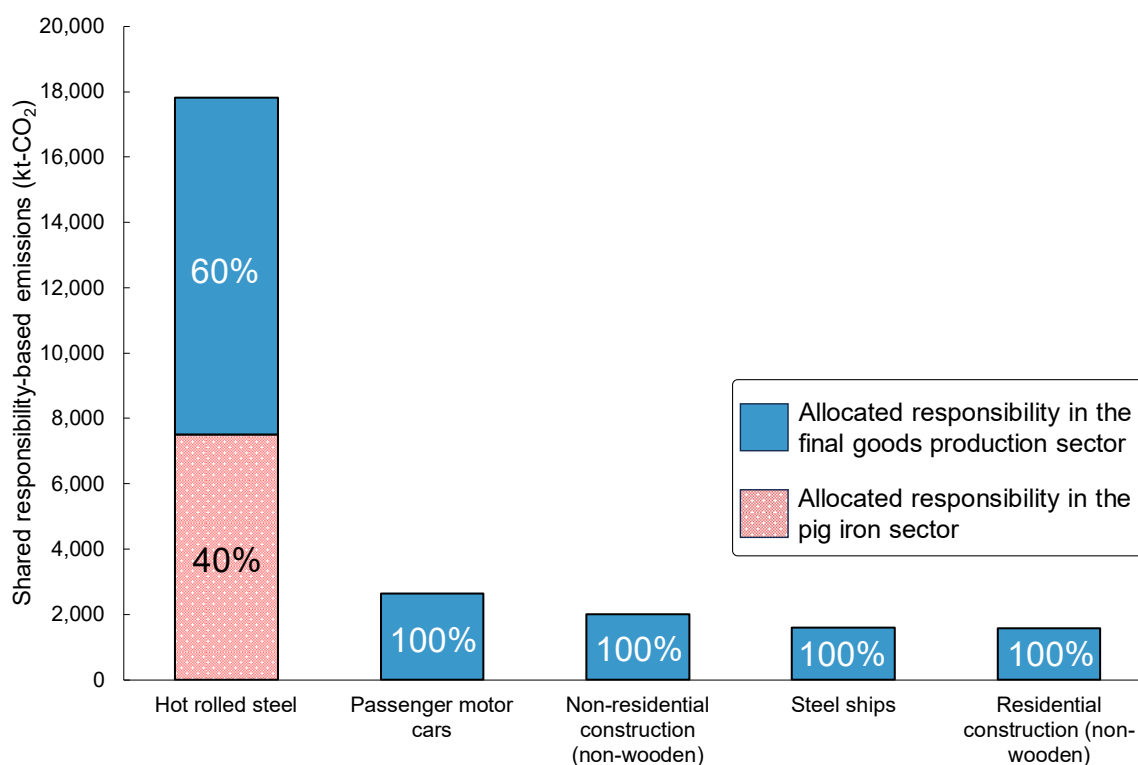


Figure 4-5. Responsibility of the final goods production sector and the pig iron sector for CO₂ emissions from the pig iron sector

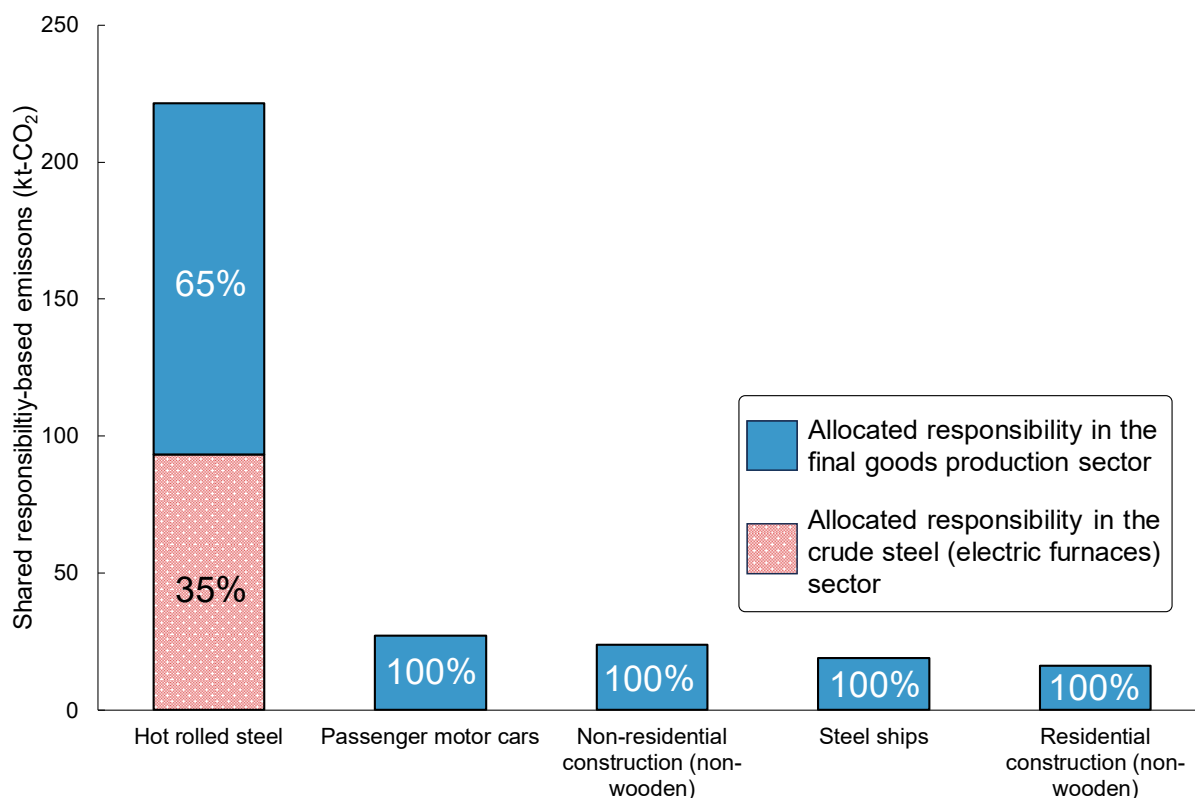


Figure 4-6. Responsibility of the final goods production sector and the crude steel (electric furnaces) sector for CO₂ emissions from the crude steel (electric furnaces) sector

4.5.3. Structural path analysis applying shared responsibility

This study estimated CO₂ emissions from the pig iron and crude steel (electric furnace) sectors based on shared responsibility. Additionally, this study decomposed the responsibility for CO₂ emissions associated with final demand into intermediate goods production sectors (the pig and iron sector and the crude steel [electric furnace] sector) and final goods production sectors (e.g., passenger motor car sector). Figures 4-5 and 4-6 show that the pig iron and crude steel (electric furnace) sectors bear no responsibility for the shared responsibility-based emissions associated with the final demand of the passenger motor car, nonresidential construction (nonwooden), residential construction (nonwooden), and steel ship sectors. This is because the pig iron and crude steel (electric furnace) sectors did not supply intermediate goods directly to these downstream sectors. In other words, the values of $\mathbf{Z}_{bk}$ and $\mathbf{Z}_{ck}$ are zero (Equations (6) and (7)). Therefore, the emissions liability of the intermediate goods-producing sector is zero, with all emissions liability being borne by the downstream sectors (i.e., $Q_b = \mathbf{e}_b \bar{\mathbf{L}}[\{(\mathbf{1} - \alpha) \circ \mathbf{Z}_{bk}\}\mathbf{i}] + \mathbf{e}_b \bar{\mathbf{L}}\mathbf{y}_k = \mathbf{e}_b \bar{\mathbf{L}}[\{(\mathbf{1} - \alpha) \circ \mathbf{0}\}\mathbf{i}] + \mathbf{e}_b \bar{\mathbf{L}}\mathbf{y}_k = \mathbf{e}_b \bar{\mathbf{L}}\mathbf{y}_k$, $Q_c = \mathbf{e}_c \bar{\mathbf{L}}[\{(\mathbf{1} - \alpha) \circ \mathbf{Z}_{ck}\}\mathbf{i}] + \mathbf{e}_c \bar{\mathbf{L}}\mathbf{y}_k = \mathbf{e}_c \bar{\mathbf{L}}[\{(\mathbf{1} - \alpha) \circ \mathbf{0}\}\mathbf{i}] + \mathbf{e}_c \bar{\mathbf{L}}\mathbf{y}_k = \mathbf{e}_c \bar{\mathbf{L}}\mathbf{y}_k$). However, these sectors participated indirectly in the supply chain (Tables 1 and 2). As intermediate good-producing sectors, the pig iron and crude steel (electric furnaces) sectors should bear the responsibility for CO₂ emissions, making it inappropriate to allocate all responsibility to the final demand sector. This study employed SPA and the final goods production sector responsibility ratio α_{ij} to determine the allocation of responsibility that the downstream sector should assume in the supply chain when the direct input from the upstream sector to the downstream sector is zero.

Table 4-1 represents the supply chain paths in which the responsibility of the passenger motor car sector exceeds 1 kt-CO₂ out of the supply chain paths between the pig iron sector (sector code: #139) and passenger motor car sector (sector code: #225). CO₂ emissions from the top 13 supply chain

paths account for approximately 99% of the CO₂ emissions associated with the final demand in the passenger motor car sector. The variable α_{ij} represents the shared responsibility ratio of sector j in a supply chain path between sectors i and j . The first path (pig iron sector [#139] → cast and forged materials [iron] sector [#149] → passenger motor car sector [#225]) represents Tier 2, indicating the production in the pig iron sector required to produce the intermediate goods of cast iron and forged products necessary to fulfill the final demand of the passenger car sector. Furthermore, CO₂ emissions from this supply chain path were approximately 10.6 kt-CO₂. The responsibility of the passenger motor car sector for CO₂ emissions in the relevant path represents CO₂ emissions which the passenger motor car sector induced production activities in other sectors (the responsibility of the passenger motor car sector equals 10.6 kt-CO₂ times 67% times 60% equals 4.3 kt-CO₂). Please refer to the SI for the specific sector code table.

Table 4-1. CO₂ emissions of the supply chain paths between the pig iron sector (sector code: #139) and the passenger motor car sector (sector code: #225) and the responsibility of the passenger motor cars sector for CO₂ emissions.

Supply chain path	CO ₂ emissions from the supply chain path (kt-CO ₂)	Shared responsibility ratio of sector <i>j</i> in a supply chain path between sector <i>i</i> and <i>j</i> (α_{ij})	Shared responsibility ratio of sector <i>k</i> in a supply chain path between sector <i>j</i> and <i>k</i> (α_{jk})	Shared responsibility ratio of sector <i>m</i> in a supply chain path between sector <i>k</i> and <i>m</i> (α_{km})	Shared responsibility ratio of sector <i>l</i> in a supply chain path between sector <i>m</i> and <i>l</i> (α_{ml})	Downstream responsibility of passenger motor cars (#225) for CO ₂ emissions from the relevant supply chain path (kt-CO ₂)
#139(<i>i</i>)→#149(<i>j</i>)→#225(<i>k</i>)	10.6	67%	60%			4.3
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#225(<i>l</i>)	1017.8	67%	76%	82%		425.0
#139(<i>i</i>)→#149(<i>j</i>)→#229(<i>k</i>)→#225(<i>l</i>)	95.1	67%	60%	56%		21.4
#139(<i>i</i>)→#149(<i>j</i>)→#228(<i>k</i>)→#225(<i>l</i>)	65.1	67%	60%	59%		15.4
#139(<i>i</i>)→#142(<i>j</i>)→#143(<i>k</i>)→#225(<i>l</i>)	27.5	67%	57%	82%		8.6
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#145(<i>l</i>)→#225(<i>m</i>)	242.0	67%	76%	82%	69%	69.7
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#228(<i>l</i>)→#225(<i>m</i>)	177.9	67%	76%	82%	56%	41.6
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#150(<i>l</i>)→#225(<i>m</i>)	126.3	67%	76%	82%	59%	31.1
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#150(<i>l</i>)→#225(<i>m</i>)	59.5	67%	76%	82%	73%	18.1
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#146(<i>l</i>)→#225(<i>m</i>)	43.7	67%	76%	82%	77%	14.0
#139(<i>i</i>)→#141(<i>j</i>)→#146(<i>k</i>)→#206(<i>l</i>)→#225(<i>m</i>)	14.7	67%	76%	82%	54%	3.3
#139(<i>i</i>)→#141(<i>j</i>)→#146(<i>k</i>)→#229(<i>l</i>)→#225(<i>m</i>)	11.6	67%	76%	82%	56%	1.8
#139(<i>i</i>)→#141(<i>j</i>)→#143(<i>k</i>)→#166(<i>l</i>)→#225(<i>m</i>)	8.6	67%	76%	82%	50%	1.8
Backward linkage effects in terms of all supply chain paths	2,630	-	-	-	-	2,630

Note: The CO₂ emissions from the supply chain path is calculated by the equation: $e_i(1 - \alpha_{ij})\alpha_{ij}(1 - \alpha_{jk})\alpha_{jk}(1 - \alpha_{kl})\alpha_{kl}(1 - \alpha_{lm})f_m$. The downstream responsibility of passenger motor cars (#225) for CO₂ emissions from the relevant supply chain path (kt-CO₂) is calculated by the equation: $e_i\alpha_{ij}\alpha_{ij}\alpha_{jk}\alpha_{jk}\alpha_{kl}\alpha_{kl}\alpha_{lm}f_m$. The backward linkage effects across all supply chain paths were estimated using the shared responsibility model presented in equation (3) (Lenzen et al., 2007). Specifically, the downstream responsibility of passenger motor cars was calculated using the second term of equation (3). Notably, the SPA based on the shared responsibility model allows for the breakdown of downstream responsibility at the path level.

Table 4-2 presents the supply chain paths in which the responsibility of the passenger motor car sector exceeds 0.1 kt-CO₂ out of the supply chain paths between the crude steel (electric furnaces) sector (sector code: #139) and passenger motor car sector (sector code: #225). CO₂ emissions from the top seven supply chain paths accounted for approximately 99% of the CO₂ emissions associated with the final demand in the passenger motor car sector. As shown in Table 2, the passenger motor car sector is responsible for approximately 10 kt-CO₂ emissions from the crude steel (electric furnaces) sector. Please refer to the SI for the results of the responsibility ratios between the pig iron and crude steel (electric furnace) sectors and the non-residential construction (non-wooden), residential construction (non-wooden), and steel ships sectors.

Table 4-2. CO₂ emissions of the supply chain paths between the crude steel (electric furnaces) sector (sector code: #142) and the passenger motor car sector (sector code: #225) and the responsibility of the passenger motor cars sector for CO₂ emissions.

Supply chain path	CO ₂ emissions from the supply chain path (kt-CO ₂)	Shared responsibility ratio of sector <i>j</i> in a supply chain path between sector <i>i</i> and <i>j</i> (α_{ij})	Shared responsibility ratio of sector <i>k</i> in a supply chain path between sector <i>j</i> and <i>k</i> (α_{jk})	Shared responsibility ratio of sector <i>m</i> in a supply chain path between sector <i>k</i> and <i>m</i> (α_{km})	Downstream responsibility of passenger motor cars (#225) for CO ₂ emissions from the relevant supply chain path (kt-CO ₂)
#142(<i>i</i>)→#143(<i>j</i>)→#225(<i>k</i>)	12.4	68%	82%		7.0
#142(<i>i</i>)→#143(<i>j</i>)→#145(<i>k</i>)→#225(<i>l</i>)	3.0	68%	82%	70%	1.2
#142(<i>i</i>)→#143(<i>j</i>)→#229(<i>k</i>)→#225(<i>l</i>)	2.2	68%	82%	57%	0.7
#142(<i>i</i>)→#143(<i>j</i>)→#228(<i>k</i>)→#225(<i>l</i>)	1.5	68%	82%	60%	0.5
#142(<i>i</i>)→#143(<i>j</i>)→#150(<i>k</i>)→#225(<i>l</i>)	0.7	68%	82%	74%	0.3
#142(<i>i</i>)→#143(<i>j</i>)→#146(<i>k</i>)→#225(<i>l</i>)	0.5	68%	82%	78%	0.2
#142(<i>i</i>)→#142(<i>j</i>)→#143(<i>k</i>)→#225(<i>l</i>)	0.4	68%	68%	82%	0.1
Backward linkage effects in terms of all supply chain paths	27.1	-	-	-	27.1

Note: The CO₂ emissions from the supply chain path is calculated by the equation: $e_i(1 - \alpha_{ij})a_{ij}(1 - \alpha_{jk})\alpha_{jk}(1 - \alpha_{kl})a_{kl}f_l$. The downstream responsibility of passenger motor cars (#225) for CO₂ emissions from the relevant supply chain path (kt-CO₂) is calculated by the equation: $e_i\alpha_{ij}a_{ij}\alpha_{jk}a_{jk}\alpha_{kl}f_l$. The backward linkage effects across all supply chain paths were estimated using the shared responsibility model presented in equation (3) (Lenzen et al., 2007). Specifically, the downstream responsibility of passenger motor cars was calculated using the second term of equation (3). Notably, the SPA based on the shared responsibility model allows for the breakdown of downstream responsibility at the path level.

Tables 4-3 and 4-3 present the total CO₂ emissions along the supply chain paths (from Tiers 2 to 5) between the pig iron sector (crude steel [electric furnace] sector) and each downstream sector based on shared responsibility. The first, third, and fifth columns of Tables 4-3 and 4-4 represent CO₂ emissions based on the shared responsibility input-output model (i.e., shared responsibility-based emissions without SPA) (Lenzen et al., 2007), the subtotal of CO₂ emissions associated with supply chain paths from tier 2 to tier 5 identified by the SPA (i.e., shared responsibility-based emissions with SPA), and consumption-based emissions, respectively. Additionally, the second, fourth, and sixth columns of Tables 4-3 and 4-4 represent the contribution ratio of each downstream sector to the CO₂ emissions from the pig iron steel and crude steel (electric furnace) sectors. The results in the first and second columns of Tables 4-3 and 4-4 show that the shared-responsibility-based emissions without SPA, resulting from the production of pig iron associated with the final demand of the passenger motor car sector, were 2,630 kt-CO₂. This represents 2.4% of the CO₂ emissions from pig iron production activities induced by the Japanese economy. In contrast, the results in the third and fourth columns of Tables 3 and 4 show that the shared responsibility-based emissions with SPA were 666 kt-CO₂, accounting for 0.6% of the CO₂ emissions from pig iron production activities. These findings highlight a 1.8% difference in the contribution of the pig iron sector to CO₂ emissions when comparing shared responsibility-based emissions without SPA to those with SPA. This difference in contribution rates is observed in other sectors and electric furnaces as well, with variations ranging from 0.7% to 1.7% (Tables 4-3 and 4-4). In addition, the results in the fifth and sixth columns of Tables 4-3 and 4-4 show that the consumption-based emissions resulting from the production of pig iron associated with the final demand of the passenger motor car sector were 11,846 kt-CO₂. This represents 11% of the CO₂ emissions from pig iron production activities induced by the Japanese economy. These findings highlight a 10.4% difference in the contribution of the pig iron sector to CO₂ emissions when comparing shared responsibility-based emissions with SPA to consumption-based emissions. This difference in contribution rates is observed in other sectors and electric furnaces as well, with variations

ranging from 3.5% to 11.9% (Tables 4-3 and 4-4).

Table 4-3. Total CO₂ emissions of the pig iron sector associated with the final demand of each sector and the contribution ratio of each sector to the pig iron sector's CO₂ emissions.

Downstream sector name	CO ₂ emissions based on shared responsibility input-output model (kt-CO ₂)	Contribution ratio of shared responsibility-based emissions of a downstream sector to CO ₂ emissions resulting from the production activity of pig iron sector (%)	Subtotal of CO ₂ emissions associated with supply chain paths from tier 2 to tier 5 identified by the SPA (kt-CO ₂)	Contribution ratio of subtotal of CO ₂ emissions associated with supply chain paths from tier 2 to tier 5 to CO ₂ emissions resulting from the production activity of pig iron sector (%)	Consumption-based CO ₂ emissions of a downstream sector (kt-CO ₂)	Contribution ratio of consumption-based emissions of a downstream sector to CO ₂ emissions resulting from the production activity of pig iron sector (%)
Passenger motor car	2,630	2.4%	666	0.6%	11,846	11%
Non-residential construction	2,009	1.8%	598	0.5%	7,374	7%
Residential construction	1,594	1.4%	560	0.5%	4,825	4%
Steel ships	1,577	1.4%	592	0.5%	4,453	4%

Table 4-4. Total CO₂ emissions of the crude steel (electric furnaces) sector associated with the final demand of each sector and the contribution ratio of each sector to the crude steel (electric furnaces) sector's CO₂ emissions.

Downstream sector name	CO ₂ emissions based on shared responsibility input-output model (kt-CO ₂)	Contribution ratio of shared responsibility-based emissions of a downstream sector to CO ₂ emissions resulting from the production activity of electric furnaces sector (%)	Subtotal of CO ₂ emissions associated with supply chain paths from tier 2 to tier 5 identified by the SPA (kt-CO ₂)	Contribution ratio of subtotal of CO ₂ emissions associated with supply chain paths from tier 2 to tier 5 to CO ₂ emissions resulting from the production activity of electric furnaces sector (%)	Consumption-based CO ₂ emissions of a downstream sector (kt-CO ₂)	Contribution ratio of consumption-based emissions of a downstream sector to CO ₂ emissions resulting from the production activity of electric furnaces sector (%)
Passenger motor car	27	2.8%	10.3	1.1%	94.0	12%
Non-residential construction	24	2.4%	9.7	1.0%	65.6	9%
Residential construction	16	1.9%	9.2	0.9%	43.7	7%
Steel ships	19	1.7%	9.8	1.0%	38.6	7%

4.5.4. Cost distribution based on shared responsibility

The Japanese government aims to leverage the country's competitive advantage in the production of high-grade steel by promoting electric furnace conversion. Additionally, it seeks to facilitate the production of reduced iron from low-grade iron ore through direct hydrogen reduction (Ministry of Economy, Trade and Industry, 2023). To achieve these goals, the Japanese government officially announced the schedule and costs for the R&D to produce four technologies related to electric furnaces and hydrogen technology (see Section 4.3). This study distributed the costs of the four announced technologies (excluding subsidies) among the passenger motor car, non-residential construction, residential construction, and steel ships sectors. Specifically, this study estimated the cost burden of each sector by multiplying the contribution ratio of each sector to CO₂ emissions by the cost of each of the four technologies. Technologies 1, 2, and 3 are the green technologies for blast furnaces. Therefore, the contribution ratio of each sector to CO₂ emissions was based on CO₂ emissions from the pig iron sector. Conversely, technology 4 is a green technology for electric furnaces (Table 4-3). Therefore, the contribution ratio of each sector to CO₂ emissions was based on the CO₂ emissions from the crude steel (electric furnace) sector (Table 4-4).

Figure 4-7 shows the cost burden of each sector based on shared responsibility and consumption-based emissions. The solid graph represents the cost burden for shared responsibility-based emissions, whereas the patterned graph represents the cost burden for consumption-based emissions. In addition, each color represents the cost burden for each technology. According to the shared responsibility results, the passenger motor car sector should cover costs ranging from 128 (million JPY) to 1,022 (million JPY) for each green technology, totaling 1,518 million JPY. The non-residential construction (non-wooden) sector should cover costs ranging from 113 (million JPY) to 903 (million JPY) for each green technology, totaling 1,348 million JPY. The residential construction

(non-wooden) sector should cover costs ranging from 107 (million JPY) to 852 (million JPY) for each green technology, totaling 1,272 million JPY. The steel ships sector should cover costs ranging from 115 (million JPY) to 920 (million JPY) for each green technology, totaling 1,372 million JPY. When comparing the cost burden based on shared responsibility with that of consumption-based emissions, the former was approximately 7–17 times lower. According to these results, using consumption-based emissions, it is possible to estimate costs based on the scale of production activity in the pig iron sector, which is directly or indirectly influenced by the final demand of each sector. This approach is limited in that it cannot estimate the CO₂ emission responsibility of pig iron as an intermediate goods production sector. However, by using shared-responsibility-based emissions, it is possible to develop a cost allocation framework to support decarbonization innovations in the ironmaking process throughout the supply chain, as it can estimate the CO₂ emissions responsibility for pig iron. The cost each sector should pay varies depending on how the standard for the responsibility ratio of CO₂ emissions between the upstream and downstream sectors is established.

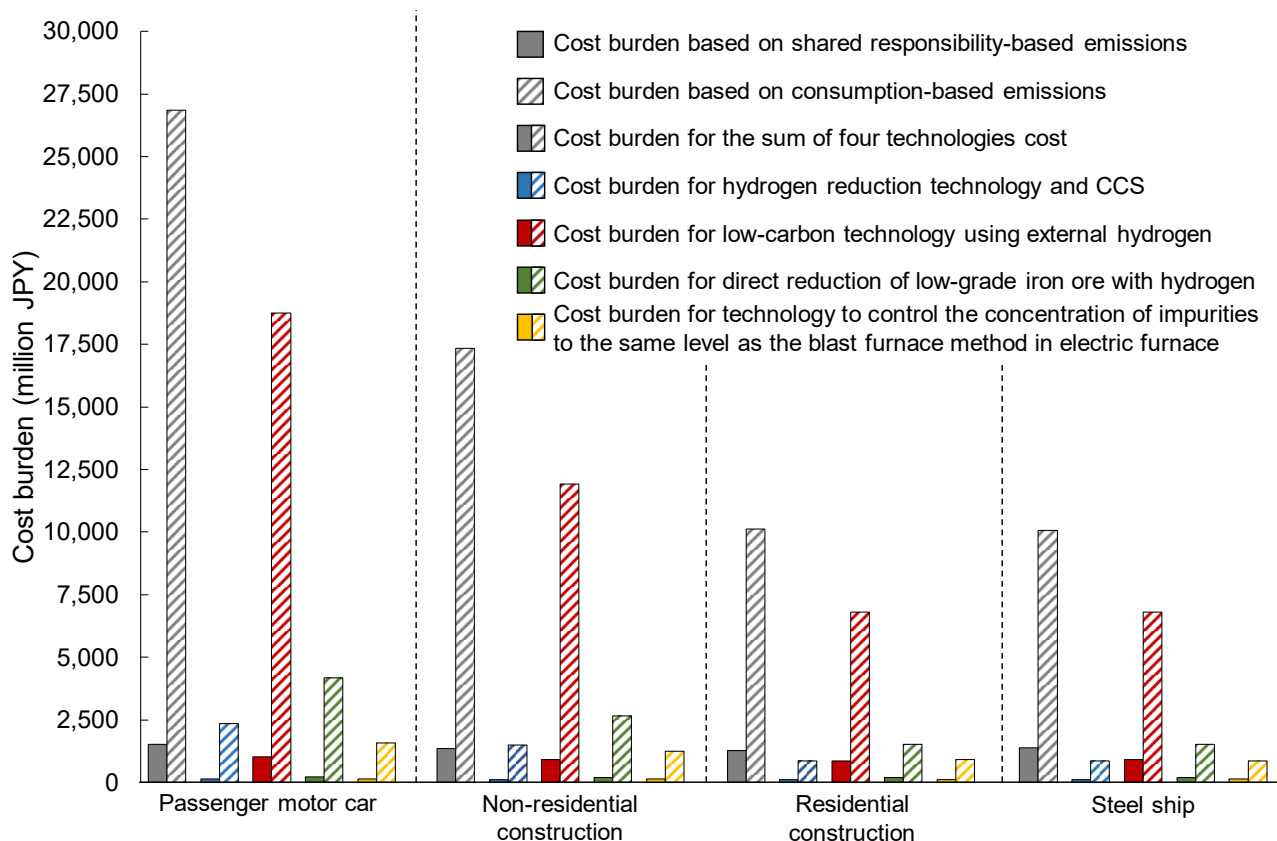


Figure 4-7. Cost burden of each sector by technologies

This study divided the cost burden of each sector by its gross operating surplus (GOS) to assess the degree to which these costs represent the burden of each sector. As shown in Figure 8, the cost burden from shared responsibility as a ratio of GOS is approximately 4–20% lower than from consumption-based responsibility. According to these results, decision-makers have the flexibility to choose which emissions responsibility estimation approach to use when providing cost support for decarbonization technologies. For example, the cost burden ratio in the passenger motor car, non-residential construction, and residential construction sectors was approximately 5%, whereas in the steel ship sector, it exceeds 20% (see Figure 4-8). Therefore, when determining the cost to be paid by the steel-ship sector, shared-responsibility-based emissions can be used so that the burden on each sector is the same. The decision-maker can implement the policy by considering the payment capacity and CO₂ emissions responsibility of each sector using the results of consumption-based emissions and

shared responsibility-based emissions clarified in this study.

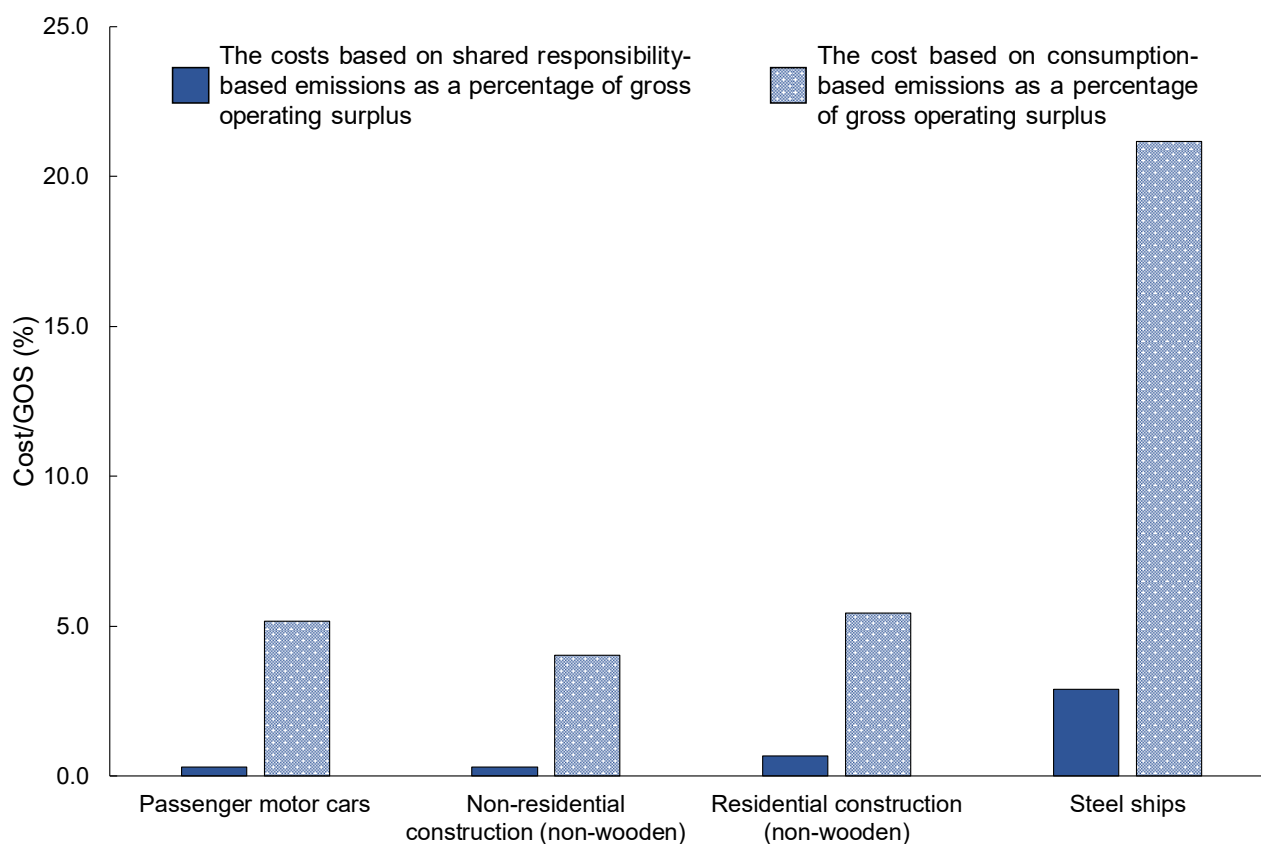


Figure 4-8. The ratio of the cost burden relative to the gross operating surplus (GOS) of each sector

4.5.5. Limitations of this study

This study clarified the costs that domestic downstream sectors should bear for decarbonization technologies in the iron and steel sector by using consumption-based and shared responsibility-based emissions. However, this study did not consider international trade and was therefore unable to connect to discussions on international technological cooperation. Discussing international technological cooperation requires a comprehensive dialogue involving not only Japanese stakeholders and the government but also global governments and international organizations. In addition, the framework of this study must be expanded to include international trade, which is a

key challenge for future studies.

This study focused on the iron and steel sector as a CO₂ emission-intensive sector, but its framework can be applied to other sectors such as the cement sector. However, this study is limited because of its inability to provide quantitative recommendations for other industries because it lacks data on the costs of implementing decarbonization technologies in the cement industry and beyond. Therefore, extending the model proposed in this study not only to the steel sector but also to other industries presents a future challenge.

4.6. Conclusions

In this study, to propose a “practical” cost allocation strategy to support decarbonization innovations in the ironmaking process throughout the supply chain, this study estimated the CO₂ emission responsibility of each sector using EEIO and SPA methods, based on shared responsibility proposed by Lenzen et al. (2007). The results of these analyses indicate that the responsibility for CO₂ emissions from the pig iron and electric furnace sectors was primarily concentrated in the final goods production sectors, such as the passenger motor car and non-residential construction (non-wooden) sectors, in terms of consumption-based emissions. In contrast, when based on shared responsibility, part of the responsibility is allocated to the intermediate goods production sectors, such as the pig iron and crude steel (converter and electric furnace) sectors. In addition, CO₂ emissions associated with the final demand of the passenger motor car, non-residential construction (non-wooden), residential construction (non-wooden), and steel ships sectors accounted for 0.6%, 0.5%, 0.5%, and 0.5% of CO₂ emissions from the pig iron sector, respectively, under shared responsibility. In contrast, in the case of consumption-based emissions, the percentages of CO₂ emissions were 11%, 7%, 4%, and 4%, respectively, and the gap ranged from 3.5% to 10.4%. Similar results were obtained for the percentage of CO₂ emissions from electric furnaces.

This study showed the cost allocation for decarbonization technologies in the steel sector and identified the amount each sector would owe based on the analysis results. The results indicate that costs based on shared responsibility are approximately 7–17 times lower than those under consumption-based emissions. In addition, the proportion of the cost burden based on shared responsibility relative to the GOS of each sector decreases by approximately 4–20% compared to consumption-based emissions. These results indicate that cost allocation based on shared responsibility is more feasible than that utilizing consumption-based emissions.

The various stakeholders in the supply chain should bear part of the costs associated with green technologies to achieve decarbonization in the iron and steel sector. To ensure fair cost allocation, it is crucial to quantify the CO₂ emission responsibilities of each sector based on shared responsibility, which considers not only the final goods production sectors but also the intermediate goods production sectors. Stakeholders and company management must pay attention to ESG investing. ESG investing refers to the incorporation of environmental, social, and governance considerations in investment decisions (Matos, 2020). Bolton and Kacperczyk (2021) focused on the relationship between CO₂ emissions and stock returns in U.S.-listed companies. They clarified that institutional investors select stocks based on the ratio of a company's total direct CO₂ emissions to its sales. Thus, ESG investments are closely linked to environmental issues. A sustainability-themed approach is a method of ESG investing that focuses on companies that engage in projects such as CO₂ emission reduction. For example, the iron and steel sector, which invests in R&D for decarbonization technologies, such as hydrogen-reduced steelmaking and electric furnaces powered by renewable energy, can attract ESG-focused investments. In addition, downstream sectors can receive a high evaluation as ESG investment partners by bearing the cost, as clarified in this study, for the iron and steel sector and disclosing that cost.

Chapter 5: Conclusions

This thesis focuses on the highly interdependent supply chain between the construction and iron and steel sectors. It presents two analytical frameworks: first, the identification of CO₂ emission hotspots within the wooden housing construction supply chain using EEIO; and second, a shared-responsibility-based input–output framework designed to ensure equitable cost allocation for the decarbonization of the iron and steel industry across the entire supply chain.

Chapter 3 combines EEIO analysis, a unit structure model, and cluster analysis to visualize the CO₂ emission hotspots within the supply chain network of an “average wooden house,” defined by a functional unit of 119 m² per house. As a result, the top ten clusters accounted for approximately 40% of the total carbon footprint of a wooden house (38 t-CO₂). Among them, the iron and steel (pig iron and crude steel) and cement (cement and ready-mixed concrete) clusters together represented about 75% of the emissions within the top ten clusters. Additionally, the carbon footprint of a non-wooden house was estimated to be approximately 82 t-CO₂ per house under the same functional unit, suggesting the advantages of wooden houses in terms of both lower construction-related carbon footprint and carbon storage capacity. From a policy perspective, promoting the renovation and reuse of vacant houses—centered on the reuse of foundation materials such as steel and cement, as well as advancing green public procurement and information disclosure (e.g., carbon footprint labeling of houses), are effective short- to medium-term mitigation measures.

Chapter 4 applies an EEIO analysis based on shared-responsibility emissions to a SPA in order to decompose emission responsibilities at the supply-chain path level. This analysis demonstrated that, under the shared-responsibility emission approach, the concentration of responsibility that typically occurs in the final goods sectors under the conventional consumption-based framework was

appropriately redistributed to the intermediate sectors—specifically, pig iron and crude steel (both basic oxygen and electric furnace) production. As a result, the cost burden on downstream sectors associated with introducing green steel technologies (such as hydrogen-based direct reduction, CCUS, and advanced electric furnaces) was reduced to approximately one-seventh to one-seventeenth of that under the consumption-based approach. In addition, the burden ratio relative to GOS was suppressed by about 4–20%, providing a rationale for policy designs such as joint investment and cost-sharing schemes that ensure equitable participation of downstream sectors in supporting upstream innovations while avoiding excessive concentration of financial burdens.

As for the limitations and future perspectives of this dissertation, Chapter 3 utilized the 2015 IOT, which does not fully capture the environmental impact of houses equipped with advanced energy-efficient technologies that have become more widespread in recent years. Therefore, future research should employ the IOT for Next-Generation Energy System Analysis (Waseda University, Research Institute for Next Generation Science and Technology, 2020) to estimate CO₂ emissions associated with the production of energy-saving equipment, such as solar panels. The cost allocation framework for supporting decarbonization innovation developed in Chapter 4 can also be applied to other industrial sectors (e.g., the cement sector). By collecting data on the costs of introducing decarbonization technologies in the cement industry and other related sectors, it will be possible to provide quantitative policy recommendations for these industries.

In conclusion, this dissertation presents a quantitative framework to address two fundamental questions: from which sectors emissions should be reduced and who should bear the costs of decarbonization technologies. It concludes that achieving an effective net-zero transition in Japan requires transparent quantification of emission responsibility and collaborative cost-sharing across the entire supply chain, driven by the coordinated efforts of both the demand and supply sides.

Supplementary information

This thesis employed the following equation to estimate the carbon storage capacity of wood, following the guidelines published by the government (Ministry of Agriculture, Forestry and Fishers, 2021).

$$\begin{aligned} \text{Carbon Storage}(\text{t} - \text{CO}_2) \\ &= \text{Wooden volume}(\text{m}^3) \times \text{Wooden density}(\text{t}/\text{m}^3) \\ &\quad \times \text{Weight of the carbon content} \times \frac{44}{12} \end{aligned}$$

To estimate the lumber volume used in an average wooden house, we utilized data on the unit cost of lumber (cubic meters/ million JPY) from the government's domestic production value table by sector (Ministry of Internal Affairs and Communications, 2019) and calculated the amount of lumber input per house. First, we estimated inputs by dividing the amount of the lumber sector input by the average number of wood-frame homes built in 2015, as reported in the intermediate input matrix of the input matrix of the Input-Output table. As a result, the input amount was 1.4 million yen. Subsequently, the lumber input was divided by the unit cost of lumber to estimate the lumber volume. This calculation yields a lumber volume of 23.1 (m³). The density of the wood is the density of cedar wood (0.38 t/m³), which is commonly used in Japanese wooden houses (Ministry of the Environment, 2005; Ministry of Land, Infrastructure, Transport and Tourism, 2017). The average carbon content of dry wood has been found to be 0.5 (Martin *et al.*, 2018). Thus, based on Eq. (A1), carbon storage can be estimated to be 16 t-CO₂.

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