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Pathways and policies

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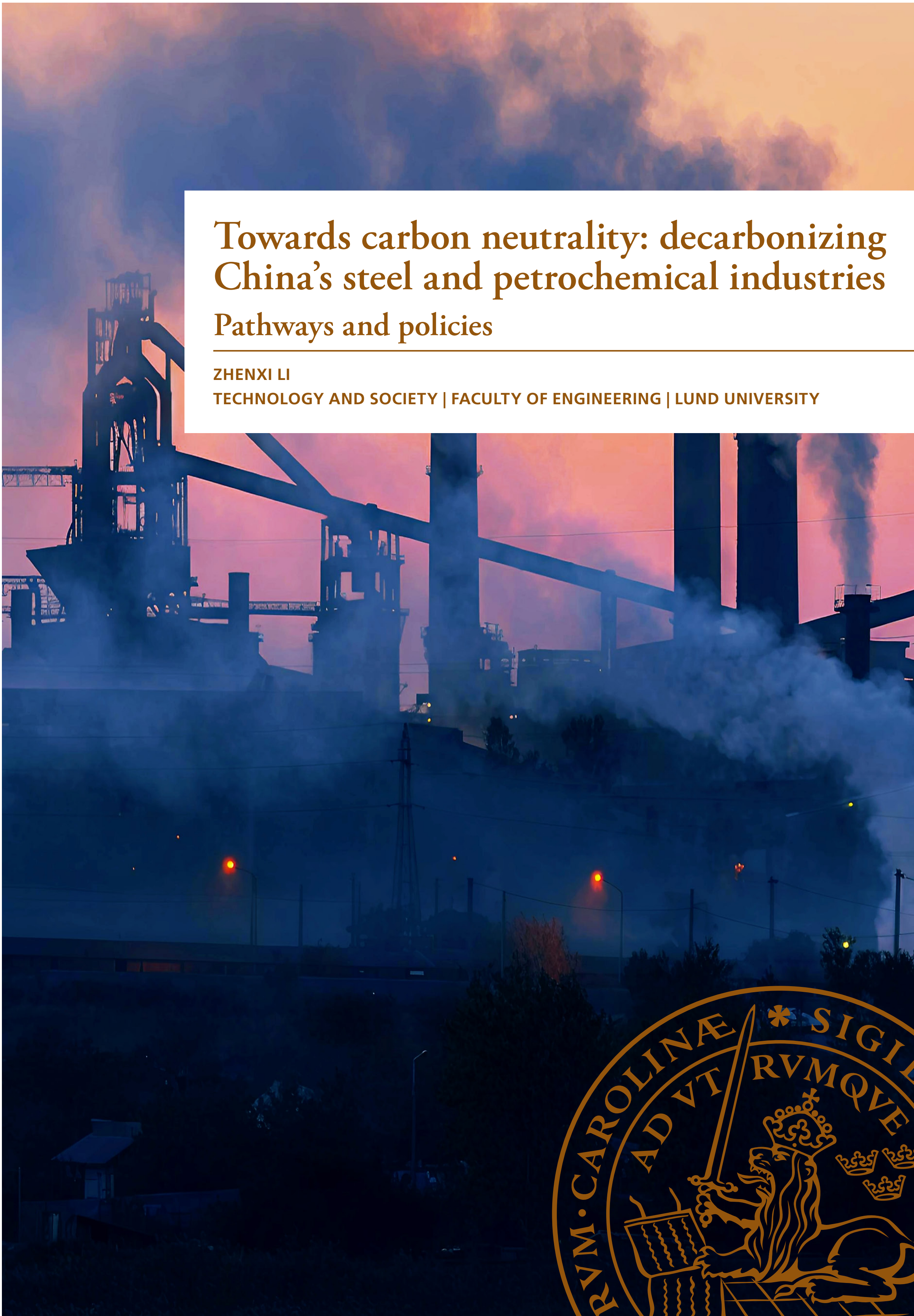

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Pathways and policies

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TECHNOLOGY AND SOCIETY | FACULTY OF ENGINEERING | LUND UNIVERSITY

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Pathways and policies

Zhenxi Li

DOCTORAL DISSERTATION

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Abstract:

Tackling climate change is one of the most pressing challenges of our time. Among the various sectors contributing to global greenhouse gas (GHG) emissions, the industrial sector plays a pivotal role, responsible for 24% of total GHG emissions. As the world's largest emitter of CO_2, China has committed to peaking emissions by 2030 and achieving carbon neutrality by 2060. The industrial sector in China accounts for 36% of China's direct emissions and around 56-60% when indirect emissions are included. In other words, the direct CO_2 emission from China's industry is responsible for approximately 12% of global emissions. Therefore, the decarbonization of China's industrial sector is not only crucial for achieving its own carbon neutrality target but also holds significant implications for global climate governance. However, reaching these targets is particularly challenging for energy-intensive industries such as steel and petrochemicals, due to the technological, economic and political barriers.

This thesis explores how China's steel and petrochemical industries can transition to a carbon-neutral future. It investigates potential technological pathways for achieving deep decarbonization in these sectors and examines the role of policy in facilitating this transformation. Using optimization models, the research identifies potential decarbonization pathways while accounting for economic, social, and geopolitical factors that may influence their adoption. Furthermore, the thesis evaluates the adequacy of China's current green industrial policies in supporting decarbonization in the steel and petrochemical sectors.

Key findings highlight that while technological solutions exist to help China achieve its carbon neutrality goals, deep decarbonization will require significant investments in technology, industrial infrastructure, and robust policy support. Regional disparities, governance structures, and geopolitical factors add further complexity to this transition. The steel and petrochemical industries face distinct challenges, ranging from differences in technological maturity to varying levels of value chain complexity and future demand projections, which will influence their respective decarbonization roadmaps. Overall, the steel industry is expected to achieve faster progress toward decarbonization compared to the petrochemical industry.

Key words: China, steel, petrochemical, carbon neutrality, energy-intensive industry, pathways

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Cover photo by Viktor Mácha (viktormacha.com), named “SIDEX Galati - blast furnace twilight”.

This image symbolizes the twilight of carbon-intensive industry and the author’s hope for a transition toward a low-carbon future.

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To my family

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Popular Summary

Tackling climate change is one of the most pressing challenges of our time. Among the various sectors contributing to global greenhouse gas (GHG) emissions, the industrial sector plays a pivotal role, responsible for 24% of total GHG emissions. This proportion rises to 34% when including indirect emissions. As the world's largest emitter of CO_2, China has committed to peaking emissions by 2030 and achieving carbon neutrality by 2060. The industrial sector in China accounts for 36% of China's direct emissions and 56-60% when indirect emissions are included. In other words, the direct CO_2 emission from China's industry is responsible for approximately 12% of global emissions. Therefore, the decarbonization of China's industrial sector is not only crucial for achieving its own carbon neutrality target but also holds significant implications for global climate governance. However, reaching these targets is particularly challenging for energy-intensive industries such as steel and petrochemicals, due to the technological, economic and political barriers.

The focus of this thesis is on exploring how China's steel and petrochemical industries can transition to a carbon-neutral future. This study investigates the potential technological pathways for achieving deep decarbonization in these sectors and examines the role of policy in facilitating this transformation. By employing optimization models, this research aims to identify potential technological pathways for these industries, considering economic, social, and geopolitical factors that may affect their adoption and implementation. In addition to examining technological pathways, this thesis also assesses the adequacy of China's current green industrial policies for the steel and petrochemical sectors.

Key findings emphasize that while technological solutions are available to help China achieve its carbon neutrality target, deep decarbonization requires substantial investments in technology, industrial infrastructure, and strong policy support. Regional disparities, governance structures, and geopolitical factors add complexity to the transition. Moreover, the steel and petrochemical industries face distinct challenges in their journeys to decarbonization, such as technological maturity, product as well as value chain complexity, and future demand, which will influence their respective decarbonization roadmaps. Overall, the steel industry is expected to progress more rapidly than the petrochemical industry.

This research provides insights into how China's steel and petrochemical sectors can align with global climate goals and achieve carbon neutrality by 2060. The findings are valuable not only to Chinese policymakers but also to businesses, international stakeholders, and researchers involved in industrial transformation for global climate targets. This thesis contributes to the discourse on industrial decarbonization, offering a comprehensive analysis of the pathways, policies, and challenges shaping China's industrial future and its role in global climate efforts.

List of Papers

Paper I
Li, Z., Andersson, F. N., Nilsson, L. J., & Åhman, M. (2023). Steel decarbonization in China–a top-down optimization model for exploring the first steps. Journal of Cleaner Production, 384, 135550. Available at: https://doi.org/10.1016/j.jclepro.2022.135550

Paper II
Li, Z., Åhman, M., Nilsson, L. J., & Bauer, F. (2024). Towards carbon neutrality: Transition pathways for the Chinese ethylene industry. Renewable and Sustainable Energy Reviews, 199, 114540. Available at: https://doi.org/10.1016/j.rser.2024.114540

Paper III
Li, Z., Åhman, M., Algers, J., & Nilsson, L. J. (2025). Decarbonizing the Asian steel industries through green Hot Briquetted Iron trade. Resources, Conservation and Recycling, 219, 108275. Available at: https://doi.org/10.1016/j.resconrec.2025.108275

Paper IV
Li, Z., Åhman, M., Lin, L., Zhang, J., Nilsson, L. J., Lu, H., & Algers, J. Assessing China's green industrial policy: the decarbonization of steel and petrochemical industries [Manuscript]

Author contributions

I am the lead author of all four papers in this thesis, having been involved in every stage of the research process. For *Papers I* to *IV*, I led the conceptualization of the research questions and the design of the overall approach. In the first three papers, I independently conducted the modelling work, performed detailed analyses, synthesized the results, and wrote the drafts of the papers. In *Paper IV*, I contributed significantly to conceptualizing the research, framing the analysis, and was responsible for data analysis and interpretation. I also played a key role in drafting the paper.

Other relevant publications

During my PhD, other related studies were either published or in progress.

Academic papers

Bilici, S., Holtz, G., Jülich, A., König, R., Li, Z., Trollip, H., ... & Meurer, A. (2024). Global trade of green iron as a game changer for a near-zero global steel industry?- A scenario-based assessment of regionalized impacts. Energy and Climate Change, 5, 100161. Available at: https://doi.org/10.1016/j.egycc.2024.100161

Johnson, C., Åhman, M., Nilsson., L. & Li., Z. Emerging green steel markets surrounding the EU Emissions Trading System and Carbon Border Adjustment Mechanism [Under review]

Otto, S., Tönjes, A., Peterson, L., Trollip, H., & Vishwanathan, S., Li, Z., Policy frameworks for the decarbonisation of energy-intensive industries: are they fit for purpose? [Manuscript]

Peng, W. *et al*. Environmental sustainability and decarbonization strategies of global steel industry. [Manuscript]

Acknowledgement

A few years ago, Sweden was a distant and unfamiliar country to me. I never imagined that one day I would study here and earn a PhD. Even now, as I approach the completion of my doctoral journey, it still feels somewhat surreal. While this acknowledgment is meant for my PhD, these four years have been far more than just a degree or the knowledge I have gained—they have been a unique life experience filled with a mix of emotions. Throughout this journey, I have often felt incredibly fortunate to have encountered so many kind and supportive people. I am grateful to everyone who has been part of this experience, whether it was someone I saw every day or just a brief encounter.

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Abbreviations

BF-BOF	Blast Furnace-Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Utilization, and Storage
DRI	Direct reduced iron
EAF	Electric Arc Furnace
EIIs	Energy-intensive industries
ESOM	Energy System Optimization Modelling
FT	Fischer-Tropsch synthesis
GHG	Greenhouse gas
HBI	Hot Briquetted Iron
Mt	Million tonnes
MTO	Methanol-to-olefins
SOEs	State-owned enterprises

1. Introduction

Combating climate change is an urgent global priority, requiring coordinated efforts across nations, industries, and policy frameworks. The Paris Agreement, adopted in 2015 and signed by 194 parties, sets a legally binding framework to limit global warming to well below 2°C above pre-industrial levels, with an aspirational goal of 1.5°C [1]. This agreement has driven many countries to establish carbon neutrality targets as part of their long-term climate strategies. For instance, Sweden announced its goal of achieving carbon neutrality by 2045 in 2017, while New Zealand and France committed to reaching net-zero emissions by 2050 in 2019.

China, the world's largest CO_2 emitter, contributing approximately one-third of global annual emissions in 2023 [2], plays a crucial role in achieving international climate goals. In September 2020, China pledged to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060. This commitment has garnered significant attention. Achieving this carbon neutrality goal requires deep decarbonization[1] across all sectors. In China, the power and industrial sectors are the largest CO_2 emitters, accounting for 48% and 36% of national emissions, respectively, followed by transport (8%) and buildings (5%) [3]. However, when indirect emissions are included, the industrial sector becomes the largest single contributor, responsible for 56-60% of China's CO_2 emissions [4, 5]. These figures are significantly higher than the global average, where direct industrial greenhouse gas (GHG) emissions account for 24% of total GHG emissions, rising to 34% when indirect emissions are included in 2019 [6]. In other words, China's direct industrial sector is responsible for approximately 12% of global CO_2 emissions in 2023[3, 7][2]. Consequently, China's industrial decarbonization has profound implications, both domestically in terms of achieving carbon neutrality and internationally for the success of climate governance and the Paris Agreement.

Energy-intensive industries (EIIs) producing basic materials like steel, cement, and petrochemicals account for 60-80% of industrial emissions [8] and approximately 22% of global CO_2 emissions [9]. In addition, CO_2 emissions from these sectors continue to increase due to rising demand driven by economic development and the

[1] Deep decarbonization here refers to reducing emissions as close to zero as possible.

[2] China's carbon emissions in 2023 totalled 12.6 Gt. Given that the industrial sector accounts for 36% of China's direct emissions, it contributed 4.536Gt of CO_2. With global emissions reaching 37.4 Gt in 2023, China's industrial sector is responsible for approximately 12% of global CO_2 emissions.

absence of effective global climate policies [10]. EIIs are often considered “hard-to-abate” due to their strong “lock-in” in fossil fuels. This “lock-in” stems from technical, economic, and institutional pathway dependencies[10].

Decarbonizing China’s EIIs presents particularly significant challenges. **First**, the scale and complexity of China’s geography and governance pose significant hurdles for nationwide decarbonization. The extensive territory results in regional disparities, leading to varying decarbonization potential and challenges across different regions. In terms of governance, although China is often viewed internationally as a centralized state controlled by the Communist Party, its 34 provinces have considerable autonomy, which results in governance variations that complicate climate governance. **Second**, China’s coal-based energy system (58% coal-derived electricity [11]) hinders the scaling up of electrification (or more specifically, green hydrogen) , a key route to deep industrial decarbonization. The reliance on coal may delay the widespread and cost-effective production of green hydrogen. **Third**, China has a substantial amount of relatively young, carbon-intensive industrial capacity. Phasing out the existing capacity in favor of low-carbon alternatives or retrofitting it with Carbon Capture, Utilization, and Storage (CCUS) would incur substantial costs and stranded capital. These elements present major obstacles to achieving carbon neutrality in China’s EIIs.

Over the past two to three decades, growth has undoubtedly been the defining feature of China’s industry. After joining the World Trade Organization in 2001, China’s GDP experienced explosive growth, accompanied by a rapid expansion of its industrial sector. The industrial added value surged from 4.39 trillion Yuan in 2001 to 39.91 trillion Yuan in 2023, marking a ninefold increase [12]. During this period, China moved from the peripheral of the global industrial system to a central position, becoming the world’s largest producer in key sectors like steel, chemicals, and cement. In addition, its role in the global value chain grew significantly, earning it the title of the “world’s factory”. However, this rapid industrial growth, characterized by high energy consumption and carbon emissions, has resulted in significant environmental and climate challenges, with China surpassing the United States in 2006 to become the world’s largest GHG emitter [13]. With the adoption of the Paris Agreement and its carbon neutrality goal, green development and a low-carbon economy are becoming central to China’s future development agenda. This shift presents both unprecedented pressures and new opportunities for industrial transformation. However, whether a “low-carbon” or even “zero-carbon” industrial sector can become a reality in China over the next 20-30 years remains uncertain.

Building on the above context, investigating the deep decarbonization of China’s EIIs is of critical important. Such deep decarbonization is a systemic shift and a broader sociotechnical transition that entails changes in industry strategies, policy, user behavior, and infrastructure [14], and requires comprehensive and coordinating green industrial policies to help industries to overcome these multiple and complex barriers [8, 15, 16]. As industrial decarbonization is a relatively nascent field, with less than a decade of focused global attention and less than five years since China's carbon neutrality announcement, developing pathways represents a crucial first step. These pathways offer a means of engaging with the future. By outlining various development pathways, we can not only envision potential futures but also analyze the challenges and obstacles that may arise in different contexts. This foresight enables proactive action in the present, informing policy formulation and concerted efforts. Furthermore, these pathways can provide a platform for the business community to consider the necessary policy supports for such a transition [10].

Thus, this thesis explores the potential decarbonization pathways and green industrial policies in China's industrial sector, using the steel and petrochemical industries as case studies. These sectors are key EIIs with some similarities. Both sectors share the need to develop several key future technology systems, such as green hydrogen, direct electrification, and CCUS, for deep decarbonization [17]. However, the sectors differ in raw material, product complexity and future demand trends. The steel industry, with a saturated or declining demand in China [18], relies on scrap or iron ore and produces primarily crude steel. In contrast, the petrochemical industry, where demand is expected to grow in the coming decades [19], relies on seven main feedstock chemicals derived from fossil feedstock to produce tens of thousands of derivative products [9]. The sectors also differ in Scope 3 emissions. For example, post-consumption plastic waste incineration significantly contributes to Scope 3 emissions [20], whereas steel is primarily recycled, resulting in minimal CO_2 emissions. These similarities and differences between the two sectors may lead to corresponding similarities and differences in their decarbonization pathways and associated policies.

Based on the above, this thesis addresses three core research questions:

1) What are the potential decarbonization pathways for China's steel and petrochemical industries to achieve carbon neutrality by 2060 (Q1)?
2) What challenges and obstacles can be anticipated in the transition of these industries towards carbon neutrality (Q2)?
3) Considering the complex interplay of regional disparities, economic, technological, and social dimensions, what policy insights can be derived from analyzing these decarbonization pathways and their associated challenges (Q3)?

These three questions not only allow us to look towards the future (Q1 and Q2) but also help take us back to the present (Q3), enabling us to start making efforts from now to achieve the carbon neutrality goals. The three questions are independent yet interconnected, and thus each of our papers addresses and explains all of them to varying degrees. The framework of the four papers in thesis is shown in **Fig.1**. This thesis is divided into two parts: an analysis of the steel industry and an analysis of the petrochemical industry. ***Papers I*** and ***III*** utilize optimization models to outline potential short-term (***Paper I***) and long-term (***Paper III***) decarbonization pathways for China's steel industry under a carbon neutrality constraint (Q1). By establishing scenarios with varying policy objectives, I examine the impacts of different policies on economic costs, decarbonization pathways, and social factors such as employment, and geopolitical challenges (Q2). ***Paper II*** focuses on the ethylene industry, a key sub-sector of the petrochemical industry. I use an optimization model to explore potential long-term decarbonization pathways (Q1) and analyze potential challenges in achieving carbon neutrality (Q2). These three studies provide a window into potential challenges and required policy support for decarbonization. Finally, ***Paper IV*** adopts a policy analysis approach to assess the challenges and gaps in China's current net-zero industrial policy for achieving the 2060 target (Q2) and to inform the design of future industrial policies aligned with carbon neutrality goals (Q3).

Chapter 1 introduces the research problem and outlines the thesis framework. **Chapter 2** provides an overview of China's steel and petrochemical industries, covering production, carbon emissions, and key policies and mitigation technologies, while also examining the impact of regional differences on decarbonization. **Chapter 3** presents the methodology, detailing the use of optimization models, scenario analysis, and policy analysis. **Chapter 4** presents the results, including key findings and reflections on the methodology. **Chapter 5** is a discussion of the results and **Chapter 6** concludes the thesis by summarizing the main insights.

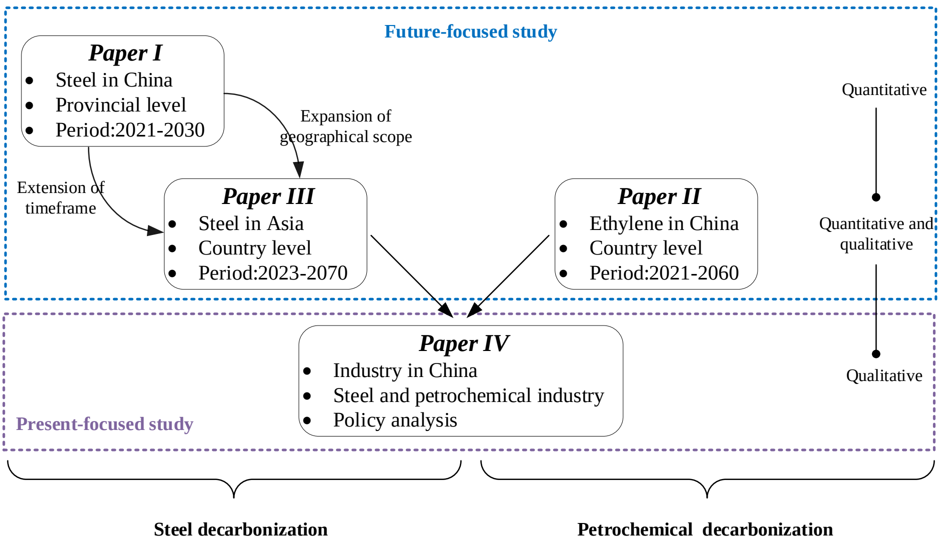


Figure 1. Thesis framework

2. Contextualizing China’s steel and petrochemical industry

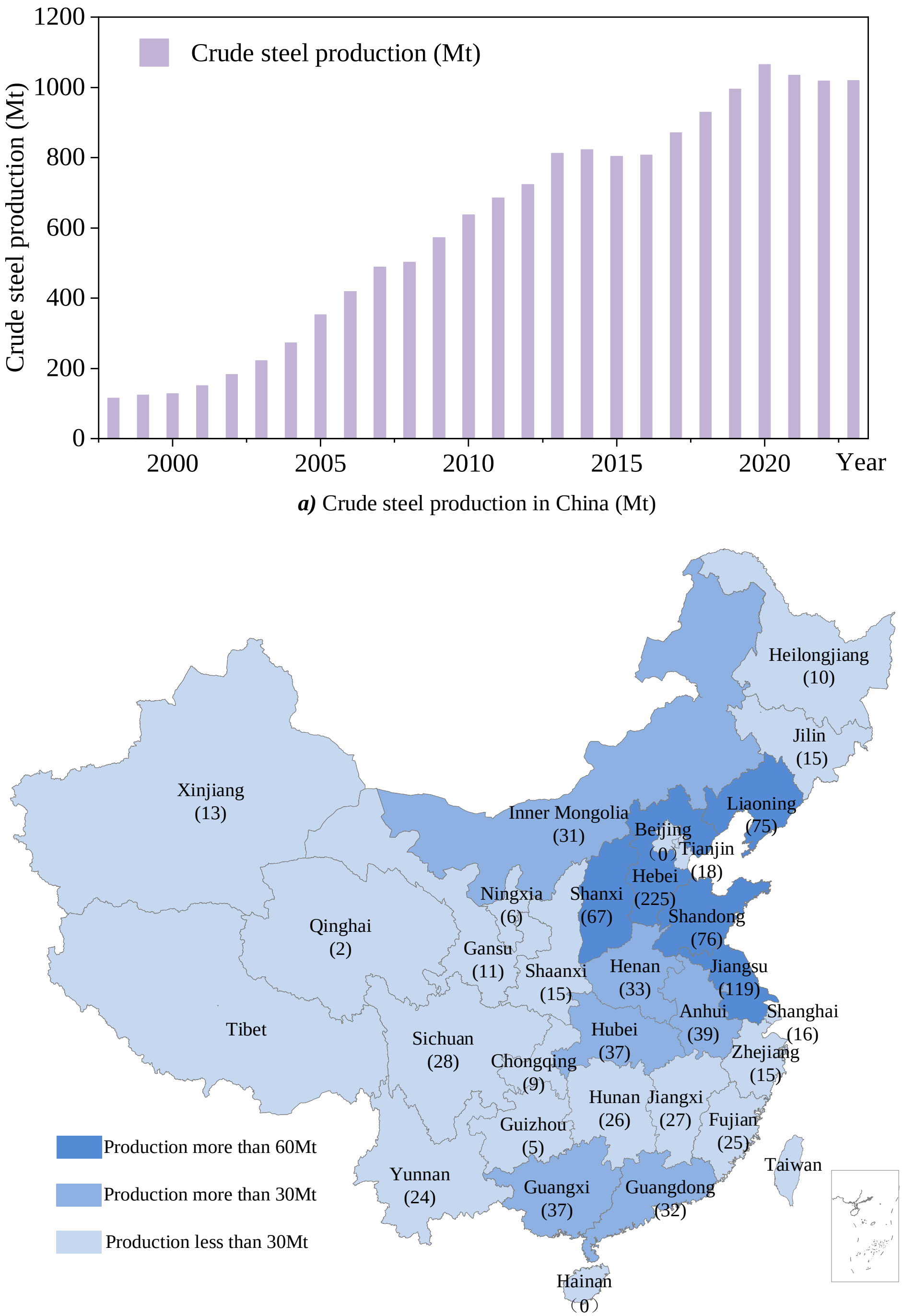
This chapter provides background information on the steel and petrochemical industries in China. **Section 2.1** examines the steel industry, offering insights into steel production, carbon reduction methods, and relevant decarbonization policies. **Section 2.2** then shifts focus to the petrochemical industry, presenting an overview of production, approaches to decarbonization, and relevant policies.

2.1 Decarbonizing China’s steel industry

2.1.1 Background of China’ steel industry: production and CO_2 emissions

China has been the world’s largest steel producer and consumer since 1996 [21]. Following its World Trade Organization accession in 2001, China’s steel production expanded rapidly. In 2023, the nation’s crude steel output reached 1,019 million tonnes (Mt), representing 54% of global production [18]. The vast majority of this steel was consumed domestically; only 8% (83 Mt net exports in 2023) was exported [18]. Steel production is geographically concentrated. In 2021, the top five producing provinces—Hebei (225 Mt, 22% of national production), Jiangsu (119 Mt, 11%), Shandong (76 Mt, 7%), Liaoning (75 Mt, 7%), and Shanxi (67 Mt, 7%)—accounted for 54% of the national total [22]. See **Figure 2** for details.

This substantial steel production generates significant CO_2 emissions, accounting for approximately 15% of China’s national total [23], considerably higher than the global average of 7% [24]. Steel is produced mainly through two routes: primary and secondary steelmaking. The dominant primary steelmaking process is the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route. In this route, iron ore is reduced to hot metal in a BF, which is subsequently transferred to a BOF for crude steel production. Since coking coal serves as the reducing agent in the BF, this route is carbon-intensive, with carbon intensity of approximately 2.1 tonnes CO_2 per tonne steel in China [25]. Another common method is the scrap-based Electric Arc Furnace (EAF), which utilizes EAF to melt preheated scrap. This process has a lower carbon intensity of approximately 1.3 tonnes of CO_2 per tonne of steel produced in China (scope 1 and 2 emissions) [25]. Currently, about 90% of China's steel is produced via the BF-BOF route, with the remaining 10% from scrap-based EAF technology [23]. This EAF production share in China is significantly lower than the global average of 29% [18]. Limited scrap availability, inadequate recycling infrastructure, and high scrap and electricity prices hinder EAF expansion in China [23]. Although China's steel scrap consumption reached 214 million tons in 2023, the majority (72%) was used in the BF-BOF route, with only 28% in EAFs [26]. This utilization pattern contrasts with other countries where scrap steel is primarily used in EAFs. A possible reason for this phenomenon is the overall lower costs of the BF-BOF process compared to scrap-based EAF production [26]. As a result, BF-BOF enterprises are incentivized to increase production by adding more scrap steel during profitable periods. Given that China began large-scale steel production and consumption in the late 19th and early 20th centuries and considering the typical lifespan of steel products (20–30 years), China's steel scrap supply is expected to grow significantly around 2030 [23]. This development could potentially drive the expansion of EAF-based steel production in China.



a) Crude steel production in China (Mt)

b) Provincial steel production in 2021(Mt)

Figure 2. Steel production National and provincial Steel Production

2.1.2 Strategies for reducing CO_2 emissions in the steel industry

Several approaches can be used to decarbonize the steel industry. The scrap-EAF route can achieve near-zero emissions if the EAF is powered by renewable electricity. However, scrap availability is limited and may not fully meet steel production demand, necessitating continued primary steel production. For decarbonizing primary steel, retrofitting existing BF-BOF capacity with CCS is a promising approach, especially given that the average age of BF furnaces in China is around 15 years [3]. A blast furnace is typically designed to operate for at least 25 years, with many remaining operational for over 40 years [27]. Implementing CCS could mitigate the potential stranded asset risks associated with early phase-outs. However, the steel industry has multiple emission sources with relatively low concentrations, making high carbon capture rate both challenging and costly. While CO_2 concentration in blast furnace gas is higher than in other processes like converters, making it a priority for capture, carbon capture in the metallurgical industry remains a high-cost technology [28].

The most promising method for decarbonizing the steel industry involves using a shaft furnace, where green hydrogen serves as the reducing agent to replace traditional blast furnaces. The direct reduced iron (DRI) produced in the shaft furnace is then transferred to an EAF. Over forty projects are in development, particularly in Europe and North America [29]. China is also pursuing similar green projects, led by major state-owned enterprises (SOEs) such as HBIS and Baowu, (details see ***Paper III***). However, cost-effective and easily accessible green hydrogen remains a significant barrier to the development of DRI-EAF. Despite China's significant renewable energy potential in regions like the "Three-North areas" (North, Northeast, and Northwest), the distribution of renewable resources does not fully align with the locations of steel production. As a result, accessing large quantities of low-cost hydrogen is challenging due to the costs associated with hydrogen storage and transportation.

Reconfiguring the value chain of the steel industry could be an effective solution to overcome the barrier of green hydrogen and accelerate the transition to a renewable-based steel industry. One approach involves importing green Hot Briquetted Iron (HBI)—iron ore reduced to iron with renewable hydrogen—from countries rich in renewable resources. This HBI can then be used in domestic EAF to produce steel. While green HBI trading has not yet been fully implemented, it is gaining increasing attention, and several projects are underway [30]. For instance, Baowu has expressed interest in cooperating with potential HBI exporters, including those from Australia, South America, the Middle East, and Africa [31].

2.1.3 Decarbonization policies in the steel industry

Following the announcement of China's 2060 carbon neutrality target, the government established decarbonization targets for various sectors. The steel industry's policy target is to peak emissions before 2030 [32]; however, a sector-specific carbon neutrality target for 2060 is currently absent. Despite an initial signal in 2021 suggesting a 2025 peak in the steel industry [23], the final policy reflects a less ambitious timeline. This delay allows the sector breathing room amidst energy and supply chain security concerns and consolidates a more achievable target for all companies, addressing industry concerns like overcapacity and pollution [33]. Despite the weakened national ambition, some major companies, such as Baowu and HBIS, have adopted more ambitious goals for carbon peaking and neutrality [23], as detailed in ***Paper IV***.

China's current decarbonization policies primarily focus on short-term goals for 2025, including increasing the share of EAF steel production to 15%, enhancing scrap recycling, reducing energy consumption, and restricting new production capacity (see ***Paper IV***). Overcapacity has been a persistent issue in the Chinese steel industry. To address uncontrolled production expansion, the government introduced a "swap policy" in 2015, later revised and strengthened in 2017 and 2021. This policy required provinces adding new BF-BOF capacity to phase out 1.25 to 1.5 times the equivalent existing capacity. New green capacity, such as EAF or hydrogen-based metallurgy, required an equivalent amount of old capacity to be retired. However, in August 2024, the government suspended this policy and prohibited any new capacity additions[3]. This suspension stems from provincial governments prioritizing regional interests and failing to enforce the capacity swap policy, exacerbating overcapacity in BF-BOF production.

The failure to implement the swap policy exemplifies the multi-level governance challenges faced by the Chinese government. While the international community might perceive China's one-party system as conducive to streamlined governance, the reality is far more nuanced. China's governance operates through a top-down, target-based responsibility system: the central government sets targets that are then cascaded down to provincial and lower-level governments for implementation. However, implementation at the regional level can be problematic due to the significant autonomy and distinct agendas of provincial authorities [34]. Climate policy implementation faces several obstacles. First, local legislation, often influenced by regional protectionism, can conflict with central government regulations [35]. Local governments may thus prioritize local regulations over central directives. Second, local leaders' political advancement is often tied to local economic growth [36], incentivizing them to disregard central policies that could hinder economic progress. Finally, limited budgets force provincial governments to

[3] As of the time of writing this thesis, no new actions have been taken by the central government.

prioritize policy implementation, often relegating climate goals to a lower priority. Provincial performance evaluations, based on the performance of lower-level governments, can incentivize collusion between different levels of government [37].

2.2 Decarbonizing China's petrochemical industry

2.2.1 Background of China' petrochemical industry: production and CO_2 emissions

Petrochemicals are a subset of industrial chemicals, as reflected in the full designation of the sector producing them: the "chemical and petrochemical sector". In this thesis, petrochemicals are defined as chemicals derived from petroleum (oil), natural gas, or coal. The petrochemical industry produces tens of thousands of derivative chemicals [9], but seven primary chemicals [4] are essential building blocks. Their production accounts for nearly two-thirds of the sector's total energy demand [38]. The global petrochemical industry is both energy-intensive and high-emission. In 2020, it emitted 1.8 Gt of direct CO_2 equivalents (scope 1) and 3.8 Gt of indirect CO_2eq emissions (scopes 2 and 3), together representing approximately 10% of global GHG emissions [20].

China is the world's largest producer and consumer of petrochemicals [39], leading in the output of ammonia[40], methanol[41], and ethylene [42]. In 2021, it accounted for 43% of global petrochemical production [43], contributing to 47% of the sector's global GHG emissions in 2020 [44]. The petrochemical industry is also responsible for approximately 12% of China's national CO_2 emissions [20].

In addition to the emissions driven by its massive production, the substantial emissions from the petrochemical sector are largely attributed to the significant role of China's coal-chemical industry, which accounted for 5.4% of the nation's total emissions in 2020 [45]. Although oil and natural gas are common feedstocks in the petrochemical industry worldwide, China's petrochemical industry is characterized by its reliance on coal-based feedstocks. Methanol and ammonia are largely produced from coal in China, while gas-based production dominates elsewhere [46]. China produced 83Mt methanol in 2023, with 84% of the production being coal based, 10% from coke-oven-gas and 5% from natural gas [47]. It also had 78Mt ammonia capacity in 2023, with 79% coal-based capacity and 16% natural-gas-based capacity [48]. This situation is similar for light olefin. Naphtha and ethane are the principal feedstocks used to make light olefins, but it can also be produced from methanol using the methanol-to-olefins (MTO) process which is done only in

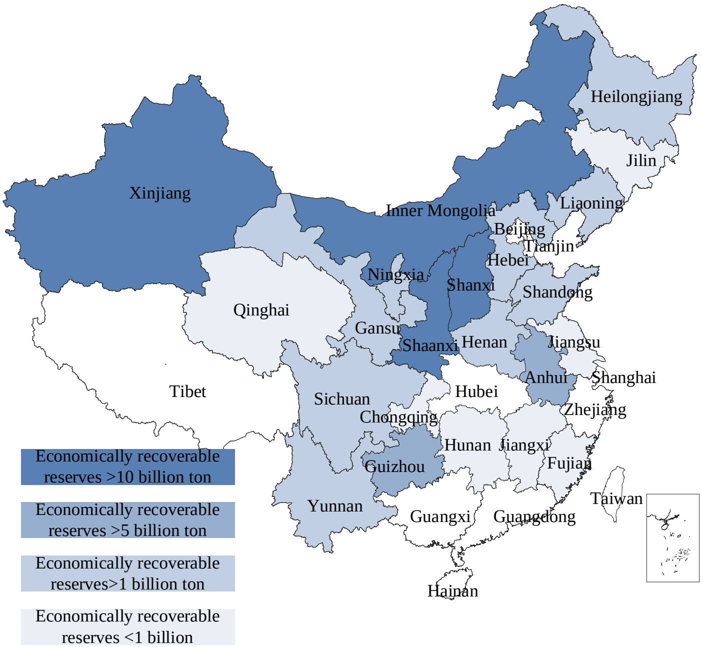
[4] They are: ethylene, propylene, benzene, toluene, mixed xylenes (collectively known as high-value products), ammonia, and methanol.

China. In 2023, China had 19 Mt coal-based MTO capacity [49], which means around 21% of the ethylene is made through this process [20].

The coal-chemical industry is highly carbon-intensive due to coal's higher carbon content compared to other feedstocks, resulting in greater emissions during the production of products with relatively low carbon content [39]. Specifically, coal must first undergo gasification to produce synthesis gas, a process that is highly carbon-intensive [38]. For instance, the carbon intensity of ammonia production from coal-based and natural gas-based routes is approximately 6 tonnes and 3.1 tonnes of CO_2 per tonne of product, respectively, while the carbon intensity for methanol production is 3.9 tonnes and 1.6 tonnes of CO_2 per tonne of product, respectively[50]. CO_2eq emissions from one tonne of naphtha steam-cracked ethylene range from 0.8 to 2.1 tonnes, whereas emissions from coal-based MTO ethylene production range from 5.2 to 11.5 tonnes [20].

The prosperity of China's coal chemical industry is largely driven by the country's abundant coal resources and the government's emphasis on energy security [51]. China is resource-poor in oil and gas but rich in coal [52]. Energy security has long been a central concern for the Chinese government. Historically, China relied heavily on crude oil and petroleum products from the Soviet Union since its founding in 1949, but following the Sino-Soviet split in the early 1960s, the Soviet Union halted its oil supply to China, leading to significant economic disruptions [53]. As a result, energy security became a key priority for China's decision-makers from the late 1990s [54]. Geopolitical factors further intensify these concerns. China imports a large volume of oil from the politically unstable Middle East, with most tankers passing through the Malacca Strait, a piracy-prone area heavily patrolled by USA forces. Given the sensitive relationship between the USA and China, these factors exacerbate energy insecurity, even as China diversifies its import sources [55].

The petrochemical industry's heavy reliance on fossil fuels means its geographical location is largely determined by resource endowments. Consequently, coal-to-chemical projects are primarily concentrated in coal-rich regions in northern and western China (see **Fig. 3(a)** for the geographical distribution of coal reserves). In 2017, the Chinese government designated four coal-chemical-demonstration areas in these provinces (see **Fig. 3(b)**) [45]. Conversely, China's non-coal-based petrochemical capacity is closely linked to refinery placement, which is mainly concentrated in coastal provinces. China imports large amounts of oil through these coastal regions and refines it there. Over three-quarters of the production capacity for high-value products is owned by and located near refineries [38], demonstrating a form of industrial symbiosis. **Fig.3(b)** illustrates the locations of the top 30 chemical industrial parks in 2023 [56], as well as the 7 petrochemical bases established by the Chinese government since 2015 [57], which allows us to identify the distinct geographical distributions of coal-based chemical and petrochemical production.



a) Economically recoverable reserves of coal in 2020

b) The numbers of the top 30 chemical industrial park in different provinces in 2023 and 7 main petrochemical bases

Figure 3. Geographic Distribution of Coal Reserves and major Chemical Industrial Parks and Bases in China

2.2.2 Strategies for reducing CO_2 emissions in the petrochemical industry

The petrochemical industry produces a diverse array of products; however, there are several general decarbonization strategies shared across different primary products. Incremental approaches, such as switching the feedstock from coal to natural gas, improvements in energy efficiency, could help decarbonize the petrochemical industry, but the mitigation potential is limited. Thus, breakthrough technologies, such as CCUS, direct and indirect electrification (e.g., green hydrogen), and bioenergy routes are essential.

CCUS can play a critical role in transforming primary petrochemical production. Retrofitting China's existing petrochemical capacities with CCUS offers several advantages. First, it mitigates the risk of stranded assets associated with phasing out relatively new infrastructure. The average age of China's facilities is around 15 years for ammonia, 10 years for methanol, and 9 years for ethylene, while their typical lifespan is 30 to 40 years [39]. Second, China possesses substantial coal-to-chemical capacity, which produces CO_2 at a higher concentration than power plant flue gas, making capture more cost-effective [58]. Captured CO_2 can be stored (CCS) or used (CCU) to produce CO-rich syngas, which, combined with green hydrogen, can create new petrochemicals. Additionally, CO_2 can be converted into the targeted C-based product, but it requires the development of a new chemical industry, organic chemistry, and catalyst [59].

Electrification, or green hydrogen, is another promising low-carbon technology. Green hydrogen can be produced through water electrolysis powered by renewable electricity, and then combined with captured CO_2 (from point sources or through Direct Air Capture) to produce chemicals [59]. Alternatively, green hydrogen can be used directly to produce carbon-free chemicals like ammonia. By replacing the source of hydrogen with low-carbon or renewable alternatives, low-carbon or even zero-emission production can be achieved.

Biomass utilization also offers a promising decarbonization pathway. Biomass contains the necessary carbon, hydrogen, and energy for chemical synthesis [59]. The biomass pathway achieves net-zero CO_2 emissions by capturing CO_2 from the atmosphere during biomass growth and releasing it during product synthesis and end-of-life. However, biomass feedstocks have less favorable chemical structures than fossil fuels, characterized by higher water content and lower energy content [59]. Furthermore, limited biomass resources and procurement challenges in China suggest that biomass-derived chemicals may remain expensive in the long term [39].

The technologies discussed above can achieve zero-carbon emissions during production. However, some chemical products generate significant Scope 3 emissions from consumption or post-consumption phases, such as plastic waste incineration. While breakthrough technologies can decarbonize fossil-based light olefin production (the raw material for plastics), the carbon atoms contained in the plastic is released as CO_2 during waste incineration, leading to unavoidable emissions[5]. Therefore, carbon recycling and implementing CCS at incineration plants are crucial. However, for plastics, the most critical measures remain reducing consumption and increasing recycling rates until breakthrough technologies become widely available and cost-effective at scale [44].

2.2.3 Decarbonization policy in the petrochemical industry

Unlike the steel industry, with its defined 2030 emissions peak target, the national petrochemical policy lacks a clear timeline for peak emissions [20], let alone long-term carbon neutrality. Despite this national vagueness, some provinces, such as Fujian [60] and Jiangsu [61], have established their own petrochemical peak emissions targets for 2030. Similar to the steel industry, overcapacity plagues certain petrochemical sectors, particularly traditional coal-based petrochemicals. The coal chemical industry comprises two distinct branches: traditional and modern. Traditional coal chemistry encompasses processes like coal-to-coke, coal-to-calcium carbide, coal-to-methanol, coal-to-ammonia, coal-to-urea, and coke-oven gas-to-methanol [58, 62]. Modern coal chemistry, an emerging field, uses coal to produce alternative petrochemical products (primarily olefins and ethylene glycol) and coal-based fuels (e.g., oil and natural gas) [63]. While traditional coal chemistry already suffers from overcapacity, leading to policies restricting new production, modern coal chemistry has experienced rapid expansion. However, since 2023, the Chinese government has moved to curb the unregulated growth of the modern coal-to-chemical industry, promoting instead the integration of these processes with green hydrogen and CCUS to mitigate CO_2 emissions [64]. Moreover, national short-term decarbonization policies also aim at reducing CO_2 emissions from the petrochemical industry focus on limiting new capacity, reducing energy consumption, developing low-carbon technologies, and increasing recycling rates. These policies are summarized in ***Paper IV***.

[5] Although non-fossil-based plastics emit CO_2 when incinerated, their lifecycle carbon emissions are neutral. With end-of-life treatment incorporating CCUS, the overall process can achieve negative emissions.

3. Methodology

3.1 Optimization model in energy and industrial system

Optimization means the selection of the optimal solution for given variables from a set of alternatives while meeting the given constraints. The selection criteria are a suitable selected function, called the objective function. Optimization models have long been the backbone of energy systems modelling [65], owing to the detailed techno-economic structure and the ability to analyze national policies [66]. Energy systems are defined as the process chain (or a subset of it) from the extraction of primary energy to the use of final energy to supply services and goods, or the combined processes of acquiring and using energy in a given society or economy [65]. We consider industrial systems as a subset of energy systems in this thesis, as industries consume a significant amount of energy. Sustainable energy system planning faces three dilemmas: minimizing environmental impact (such as CO_2 emissions), ensuring energy security (such as meeting demand), and maintaining affordability (such as cost) [67]. These interrelated challenges highlight the necessity of analyzing emissions reduction targets not only from an environmental perspective but also in the context of energy security and affordability [66]. In this regard, the optimization paradigm plays a crucial role by incorporating cost, environmental constraints and energy security constraints to determine the optimal energy mix. In short, Energy System Optimization Modelling (ESOM) can operationalize the three central objectives of energy trilemmas as follows: *a)* affordability: minimize total system costs; *b)* environmental goals: diminish total GHG emissions; *c)* energy security: satisfaction of demand plus model-specific constraints [66].

ESOM can be categorized based on different criteria [66]. For example, in terms of geographic coverage, ESOM can be classified into local, national, regional, and global scales. ***Paper I*** in my thesis presents a local-national scale model, focusing on the provinces of China; ***Paper II*** is a national scale model, focusing on China as a whole; and ***Paper III*** explores a national-regional scale, covering eight jurisdictions in Asia. Regarding the time horizon, ESOM can be classified into short-term, mid-term, and long-term. ***Paper I*** focuses on the short-term, while ***Paper***

II and ***III*** are long-term studies. In terms of the analytical approach, model [6] is typically classified as bottom-up, top-down, or hybrid. Among these, bottom-up models are the most commonly used in optimization because they provide detailed technical specifications and descriptions [65]. Top-down models, on the other hand, are primarily used for macroeconomic and general equilibrium modeling based on econometrics [67]. However, this top-down logic can also be applied to optimization models. ***Paper I*** in my thesis employs a hybrid approach or logic [7], where the top-down aspect involves the allocation of national emission reduction targets to individual provinces, and the bottom-up aspect focuses on how provincial technical decarbonization pathways can meet the national targets. ***Paper II*** and ***III*** by contrast, are entirely bottom-up based.

The fundamental purpose of modelling is to help understand the future, to support planning or adaptation [68]. Energy system optimization models are widely recognized as powerful tools for supporting decision-making in climate and energy policy [66, 69, 70] . The value of energy system modeling lies in highlighting policy implications rather than providing absolute numbers—offering insights rather than definitive answers [70]. Their appeal to policymakers stems from their ability to (*a*) represent a quantitative method that yields specific recommendations, (*b*) ensure economically optimal solutions under existing conditions, (*c*) enable the forecasting and exploring of optimal future systems based on incorporated assumptions, and (*d*) avoid emotional biases and irrationality [69].

ESOM also comes with certain challenges and drawbacks. Transparency and uncertainty are two major challenges [65]. One drawback of ESOM is the lack of transparency in the model structure, as the inner workings of the model cannot be described in detail. Increasing modeling transparency, specifically, making the model publicly available, including the source code, used data, and documentation of the model structure, has been proposed as a strategy to address the opacity of model structures [66]. Uncertainty is another significant challenge in energy system optimization [66]. For example, uncertainty in energy prices affects industrial transformation, with GHG emissions potentially fluctuating significantly in response to changes in fuel prices. Technological maturity and cost also play a role in industrial transformations, such as whether affordable CCUS can be successfully scaled up in the future, which will directly influence the selection of future decarbonization pathways and overall emissions. In such cases, sensitivity analysis can be implemented to explore key parameters' impact on model outputs. A good

[6] Note that here we are referring to energy system models rather than energy system optimization models, as we aim to provide a broader picture for readers to better understand the top-down and bottom-up approaches.

[7] Although *Paper I* emphasizes the top-down approach in its title, the optimization model employed is in fact bottom-up. We chose to highlight "top-down" to reflect the governance structure in which national targets are allocated to provinces.

sensitivity analysis can mitigate overconfidence in the results by delineating the boundaries of the outcome's usefulness [71]. Apart from sensitive analysis, modeling can also articulate in non-technical terms the fundamental forces that shape the results and characterize the uncertainty surrounding those findings [71]. Finally, other solutions including stochastic programming, and Monte Carlo analysis could also reduce uncertainty [66, 70]. These methods typically address uncertainty by incorporating probability distributions into model inputs, parameters, and structures, leading to a range of possible outputs around a "best-guess" estimation [68]. However, when facing a future fraught with uncertainties driven by climate, technological, socio-economic, and political changes, along with corresponding policy and societal responses, the premise of identifying a single "best-guess" output may no longer be feasible or suitable [68, 72]. Instead, multiple plausible futures need to be considered, and scenario analysis provides a structured approach to exploring them [68].

3.2 Scenarios analysis

Scenarios are possible futures that are built up from a consistent set of assumptions [73]. The use of scenarios, originally developed in military planning and simulations, was extended in the early 1960s to strategic planning in businesses and organizations, where decision-makers sought to systematically analyze the long-term implications of investment and other strategic decisions [74]. The goal of working with scenarios in ESOM is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures [74, 75].

There is no consensus on the classification of scenarios, as different typologies exist. However, several typologies reflect the view that futures studies explore possible, probable and/or preferable futures [76]. Börjeson et al. [76] proposed a typology that categorizes scenarios based on the questions the users seek to answer: (a) What will happen? (predictive scenarios), (b) What can happen? (explorative scenarios), (c) How can a specific target be reached? (normative scenarios). Each category is further divided into two subtypes (see **Fig.4** for details). **Predictive scenarios** are categorized into two types based on their conditions for future developments. *Forecasts* address the question: what will happen if the likely development unfolds? *What-if scenarios* explore: what will happen under specific conditions? **Explorative scenarios** are divided into *external scenarios* and *strategic scenarios*. *External scenarios* respond to the user's question: What can happen to the development of external factors? *Strategic scenarios* respond to the question: What can happen if we act in a certain way? Explorative scenarios resemble what-if scenarios. However, unlike what-if scenarios, they adopt a long-term perspective, allowing for structural transformations. They often start from a future state rather than the present. **Normative scenarios** consist of two different types, distinguished by how the system structure is treated. *Preserving scenarios* respond to the question: How can the target be reached, by adjustments to the current situation? *Transforming scenarios* respond to the question: How can the target be reached, when the prevailing structure blocks necessary changes?

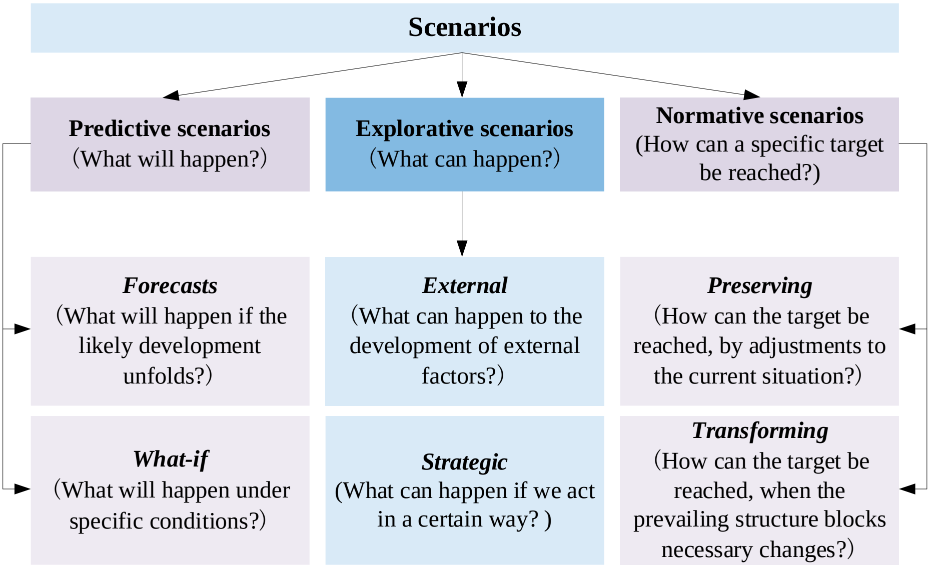


Figure 4. Scenarios classification based on Börjeson et al. [76].

In the first three papers, I employ three types of scenario analysis. ***Paper I*** examines how different provinces should adjust their steel production capacities to meet the national 2030 decarbonization targets for the steel sector. Two policy scenarios are constructed: one where the government prioritizes minimizing air pollution impact, and another where cost minimization is prioritized. This allows for an analysis of how various policy preferences influence regional capacity allocation. The scenarios in this paper are primarily *what-if scenarios*, as the study explores the impacts of different policy choices on regional capacity—addressing the central question, "What will happen if different policies are adopted?" Since the study focuses on short-term outcomes, it falls under *what-if scenarios* rather than *explorative scenarios*. ***Paper II*** examines the decarbonization pathways of China's ethylene industry under three policy scenarios: ambitious climate policies, aggressive plastic policies, and integrated actions. These scenarios explore how policy orientations shape technological pathways, cumulative emissions, and other key factors. Thus, the paper primarily employs a normative scenario approach while integrating explorative elements. The normative aspect is reflected in ensuring all pathways align with the carbon neutrality goal, answering “How can the target be reached?” Meanwhile, the explorative aspect emerges in analyzing variations in technological roadmaps, emissions, and costs under different policies scenarios, aligning with “What will happen under specific conditions?”. ***Paper III*** investigates how green HBI trade influences steel decarbonization in Asia through four scenarios: HBI trade, No HBI trade, Rapid grid decarbonization, and Paris-compliant scenario. These scenarios assess how HBI trade and varying decarbonization ambitions shape steel technological pathways, all constrained by a carbon neutrality target between 2050 and 2070. This study primarily employs explorative scenarios but incorporates normative elements—the former explores “*What can happen if HBI trade is introduced or stronger climate actions are implemented?*”, while the latter focuses on “*How can the target be reached?*”

In practice, distinguishing between normative and explorative scenarios is often challenging, as narrative framing could influence classification. For instance, if I reframe ***Paper II***’s focus from achieving carbon neutrality to how different policies shape decarbonization pathways, it will shift from a normative scenario approach to an explorative scenario with normative elements. Indeed, combining these approaches is common. As Vliet et al. [77] highlight, a combined backcasting and exploratory scenario approach leverages exploratory scenarios as external socio-environmental contexts, and by backcasting within different exploratory scenarios, key uncertainties in major drivers are considered, allowing for a robustness analysis of strategies. For example, my second paper demonstrates that CCUS is not a viable option for ethylene decarbonization, as it is absent in all mitigation pathways.

3.3 Policy analysis

The uncertainty of the future makes policymaking challenging, as different policy options have diverse and far-reaching impacts, and various groups evaluate their value differently. However, public policymakers have a responsibility to develop and implement policies that are most likely to promote citizens’ health, safety, and well-being. Under high uncertainty and limited data, identifying key policy issues is already a difficult task. Without analysis, policy decisions often rely on intuition and guesswork, potentially leading to regrettable outcomes [78]. Thus, undertaking public policy analysis is necessary.

Policy analysis is a multidisciplinary inquiry aimed at generating, critically assessing, and communicating policy-relevant information [79]. It originated from operations research in the late 1940s and 1950s, evolved into systems analysis in the late 1950s and 1960s, and ultimately became a problem-oriented approach to governmental decision-making in the 1960s and 1970s [80]. Rather than replacing policymakers' judgment, policy analysis seeks to strengthen it by clarifying problems, identifying alternatives, and comparing their consequences in terms of costs and benefits [80]. Thus, policy analysis not only describes and explains the causes and consequences of policies but also engages with policymakers through normative evaluations of what policies should be [79].

Policy analysis is not a way of solving a specific problem but is a general approach to problem solving. Instead of relying on a single methodology, it integrates multiple methods within a broader analytical framework [80].Therefore, in ***Paper IV***, I employed Nilsson's [81] green industrial policy analysis framework, combined with a literature review and interviews, to analyze China's green industrial policies.

Green industrial policies are considered key to accelerating climate action [82], as decarbonization of energy-intensive industries requires overcoming multiple and systemic barriers and breaking the dependence on fossil fuels and feedstock [10, 16, 83]. This is especially true for the extremely carbon dependent steel and petrochemicals industries [9, 84]. Decarbonization of energy-intensive industries requires breaking their dependence on fossil fuels, addressing technical, economic and institutional path dependencies [10, 16]. **Technical path dependency** is evident, as industrial production remains heavily reliant on the fossil fuels infrastructure for both energy and feedstock. Breakthrough technologies are essential since the Best Available Technologies cannot fully decarbonize the sector [84]. Most breakthrough technologies remain in the pilot or demonstration stage and will struggle to compete with traditional processes, which have evolved into highly energy-efficient, complex, and integrated systems [16]. **Economic barriers** also hinder decarbonization. Energy-intensive industries require substantial capital investment and have long asset lifespans, making major technological transformations and investments in low-carbon processes infrequent and the industry risk averse [14]. Additionally, large industrial sites—including access to power grids, gas pipelines, harbors, and railways—are developed for existing fossil technologies [10]. Shifting production processes will render most of this infrastructure obsolete, requiring substantial investment in infrastructure for e.g. renewable energy technologies and Carbon Capture, Utilization, and Storage (CCUS) [84]. Finally, most low-carbon products will remain more expensive than fossil-based alternatives unless carbon emissions are properly priced. **Institutional inertia and political barriers** further lock industries into existing carbon-intensive technologies. Energy-intensive industries have developed many decades, and have influential lobbying groups, primarily composed of industry associations with close ties to policymakers [14]. These groups exert significant regional political influence due to EIIs' economic and employment contributions and typically adopt conservative positions, and they oppose regulations perceived as a threat to the current competitiveness [14]. Furthermore, the international trade dynamics of these industries often raise concerns about competitive disadvantages, leading to exemptions from strict national climate policies [16].

4. Results and methodological reflection

4.1 Steel decarbonization (Paper I, III and IV)

(1) Paper I: Short-term steel decarbonization at provincial level in China: minimizing cost or air pollution impact?

The steel industry is a major contributor to emissions of CO_2 and key air pollutants. Reducing air pollution has been a policy priority in China in the past decade. Reducing CO_2 emissions has more recently also become a key priority partially manifested through the signing of the Paris Agreement in 2015 and China's carbon neutrality commitment. In 2021, the Chinese government unofficially indicated its short-term steel decarbonization targets: to peak CO_2 emissions in 2025 and reduce them by 30% by 2030. However, the official target eventually reduced its ambition to the 2030 carbon peaking goal. In the short term, reducing steel production capacity or replacing traditional BF-BOF capacity with scrap-based EAF capacity can simultaneously reduce air pollution and CO_2 emissions. Since different policy preferences may influence provincial actions, the key question is: which provinces should implement these measures under varying policy preferences? In China, the central government sets national targets and then assigns targets to provincial and lower levels governments for implementation. Since phasing-out capacity will have negative effects on provincial GDP and local employment, provincial governments may engage in nominal compliance while acting contrary to the central directives. In fact, the persistent issue of overcapacity in China's steel industry is largely the result of the strategic game between the central and provincial governments. The above is the starting point for this research.

Based on the above, ***Paper I*** developed an optimization model to analyze how different policy preferences in scenarios, focusing on cost minimization or air pollution impact minimization, will affect geographical distribution of steel capacity and provincial decarbonization strategies. We first provided provincial decarbonization pathways (See **Figure 5**) and then analyzed the factors required for emission reductions, such as scrap demand, and the social factors that may arise, such as the impact on local air pollution, under different policy contexts. Finally, a sensitivity analysis was provided. All the above is based on the assumption that

China’s steel industry could peak carbon emissions by 2025 and achieve a 30% reduction in carbon emissions by 2030. We aim to assess whether this ambitious target is feasible and explore the potential conditions in technical, economic, and policy-related aspects for its achievement.

The results indicate that China’s steel industry can peak CO_2 emissions in 2025 and achieve a 30% reduction by 2030, which may suggest that current carbon reduction policies in the steel sector are relatively weak. To meet this target, scrap availability will be a significant challenge, with an estimated need to import at least 68-76 Mt of scrap annually from 2026 to 2030. Therefore, trade may play a crucial role in steel decarbonization. The paper also emphasizes the importance of policy balance. Although the total cost remains nearly the same across all scenarios, a strategy focused on minimizing costs could reduce CO_2 emissions by an additional 68–148 Mt, compared to a strategy focused on reducing air pollution impact. On the other hand, prioritizing reduced air pollution impact as the primary objective leads to 22–26% less air pollution impact compared to the minimized mitigation cost strategy. Furthermore, different policy strategies will result in varying geographical distributions of primary and secondary steelmaking capacity, due to regional heterogeneity. This, in turn, will affect local economies and lead to different effects in different provinces, such as scrap demand.

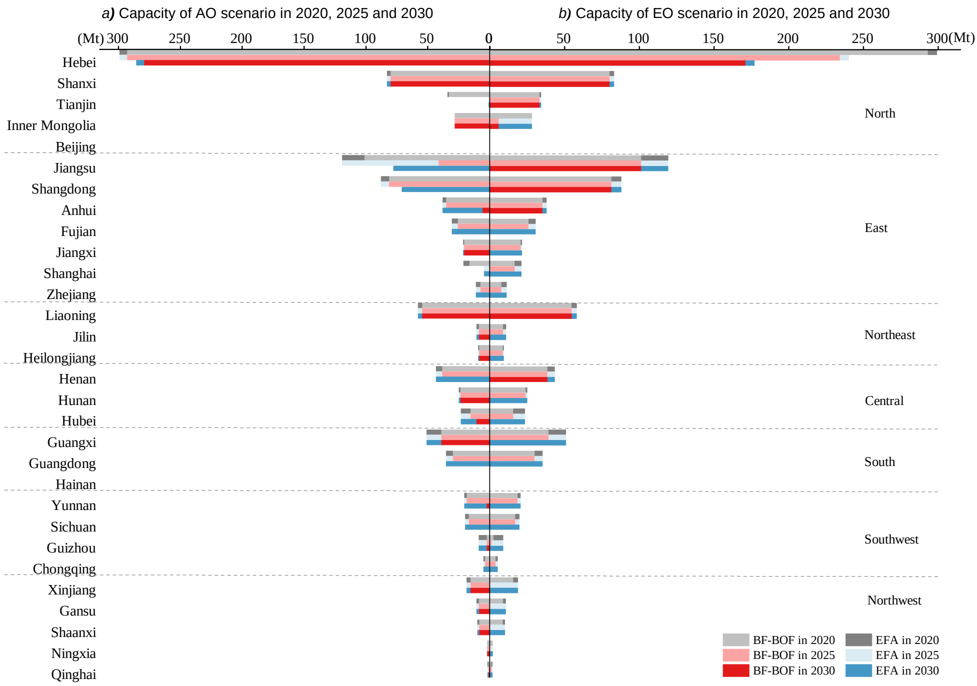


Figure 5. Result from *Paper I* : Comparison of capacity in 2020, 2025 and 2030 in EO (Economic objective model) and AO (Air pollution impact objective model) of BAU (Business As Usual Scenario).

(2) *Paper III: Long-Term decarbonization in the Asian steel industry: to trade or not to trade?*

Paper I highlighted the significance of trade and the impact of regional heterogeneity on steel decarbonization. This provides inspiration for ***Paper III***, where we broaden our research focus from China to the entire Asian region and extend the study's scope to a more comprehensive, long-term perspective. The Asian steel industry accounts for 73% of global production and is expanding. Similar to China, many large steel-producing countries in Asia either have significant BF-BOF capacities or plan to invest heavily in them. In addition, power systems in Asian countries are predominantly coal-based, and decarbonizing the grid will take considerable time, potentially delaying the availability of green H-DRI, which is the current most promising green technology. These factors will affect the pace of steel decarbonization in these countries and deepen their carbon lock-in. Importing green HBI, iron ore reduced with renewable hydrogen, from renewable-rich countries such as Australia, Brazil, and South Africa could be a viable solution to overcome constraints related to access to renewable energy. This concept is gaining popularity, with several projects currently in the pipeline. The above is the background of ***Paper III*** (see **Figure 6**).

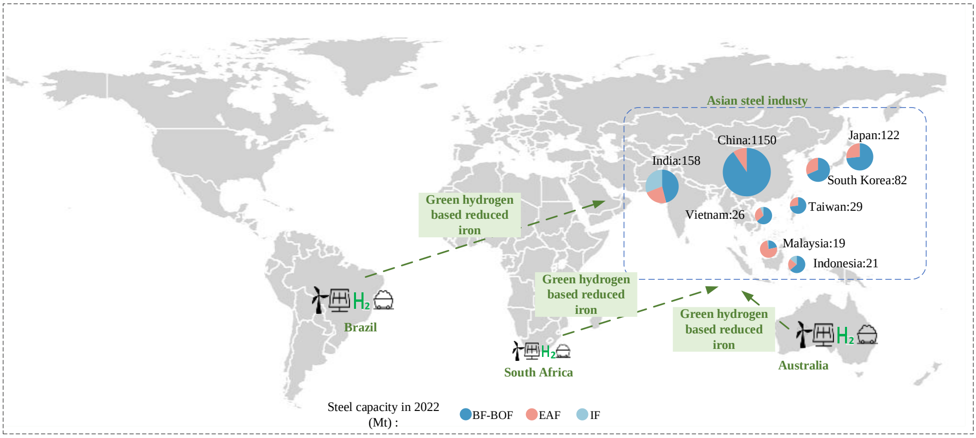


Figure 6. Graphical Abstract for *Paper III*

Therefore, ***Paper III*** examines the effects of green-HBI trade from Australia, Brazil, and South Africa, along with steel decarbonization strategies for the top eight Asian steel producers. We develop a cost optimization model, spanning from 2023 to 2070, to study how the implementation of green HBI trade will affect the eight Asian jurisdictions in achieving their Nationally Determined Contributions and the Paris Agreement targets. We outline four scenarios based on the presence or absence of HBI-trading, as well as varying climate ambitions related to grid power decarbonization and steel industry emissions. Given the long-term nature of the model that the significant uncertainties are involved, we discuss the challenges and opportunities green HBI trade might present to Australia, Brazil, and South Africa in areas such as iron ore, renewable electricity, green hydrogen, and labor force. Additionally, we also presented the geopolitical barriers faced by the Asian region in facilitating HBI trade.

The study showed that green HBI trading can help the Asia ease and speed up the transition to a renewables-based steel industry: it helps Asian steel industry avoid the barrier of limited speed to scale up renewables, reduce cost, and total cumulative CO_2 emissions, thus mitigating the global temperature increases. Specifically, even though the total cost is similar, scenarios with green HBI trade could reduce 2-4% compared with the scenario without HBI trade. In addition, HBI-trade could accelerate the phase-out of BF-BOF steel by 2 to 5 years and reduce BF-BOF steel production by 2 Gt, thus lowering the cumulative CO_2-emissions from the steel sector by 4 Gt (see **Figure 7** for the technological pathways). Consequently, current plans to expand BF-BOF capacity may lead to stranded assets when steel is decarbonizing. These insights might help industries and policy makers to redirect their focus in their investment plans of BF-BOF.

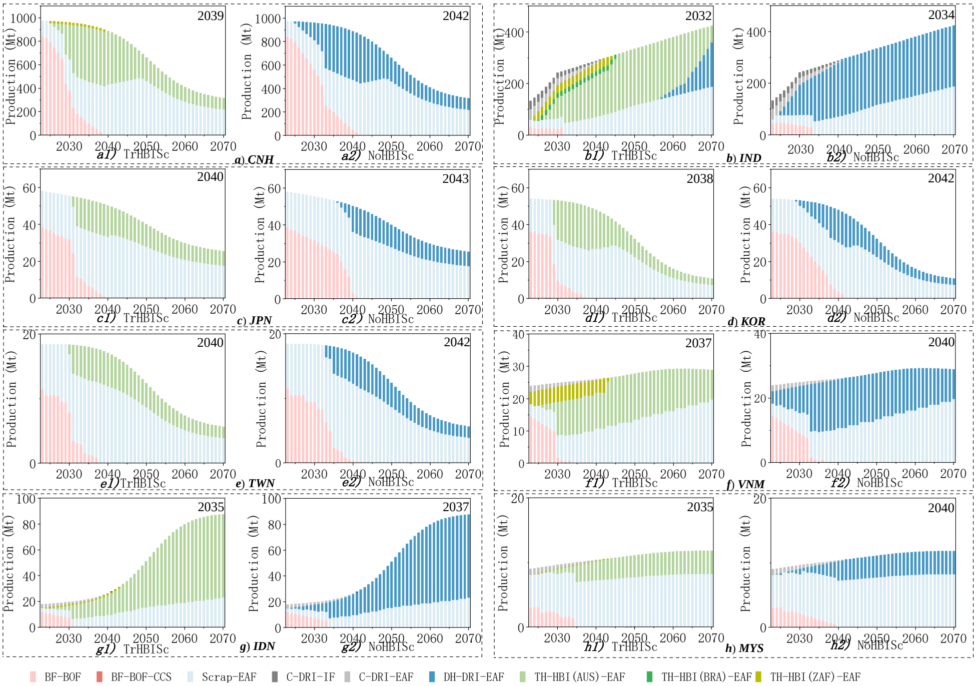


Figure 7. Result from *Paper III*: Steel production pathways in TrHBISc (Traded green HBI scenario) and NoHBISc (No trade HBI scenario)

(3) Paper IV: Back to the present: are existing green industrial policies sufficient for decarbonating the steel industry deeply?

Paper I and ***Paper III*** demonstrate that achieving carbon neutrality in the steel industry is feasible from a technical-economic perspective. However, the scenarios described in papers will not occur spontaneously; they require policy intervention to overcome technological, economic and political barriers. Understanding existing policies, assessing whether they are sufficient to facilitate carbon neutrality, and identifying their potential challenges are thus important. This insight inspired ***Paper IV***.

In ***Paper IV***, we employed qualitative analysis, to assess China's current green industrial policies on deep decarbonization in the steel and petrochemical industry, and how the future industrial policies could be designed and utilized to accelerate and achieve the carbon neutrality goal. The framework we adopted from Nilsson et al. [81] which relies on six pillars: directionality, knowledge creation and innovation, creating and reshaping markets, building capacity for governance and change, international coherence, and sensitivity to socio-economic implications of phase-outs.

The results regarding to the China’s steel industry are as follows: China’s green industrial policy for the steel sector has begun to take shape but remains insufficient to achieve carbon neutrality. While the country has established a clear directionality for carbon neutrality, the steel industry lacks long-term, specific policies, which may weaken this directionality. Among steel companies, state-owned enterprises have taken the lead in defining clear pathways, often setting more ambitious targets than national goals. In terms of knowledge creation and innovation, China has launched several pilot steel decarbonization projects, primarily led by SOEs. Among these, hydrogen-based reduction, whether through direct reduction or hydrogen injection into blast furnaces, has progressed further in both the number of projects and their maturity compared to CCUS projects. Despite some policies aimed at market creation and reshaping, their impact has been limited. Most policies are the production regulation, while market pull polices remain largely absent. Regarding phase-out policies and their social implications, China has implemented phase-out policies for the steel industry. However, these policies are not driven by climate concerns, and their implementation has been weak. Additionally, unemployment in the sector may worsen during the decarbonization process.

4.2 Petrochemical decarbonization (Paper II and IV)

(1) Paper II: What are the potential decarbonization pathways for China’s ethylene industry to achieve carbon neutrality?

Paper II developed an optimization model to explore potential long-term carbon reduction pathways for the ethylene industry in China. Ethylene is a valuable research subject for several reasons. First, it is one of the seven major primary products in the petrochemical industry. Additionally, ethylene is a key raw material for plastic production, and plastics have a very long and complex value chain, which includes primary production, compounding, converting, recycling, and waste incineration. Research on the long-term carbon reduction pathways of the ethylene industry in China remains relatively scarce. This is likely due to technological complexity and the high uncertainty in long-term studies, such as those related to technology choices and future policy orientations. Therefore, ***Paper II*** aims to address this research gap by exploring future long-term zero-emissions production pathways for the ethylene industry in China, by considering different policy scenarios. Although this paper focuses solely on ethylene, by analyzing its production, consumption-plastic products, and post-consumption processes, such as plastic recycling and waste incineration, a deeper understanding of the entire value chain is gained and a more comprehensive understanding of the complexity of the petrochemical industry is developed.

A techno-economic bottom-up optimization model was developed to explore China's potential decarbonization pathways for the ethylene industry. To describe potential future policy uncertainties, four scenarios were generated by varying climate ambitions (ambitious climate policy orientations), as well as plastic and plastic waste management ambitions (aggressive plastic policy orientations). All scenarios are designed to meet China's current CO_2 target, i.e., to peak by 2030 and to achieve carbon neutrality by 2060, at minimum cost. Since the primary use of ethylene is for plastic production, this study also considers the end-of-life emissions from waste incineration (downstream Scope 3 emissions) and solutions such as CCS for waste incineration. Based on the above, we assessed the cumulative total emissions and the timing of technology options. Due to the uncertainties inherent in long-term research, we conducted extensive qualitative analysis of the policy challenges that remain for each scenario in achieving carbon neutrality.

The paper found that the cumulative CO_2 emissions across the scenarios differ significantly, ranging from 4.3 to 7.8 Gt, even when carbon neutrality by 2060 is achieved in all scenarios. The results suggest that ambitious policies targeting plastics can lead to lower costs and reduced cumulative emissions compared to ambitious climate-focused policies. This may encourage policymakers to start developing relevant policies for controlling plastic usage and promoting recycling. The paper also highlights the importance of adopting CCS for waste incineration, which could reduce cumulative CO_2 emissions by up to 2 Gt. However, reduced overall demand and increased recycling rates should be prioritized due to the challenges associated with CCS. The results suggest that the Chinese ethylene industry should adopt a mixed portfolio of production technologies, where the share of emission-intensive coal-based methanol-to-olefins is limited. These insights might help industries and policymakers to redirect their investment strategies for coal-based projects.

(2) Paper IV: Back to the present: are existing green industrial policies sufficient for the petrochemical industry?

Paper II provides an in-depth understanding of the petrochemical product ethylene. The paper illustrates some challenges of decarbonizing the petrochemical industry, including technical, economic, infrastructure-related, and political issues. However, the analysis is not comprehensive enough to fully understand the petrochemical industry. Therefore, in ***Paper IV***, in addition to considering the emission reduction policies for the steel industry which were previously mentioned, we expand the scope of our study to the entire petrochemical industry, aiming to provide a more comprehensive analysis that helps both Chinese policymakers and international readers better understand China's petrochemical industry policies.

We found that: while green industrial policies for the petrochemical industry have begun to take shape, they remain weaker than those for the steel industry. Despite a clear national carbon neutrality target, the absence of specific peak and neutrality policies for petrochemicals weakens the industry's decarbonization directionality. However, the release of carbon neutrality roadmaps by four major petrochemical companies provides some reinforcement. In terms of knowledge creation and innovation, the petrochemical industry has launched several decarbonization pilot projects, but they remain in the early stages, focusing primarily on green hydrogen, green ammonia, and green methanol, with little attention to other petrochemical products. Policy support for market creation and restructuring is notably lacking. Although phase-out policies exist, overcapacity remains a challenge, particularly in traditional coal-based chemical production. Compared to the steel industry, the social impact of the petrochemical sector's low-carbon transition is expected to be less significant.

4.3 Comparisons between steel and petrochemical industries

In this thesis, I aim to explore the potential decarbonization pathways and policies for the steel and petrochemical industries. While both sectors are highly energy-intensive and major contributors to global CO_2 emissions, they differ significantly in terms of technological feasibility, policy design, and the pace of transition required to align with climate targets. Throughout the research process, I have gathered several observations about these two sectors. These insights may highlight the unique challenges in each industry.

(1) *My initial observation is that modeling the petrochemical industry poses greater challenges compared to the steel industry, owing to its higher level of complexity, which is reflected in both the diversity of technological choices and the difficulty of data acquisition.*

(1.1) The variety of technologies makes modeling in the petrochemical industry complex

The petrochemical industry produces a wide range of products and follows diverse technological routes. Given this complexity, it is crucial to carefully define the research scope and consider the interrelationships between different products when building the model. In ***Paper II***, we focused on the ethylene industry, a choice informed by extensive literature analysis and a comprehensive review of the petrochemical sector. Additionally, the study not only examined ethylene but also its links to plastics, one of the most significant petrochemical products. In contrast, research on the steel industry typically centers on crude steel production, which simplifies model construction.

The technological complexity of petrochemical production further complicates modeling. Taking ethylene as an example, its production involves various feedstocks, including naphtha, coal, biomass, CO_2, and hydrogen, as well as multiple processes such as steam cracking, MTO, and Fischer-Tropsch synthesis (FT). These elements can be combined in numerous ways, resulting in a variety of production routes that increase both modeling complexity and computational difficulty. Moreover, the future viability of emerging technologies, such as biomass-based MTO or FT, remains uncertain, further complicating model development. In ***Paper II***, selecting the specific production routes was challenging, as an excessive number of routes could introduce too many decision variables, increasing the difficulty of solving the model. After careful evaluation, I ultimately selected eight routes, considering technological maturity and feedstock impact, which was detailed in the paper for clarity.

In contrast, the steel industry relies on a more limited set of mainstream technologies, primarily BF-BOF and EAF. There is also a general consensus on the most promising future technologies, such as hydrogen-based metallurgy or, as some argue, CCUS. This relative technological stability makes modeling steel industry pathways comparatively less complex [8].

(1.2) The ambiguity of data complicates petrochemical industry modeling

Compared to the steel industry, obtaining relevant data for petrochemical modeling is more challenging. Taking ethylene in ***Paper II*** as an example, its carbon emissions mainly include direct emissions, and indirect emissions from electricity and heat/steam consumption, if excluding Scope 3 emissions. Accurate data on both types of emissions are essential. While direct emissions can be assumed constant (if we don't consider energy efficiency improvements), indirect emissions vary due to power sector decarbonization. As the power system shifts toward low-carbon sources, carbon emission factors will decrease. Consequently, emission data from short-term studies, which often aggregate direct and indirect emissions, cannot be directly applied.

Although my ***Papers I*** and ***III*** on the steel industry also require such data, a key distinction lies in the carbon fate of fossil fuels. In steel production, nearly all fossil fuel carbon is emitted as CO_2, whereas in ethylene production, a portion is locked within the product. This difference arises because fossil fuels primarily serve as energy sources in steelmaking, while in petrochemicals, they function as both energy and feedstock. As a result, steel industry emissions can be estimated using well-documented energy consumption data and corresponding carbon emission

[8] However, this does not imply that steel modelling is easy.

factors [9]. However, this approach is not applicable to ethylene production, where the retained carbon fraction is often unclear or underreported in the literature, making direct emission calculations more complex [10].

To address this challenge, I derived emission data from existing literature. However, this process was not straightforward [11]. Although many studies report carbon emission factors for ethylene in China, their scopes vary, leading to inconsistencies. Many also fail to distinguish between direct and indirect emissions. To ensure accuracy, I systematically collected nearly all available studies on ethylene-related emissions in China, listed and analyzed their reported emission factors, and deconstructed them to estimate the most likely direct emissions. Additionally, I cross-referenced other sources for adjustments and corrections, ultimately deriving the most probable direct emission values. Overall, the data used in each article undergoes extensive literature verification before being disclosed in the paper, with the hope that it will be helpful to future readers.

This case of ethylene exemplifies the broader data challenges in petrochemical modeling. The industry encompasses numerous products, each with multiple production routes, where emission factors and economic coefficients vary based on scope definitions. Moreover, as long-term studies remain limited, relevant data are scarce, further complicating model development.

(2) My second observation is that the decarbonization in the petrochemical industry is slower than that in the steel industry in China.

(2.1) Limited research on decarbonization pathways in the petrochemical industry

When I began drafting my first paper on the steel industry in 2021, research on its long-term deep decarbonization pathways was relatively limited. However, by the time I completed that paper and tried to expand the model in 2022, approximately ten studies had been published on China's steel industry carbon neutrality pathways. In contrast, research on the petrochemical industry's long-term decarbonization remains sparse. Most existing studies focused on targets around 2030, leaving a significant gap in understanding long-term strategies. Recognizing this disparity, I decided to shift the focus of my second paper to explore the long-term decarbonization pathways of the petrochemical industry.

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[9] In steel production, "carbon-lock-in" reactions—where carbon forms stable compounds such as carbonates in slag—also occur. However, the amount of carbon locked this way is negligible compared to total emissions and is usually ignored.

[10] The excessive production routes of ethylene, along with China's unique MTO process, further complicate the difficulty of obtaining relevant data.

[11] I spent over three months collecting various data required for my ethylene paper, a time span that far exceeded the time I spent gathering data for my steel papers.

(2.2) Findings from interviews support this observation

This discrepancy is also evident in the interviews conducted for my fourth paper. We interviewed nine colleagues from industrial decarbonization groups in various NGOs, most of whom demonstrated a deeper understanding of steel industry decarbonization than petrochemicals (which is also true for myself). Admittedly, the sample size is relatively small. However, when combined with discussions with other professionals working in industrial decarbonization, online news, and academic literature, this observation is indirectly substantiated. Moreover, in these interviews, three colleagues explicitly mentioned that China's steel industry may have peaked between 2021 and 2023. In contrast, no clear opinions were provided regarding the peak carbon timeline for the petrochemical industry.

(2.3) Policy and corporate commitments further reflect the disparity
Paper IV, which compares the decarbonization progress of China's steel and petrochemical industries, also provides supporting evidence for this observation:

(i) Stronger policy support for the steel industry

For example, policies explicitly require the steel industry to peak carbon emissions by 2030, whereas no such mandate exists for the chemical industry. Additionally, China's carbon trading market currently includes the steel sector but has yet to incorporate the petrochemical industry. Another example is that the Chinese steel industry has an official green steel standard, while the petrochemical industry has only issued standards related to renewable hydrogen.

(ii) More companies in the steel industry have decarbonization roadmaps

Among the companies analyzed, nine in the steel sector have publicly disclosed decarbonization roadmaps, compared to only four in the petrochemical sector. Furthermore, five steel companies have committed to carbon neutrality by 2050, whereas only three chemical companies have made similar commitments.

(iii) Decarbonization efforts in the petrochemical industry are primarily driven by energy system integration rather than direct product transformation.

Although the petrochemical industry has implemented more decarbonization projects than the steel industry, these projects are not mature and primarily focus on co-producing green hydrogen, green ammonia, and methanol in regions with abundant renewable energy resources. The primary objective of such projects is energy storage—consuming renewable electricity while addressing challenges in green hydrogen storage and transportation. As a result, current decarbonization efforts in the petrochemical industry are more aligned with energy sector transitions rather than fundamental changes in petrochemical production itself.
Of course, these observations do not imply that achieving carbon neutrality in the steel industry is easier. The sector faces additional challenges, such as overcapacity and declining future demand, which will necessitate the phase-out of existing fossil-

based capacity. This transition is likely to lead to unemployment and associated social issues, further complicating the decarbonization process.

4.4 Methodological reflection

4.4.1 From quantitative to qualitative analysis

Across my four papers, the methodological focus shifts from quantitative to qualitative analysis. ***Paper I*** relies almost entirely on model results. In ***Papers II*** and ***III***, while modeling remains central, substantial sections analyze factors within and beyond the model, such as the carbon market (***Paper II***) and geopolitical barriers (***Paper III***). By ***Paper IV***, I fully adopt a qualitative approach, analyzing China's green industrial policies without quantitative modeling. The methodological shift from ***Paper I*** to ***Papers II*** and ***III*** is driven by their longer research periods.

Paper I focuses on short-term research (2021–2030), whereas ***Papers II*** and ***III*** extend to 2060–2070. In short-term studies, uncertainty is relatively low, so parameters exhibit minimal variation, and their changes can be reasonably estimated. Moreover, event trends tend to be more stable, making it easier to incorporate detailed constraints into the model. As discussed in **Section 3.2**, ***Paper I***'s scenarios (*what-if scenarios*) and models are more predictive in nature. This justifies the model-driven focus in short-term research, as accurate model outputs offer actionable insights, aiding decision-makers in formulating effective and practical response strategies.

In contrast, long-term research faces greater uncertainties due to potential transformation in external factors, making it difficult to define specific parameters and constraints. As a result, these factors require non-technical discussions. Taking ***Paper II*** as an example, I aimed to incorporate carbon pricing into the model when analyzing the ethylene decarbonization pathway. However, China has yet to establish a mature carbon market, and the petrochemical industry is not even included in the existing carbon trading system. Consequently, predicting the carbon price for the next 40 years is highly challenging. Thus, although I referred to possible carbon price projections from existing literature under different scenarios, I also provided a qualitative discussion on China's carbon market. This aimed to offer additional information, helping readers better understand the model and results, and ultimately providing deeper insights for policymakers. Another example comes from ***Paper III***, where I examined the impact of importing green HBI from renewable-rich countries like Australia on Asia. When initially constructing the model, I considered setting an upper limit on annual green HBI imports. My concern was that, without such a constraint, the cost-minimization optimization model might suggest that all Asian countries would rely solely on imported HBI instead of developing domestic production, given the lower cost of imported HBI. However, this outcome would not align with reality. The challenge was determining a reasonable constraint. For instance, arbitrarily assuming that each country could import at most 50% of its HBI lacked solid empirical support. My supervisors proposed an alternative approach: rather than imposing an arbitrary constraint, why not let the model generate extreme results? While real-world scenarios typically lie between extremes, analyzing such cases can help identify potential risks and challenges, informing strategies to mitigate them. Thus, I then adopted this method and conducted a non-technical discussion to help readers better understand the opportunities and challenges associated with HBI trade.

Paper IV, unlike the previous ones, does not involve modeling and adopts a purely qualitative approach. This contrasts with quantitative analysis, which focuses on transforming phenomena into measurable data and identifying relationships between variables. In qualitative analysis, the emphasis shifts to describing, understanding, and explaining phenomena. In **P*apers I***, ***II***, and ***III***, most non-numeric information is eventually converted into numerical data for analysis, and a significant portion of my time spent on sourcing and validating data. When I began ***Paper IV***, I initially brought my quantitative research habits into qualitative work, focusing too much on figures and details. For example, I spent considerable time collecting R&D investment rates from various SOE steel companies to demonstrate that SOEs invest heavily in R&D. However, after several revisions, I removed this data, as specific R&D numbers were less crucial than understanding the underlying reasons for readers.

Another key difference is that qualitative research demands a higher level of logical structuring and linguistic precision compared to quantitative analysis. In quantitative studies, once the model generates results, it becomes clear which aspects can be discussed—such as costs, carbon emissions, and decarbonization pathways. The model itself helps shape the structure of the paper, ensuring a structured discussion. Additionally, numerical results provide a clear basis for interpretation, where the language primarily serves to describe patterns and explain underlying principles. In contrast, qualitative research lacks numerical results to offer a predefined logical framework. Although theoretical frameworks can provide some structure, they are often more flexible and require additional reasoning to develop a coherent narrative. This necessitates extensive literature review and critical analysis to establish a well-founded argument and overcome subjectivity. Furthermore, qualitative research places greater demands on linguistic accuracy and maintaining an unbiased perspective, as arguments rely solely on interpretation rather than numerical evidence. For example, in ***Paper IV***, although the framework I used provides six pillars for analysis, how to adapt each pillar to the specific context of China and create a coherent storyline under each pillar was a challenge for me. To address this, I spent a significant amount of time reviewing literature, conducting interviews, extracting relevant information, and constructing the storyline. At the same time, objectivity was also a challenge. This study focuses on China's policies, and many international readers hold biased views toward China's climate policies. As a Chinese, I might also have a positive bias towards my country's policies. In this context, achieving a fair and objective analysis became a significant challenge. This required me to use neutral language to describe things comprehensively, ensuring an objective presentation of all facts.

Quantitative and qualitative research share certain fundamental similarities. In the first three papers, I applied optimization principles and developed sophisticated models tailored to the research questions. In ***Paper IV***, while the theoretical framework provided a foundational structure for analysis, I still had to refine and adapt it based on my understanding of the problem to ensure its applicability to the research context. This process closely parallels the construction and refinement of models in quantitative research. Moreover, both approaches follow a similar cognitive process, characterized by a "divergence-convergence-divergence" pattern. In the first three papers, I began with an extensive literature review to establish the background and identify key research questions. I then concentrated on developing and solving an optimization model. Once the results were obtained, I expanded the discussion to explore their broader policy and practical implications. Qualitative research follows a comparable logical structure. It also begins with a comprehensive literature review to develop familiarity with existing theories. The next stage involves refining the research focus, employing a theoretical framework for analysis, and synthesizing insights from literature and interviews. Finally, the findings are contextualized within a broader framework, assessing their implications for policy or industry development.

4.4.2 Transparency and robustness

Transparency is a key consideration in the papers. As stated in **Section 3.1**, a key limitation of optimization models is the difficulty in observing their internal operations. However, this opacity can be addressed by making the model publicly available, including its source code, input data, and documentation of the model structure. To enhance transparency in ***Paper I***, ***II*** and ***III***, I have provided relevant data, model structures, and algorithms in the main text and appendix, along with detailed explanations of model assumptions and limitations. Additionally, qualitative analysis is incorporated to make the model's functioning more intuitive. In ***Paper IV***, I further ensure transparency by explaining the rationale and applicability of the analytical framework, as well as providing a detailed description of the research methodology.

Robustness is assessed throughout all papers. Sensitivity analysis is conducted to evaluate the model's robustness, in ***Paper I***, ***II*** and ***III***. Moreover, setting multiple scenarios and examining whether the model produces reasonable results under different assumptions is also a crucial approach for assessing robustness. In ***Paper IV***, robustness is further reinforced by combining multiple interviews and literature reviews, with interviews conducted and recorded independently by two researchers to ensure data reliability.

5. Discussion

China faces several challenges and dilemmas in its climate governance in industrial sectors, including energy security, economic stability, and geopolitical factors. **Energy and recourse security** has always been a core consideration in China's governance, which explains the country's heavy reliance on coal. For instance, the rapid development of coal-based chemical industries is a typical example of focusing on energy security. Moreover, the Chinese steel industry's emphasis on CCUS (e.g., the use of hydrogen in blast furnaces combined with CCUS) reflects this issue, as such technological routes can help reduce stranded capacity and maintain industry stability. However, it remains uncertain whether CCUS can be commercialized and scaled up at low cost in the future, so dependence on this technology must be cautiously evaluated. Nonetheless, in the long term, climate goal may help alleviate China's energy security concerns. For example, large-scale adoption of scrap-EAF steelmaking can reduce dependence on imported iron ore. Similarly, in the petrochemical industry, the current heavy reliance on imported oil as feedstock may decrease if green hydrogen and renewable carbon can replace fossil-based carbon sources in the future.

Economic stability is another significant challenge for China's industrial decarbonization. One example of China's emphasis on stability is the ex-post allocation of free allowances in the carbon market, which has minimal impact on product prices and output levels [85], thereby contributing to the stability of the economy and production. However, this strong focus on economic stability may somewhat slowdown industrial decarbonization, particularly in the face of post-pandemic economic downturn pressures. The economic shock in the post-pandemic era, the real estate bubble in China, and the slowdown in urbanization have exacerbated the existing overcapacity in the steel industry, leading to declining industry profitability and rising unemployment. In fact, due to reduced production, China's steel industry may have already reached its carbon peak between 2021 and 2024, whereas the policy originally required a peak by 2030. Given the slowdown in economic growth, industrial restructuring, and market volatility, the steel sector's decarbonization efforts may slow down in the short term.

Geopolitical factors, such as the implementation of **carbon tariffs**, may exacerbate the challenges China faces in industrial decarbonization. With the European Union introducing the Carbon Border Adjustment Mechanism (CBAM) and more countries considering carbon tariffs, the Chinese steel industry will inevitably be impacted. CBAM has entered into force in its transitional phase as of October 2023, while the obligation for importers to pay a levy will kick in as of 2027. Six products have been included in the CBAM: cement, iron and steel, aluminum, fertilizers, electricity and hydrogen [86]. In 2022, China's exports to the EU totaled approximately 19.97 billion EUR products covered by CBAM, accounting for about 3.2 % of total EU imports [87]. Steel products account for 76% of the total traded value, followed by aluminum 23% [88], and thus the steel industry will be the most affected one by CBAM [89]. First, China's carbon price, with the average carbon price of 68 RMB/ton (around 9 EUR/ton) in 2023 [90], is far lower than that in EU of 83 EUR/ton [91]. Thus, Chinese companies should pay the carbon price gap to EU. Second, the carbon intensity of China's steel is higher than that of EU. In China, the emissions intensity of BF-BOF steel is approximately 2.1 tonnes CO_2 per tonne steel [25], while that number is 1.9 in EU [92]. If the indirect emissions is included in CBAM in the future, China's export of EAF steel will be hugely impact since China's coal based electricity system have high carbon intensity (0.581 ton/Mwh) that that of EU of 0.244 ton/Mwh [93]. In addition, because of China's lack of effective supervision over energy use in the industrial value chain, leading to accounting data being manipulated easily, the EU is reluctant to recognize China's carbon data and carbon trading based on this data [87]. All the above will affect China and literature have highlight that CBAM will cause negative impacts on China's industry profit in the long term [89, 94]. However, since the specifics of CBAM implementation are still unclear, the actual impact on China's steel industry remains uncertain. In the short term, production reshuffling and export adjustment policies, such as export exemptions or export tax rebates, could serve as potential measures for China to mitigate the impact of CBAM [95].

In addition to carbon tariffs, **trade policies** are another important geopolitical factor influencing industrial decarbonization. Our research indicates that green HBI trade can accelerate the decarbonization process in the global steel industry. However, the restructuring of industrial chains could lead to job losses in the domestic steel sector, which may generate resistance in China. Furthermore, the uncertainty surrounding **international climate cooperation** presents another challenge. For instance, the U.S. withdrawal from the Paris Agreement, coupled with the China-U.S. trade war, has hindered many climate cooperation projects between the two countries, potentially slowing down China's decarbonization efforts.

Faced with these challenges, China's industrial carbon neutrality seems daunting. However, China has continuously created a green miracle over the past few decades, with the renewable energy and electric vehicle industries serving as examples. China is the world's largest country in terms of installed renewable energy capacity, accounting for one third of the global total in 2023 [96]. Large-scale development has driven significant reductions in wind and solar power costs. Moreover, China is the world's largest electric vehicle makers. Chinese carmakers produced more than half of all electric cars sold worldwide in 2023. Moreover, China also consumed 60%

of the world's electric vehicles. Intense competition has driven down costs: over 60% of electric cars sold in China were already cheaper than their average internal combustion engine counterparts, whereas in Europe and the United States, electric cars remained 10% to 50% more expensive [97]. China's industrial policies can learn from the success of these two industries to promote the industrial decarbonization. For example, the steel and petrochemical industries could adopt fiscal subsidy policies, similar to those used in the early stages of electric vehicle promotion, to lower the initial costs of green technologies. They could also draw on mechanisms like the Renewable Portfolio Standard from the renewable energy sector to create stable market demand. Whether such a green miracle can be replicated remains uncertain, yet it represents a prospect China should realize.

Given China's position as the world's largest carbon emitter, the second-largest economy, and a key player in the Global South, its future industrial decarbonization efforts will have far-reaching implications for other countries and the global economy. China's strong economic and military power, its historical experiences with colonialism, and its past economic struggles have collectively shaped a shared "anti-imperialism" narrative with other developing countries, strengthening its role as a climate leader in the Global South in both soft and hard power dimensions [98]. Despite controversies surrounding the Belt and Road Initiative and South-South cooperation, such as the construction of new coal-fired power plants in the past, China has increasingly facilitated the dissemination of renewable energy, with most green Belt and Road Initiative projects focusing on renewables now. In parallel, China's economic development and technological progress offer a model for other developing countries. A critical question remains whether China can replicate its decarbonization strategies in the industrial sector and extend them to other countries. The success of such efforts will shape the trajectory of global industrial emissions and how China navigates this transition will be crucial in determining the balance between economic growth and environmental responsibility in emerging economies.

6. Conclusions

Industry accounted for 24% of global direct greenhouse gas emissions, rising to 34% when including indirect emissions in 2019. Deep decarbonization of industry is thus essential to achieving the Paris Agreement targets. As the world's largest carbon emitter, China committed in 2020 to achieving carbon neutrality by 2060. Given that China's industrial CO_2 emissions account for 12% of the global total, decarbonizing its industrial sector is not only crucial for its own carbon neutrality goal but also for global climate efforts. However, industrial decarbonization faces economic, technological, and political challenges, necessitating a thorough examination of mitigation pathways, key technological and cost barriers, and the policy support required. This thesis investigates the decarbonization pathways and policies for China's steel and petrochemical industries. The first three articles employ optimization models to explore carbon neutrality pathways in China's steel and ethylene sectors, while the fourth assesses whether China's green industrial policies are sufficient to enable deep decarbonization. The key findings and conclusions of this thesis are as follows.

(1) ***Papers I*** to ***III*** examine potential decarbonization pathways for the steel and ethylene industries in China. From a techno-economic perspective, carbon neutrality in these sectors is achievable in China by 2060 under all examined scenarios and pathways, and even potentially by 2050. However, beyond technological breakthroughs, achieving full decarbonization requires systemic support. Key enablers include, but are not limited to, efficient scrap steel and plastic collection systems (***Papers I*** and ***II***), rapid power grid decarbonization (***Paper III***), large-scale low-cost hydrogen production (***Papers II*** and ***III***), national and international trade in scrap and HBI (***Papers I*** and ***III***), and a well-functioning carbon market (***Paper II***). Effective and well-coordinated policies are essential to address these systemic barriers. While China's green industrial policies have begun to take shape, they remain insufficient to fully achieve carbon neutrality, necessitating further policy reinforcement (***Paper IV***).

(2) Although China's steel and ethylene industries can achieve carbon neutrality by 2060, cumulative carbon emissions vary significantly across different scenarios. In cost-minimization scenarios, cost differences remain relatively small, whereas cumulative emissions exhibit substantial variation. Specifically, in ***Paper II***, the costs range from 4687 to 5751 trillion RMB (670 to 822 trillion USD) across the four scenarios, a variation of approximately 23%, while

cumulative carbon emissions from 2021 to 2060 differ significantly, ranging from 4.3 Gt to 7.8 Gt, representing a variation of about 81%. In ***Paper III***, the costs for eight Asian jurisdictions over 48 years range from 5.6 to 5.8 trillion RMB (800-829 billion USD), with a variation of 3.6%, while CO_2 emissions vary between 19 Gt and 26 Gt, a variation of approximately 37%. Therefore, existing policy targets should not only specify the timeline for carbon neutrality but also establish clear carbon emission caps.

(3) The steel and petrochemical industries face distinct challenges in achieving deep decarbonization and carbon neutrality. In addition to technological challenges such as the availability and cost of green hydrogen and CCUS, which are critical for deep decarbonization, China's steel industry also grapples with overcapacity, short-term scrap shortages, geopolitical issues (e.g., industrial chain restructuring and potential job losses due to HBI trade), and trade frictions that may arise from the CBAM. In contrast, the decarbonization of the petrochemical industry faces not only challenges related to hydrogen and CCUS but also energy security concerns, particularly regarding coal-based chemical production. Moreover, growing demand in the sector may further drive emissions in the future. Overall, the steel industry is more advanced in the development of green industrial policies and corporate action compared to the petrochemical sector.

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Towards carbon neutraliy

The decarbonization of the steel and petrochemical industries represents a critical step toward achieving global climate goals. As major contributors to industrial emissions, these sectors offer substantial potential for deep emission reductions through technological innovation, supportive policies, and coordinated international action. In 2020, China announced its goal of achieving carbon neutrality by 2060. Given the scale and huge emissions of its steel and petrochemical industries, decarbonizing these sectors is essential not only for fulfilling China's climate commitments but also for advancing global climate governance. This thesis investigates potential decarbonization pathways for these two sectors in China and emphasizes the key policy measures required to support their low-carbon transition.

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