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Innovation, clean power and modern industrial policy

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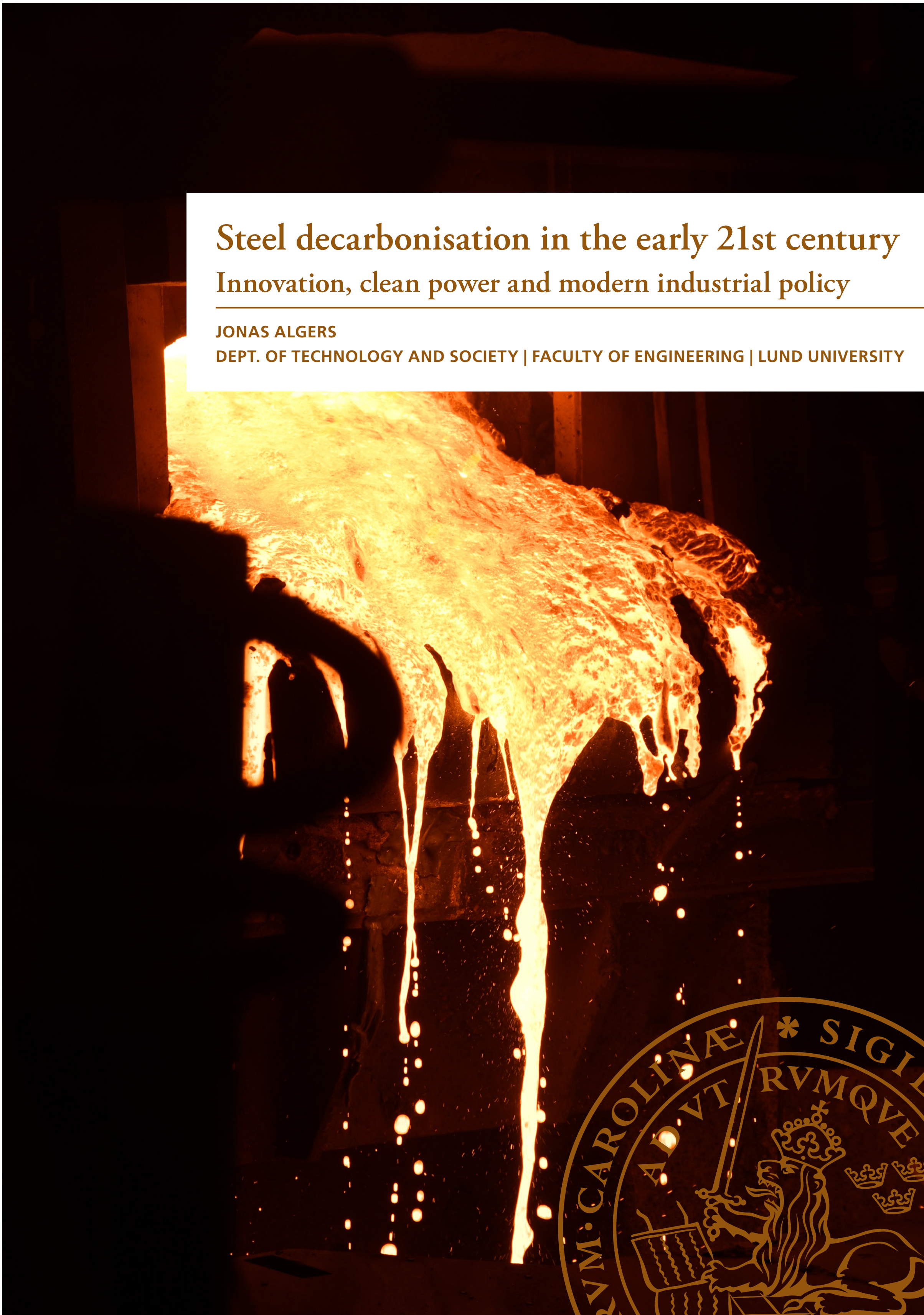

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Title and subtitle: Steel decarbonisation in the early 21st century: Innovation, clean power and modern industrial policy

Abstract: The global steel industry is a complex socio-technical system of strategic importance, producing about 10 percent of global emissions. Decarbonizing this system will significantly impact energy use, supply chain configurations, and international competitiveness, with geopolitical implications. Governments across the world are therefore turning towards industrial policy to accelerate a transformation and boost competitiveness of domestic industries.

This thesis investigates the role of green industrial policy for the decarbonisation of steelmaking at three different levels of analysis: the firm, domestic policy and global market level. First, by applying the theory of innovative enterprise on the first radical decarbonising innovation project HYBRIT in Northern Sweden. Favourable internal strategic, organisational and financial conditions enabled the project, with spillover effects on the rest of the steel industry. Second, by combining theoretical insights from the literature on energy systems and industrial policy on the factors affecting the reconfiguration of global steel supply chains. Energy costs are pivotal for the decarbonisation of energy-intensive industry, and one of multiple factors shaping international competitiveness. Third, by exploring the potential of policies for deliberate decline in breaking the carbon lock-in associated with steel overcapacity. While supportive policy has enabled the early development of low-carbon steelmaking, the acceleration of sector-wide decarbonisation will require a growing focus on policies of deliberate decline and a reduction of sectoral overcapacity.

By applying theoretical insights from the literatures on innovation, energy systems, and green industrial policy, this thesis argues that ambitious industrial policy initiatives are critical enablers of the emergent transformation of steelmaking. These initiatives have not only been motivated by sustainability targets, but also by geopolitical competition. Policy achievements are constrained however by political fragmentation and discontinuity in the EU and the US.

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MADE IN SWEDEN

In loving memory of my mother, Anne Algers

Science, (...) cannot create ends and, even less, instil them in human beings; science, at most, can supply the means by which to attain certain ends. But the ends themselves are conceived by personalities with lofty ethical ideals and—if these ends are not stillborn, but vital and vigorous—are adopted and carried forward by those many human beings who, half unconsciously, determine the slow evolution of society.

- *Albert Einsten, Why Socialism?, 1949.*

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Abstract

The global steel industry is a complex socio-technical system of strategic importance, producing close to 10 percent of global emissions. Decarbonizing this system will significantly impact energy use, supply chain configurations, and international competitiveness, with geopolitical implications. Governments across the world are therefore turning towards industrial policy to accelerate a transformation and boost competitiveness of domestic industries.

This thesis investigates the role of green industrial policy for the decarbonisation of steelmaking at three different levels of analysis: the firm, domestic policy and global market level. First, by exploring the first radical decarbonising innovation project HYBRIT in Northern Sweden through the lens of the innovative enterprise. Favourable internal strategic, organisational and financial conditions enabled the project, with spillover effects on the rest of the steel industry. Second, by combining theoretical insights from the literature on energy systems and industrial policy on the factors affecting the reconfiguration of global steel supply chains. Energy costs are pivotal for the decarbonisation of energy-intensive industry, and one of multiple factors shaping international competitiveness. Third, by exploring the potential of policies for deliberate decline in breaking the carbon lock-in associated with steel overcapacity. Although supportive policies have enabled early progress in low-carbon steelmaking, accelerating sector-wide decarbonization will require greater emphasis on deliberate decline and reducing overcapacity.

By applying theoretical insights from the literatures on innovation, energy systems, and green industrial policy, this thesis argues that ambitious policy initiatives are critical enablers of the emergent transformation of steelmaking. These initiatives have not only been motivated by sustainability targets, but also by geopolitical competition. Policy achievements are however constrained by political fragmentation and discontinuity in the EU and the US.

Populärvetenskaplig sammanfattning

Stålindustrin är en strategiskt viktig och energiintensiv sektor, som producerar insatsvaror för flera nedströms sektorer. Det är också en sektor som är beroende av infrastrukturer och som domineras av stora etablerade företag, vilket skapar trögheter och låser in fortsatt användning av fossil energi. För att stötta omställningen av stålindustrin har allt fler beslutsfattare därför utvecklat grön industripolitik där man genom subventioner, innovationsstöd, handelspolitik, energipolitik och statliga bolag försöker möjliggöra en omställning från fossil till grön energi i industrin.

Dessa industripolitiska insatser har tagit olika former och gett varierande resultat. Politiken har i vissa fall varit framgångsrik i att stötta innovation och utveckling av projekt men i andra fall redan rullats tillbaka eller avböjts av företagen. I några länder har den varit kraftfull och lett till snabba resultat men i andra fall varit för svag för att kunna främja investeringar. I flera tillfällen har stöd till gröna stålprojekt inneburit en omställning, men i andra fall har stöd gått till ett nytt projekt som läggs till existerande stålproduktion och därmed inte minskar utsläppen.

I denna avhandling undersöker jag hur grön industripolitik formar stålindustrins omställning och frågar om industripolitikens inverkan på tre nivåer; på bolagsnivå, på nationell policy-nivå och på global marknadsnivå. I de fem artiklarna som utgör avhandlingen studerar jag industripolitiken på varje distinkt nivå, samt visar på sammanhanget mellan de olika nivåerna. På varje nivå finns möjligheter och begränsningar för industripolitiken att få effekt för en omställning.

Avhandlingen visar hur etablerade bolag i industrin ser avvägningar mellan vinstutdelningar samt investeringar i omställning, och hur innovationssatsningar och investeringar kan möjliggöras av förändrade strategiska och finansiella mål i statliga bolag. På nationell policy-nivå visar jag hur den gröna stålproduktionens konkurrenskraft formas av flera faktorer, där policy-stöd är en avgörande faktor i tillägg till naturliga tillgångar som förnybar energi. På global marknadsnivå visar jag att stålindustrins tröghet försvårar nedstängningar av olönsamma stålverk vilket innebär en tendens till överkapacitet och att ny grön produktion läggs till snarare än ersätter konventionell produktion.

I kappan samlar jag bidragen på de tre distinkta nivåerna i ett gemensamt ramverk och förklarar hur de kompletterar varandra. Därmed bidrar jag med en studie av industripolitikens roll för att möjliggöra och forma den framväxande omställningen av stålindustrin.

Popular science summary

The steel industry, a strategically important and energy-intensive sector, supplies inputs to numerous downstream industries. It is also a sector heavily dependent on infrastructure and dominated by large incumbent firms, which creates inertia and locks in continued use of fossil fuels. To support the transition of the steel industry, policymakers have increasingly developed green industrial policies— through vehicles such as subsidies, innovation support, trade policy, energy policy, and state-owned enterprises—to enable a shift from fossil to green energy in the industry.

These industrial policy efforts have taken various forms and yielded mixed results. In some cases, policies have successfully supported innovation and project development, while in others, they have been rolled back or rejected by firms. In certain countries, policies have been robust and led to rapid results, but elsewhere, they have been too weak to stimulate investment. On several occasions, support for green steel projects has driven transformation, but in other cases, funding has gone to new projects that add to existing steel production, failing to reduce emissions.

In this thesis, I examine how green industrial policy shapes the transition of the steel industry, focusing on its impact at three levels: the corporate level, the national policy level, and the global market level. The five articles that make up the thesis analyse industrial policy at each distinct level and demonstrate the interplay between them. At each level, there are both opportunities and limitations for industrial policy to effectively drive transformation.

The thesis shows how established companies in the industry weigh dividend payouts against investments in transition, and how innovation initiatives and investments can be enabled through strategic and financial objectives of state-owned enterprises. At the national policy level, I demonstrate that the competitiveness of green steel production is shaped by multiple factors, with policy support being crucial alongside natural resources such as renewable energy. At the global market level, I show that the steel industry's inertia makes it difficult to shut down unprofitable steel plants, leading to overcapacity and a tendency for new green production to supplement rather than replace conventional production.

In the kappa (overarching summary), I bring together the contributions from the three distinct levels into a common framework, explaining how they complement each other. Thus, I provide a study of the role of industrial policy in enabling and shaping the emerging transition of the steel industry.

List of papers

Paper I

Algers, J., Åhman, M., & Nilsson, L. J. (2025). Steel Decarbonisation—from Optimization to Transformation. *Annual Review of Environment and Resources*, 50. https://doi.org/https://doi.org/10.1146/annurev-environ-111523-101851

Paper II

Algers, J. (2026). The innovative state-owned enterprise. [MANUSCRIPT].

Paper III

Algers, J., Gong, J., Nykvist, B., & Åhman, M. (2025). Competition and climate policy in the steel transition: Comparing costs and subsidies in the US and the EU. *Energy Policy*, 198. https://doi.org/10.1016/j.enpol.2025.114507

Paper IV

Nykvist, B., Gong, J., Algers, J., & Åhman, M. (2025). Renewables pull and strategic push – What drives hydrogen-based steel relocation? *Applied Energy*, 395. https://doi.org/10.1016/j.apenergy.2025.126189

Paper V

Algers, J., & Åhman, M. (2024). Phase-in and phase-out policies in the global steel transition. *Climate Policy*, 1-14. https://doi.org/10.1080/14693062.2024.2353127

Author contributions

I am the corresponding lead author of papers I, III and V, and the sole author of paper II. I led the conceptualisation, data collection and data analysis for papers I, II, III and V, and was a key contributor in the conceptualisation, data collection and analysis in paper IV.

Other relevant publications

Academic papers

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. https://doi.org/10.1016/j.resconrec.2025.108275

Åhman, M., Nykvist, B., Morales, E. T., & Algers, J. (2023). Building a stronger steel transition: Global cooperation and procurement in construction. *One Earth*, 6(11), 1421-1424. https://doi.org/10.1016/j.oneear.2023.10.024

Reports

Algers, J. (2024). Leading with Industrial Policy: Lessons for Decarbonisation from Swedish Green Steel. In T. Tucker (Ed.), Industrial Policy 2025: Bringing the State Back In (Again). Roosevelt Institute.

Algers, J., & Bataille, C. (2025). Strategic decarbonisation of the Canadian iron and steel industry: worker-centred path to cut emissions, increase value added and strengthen global supply chains. Lund University.

Algers, J., Giua, L., Corneille, A., & Raes, S. (2025). The carbon capacity nexus: A framework for supply-side industrial emission reduction pledges. The Climate Club.

Algers, J., Seguineaud, C., & Gu, D. (2024). Addressing steel decarbonisation challenges for industry and policy. OECD.

Andersson, F. N. G., Algers, J., Bauer, F., Nilsson, L. J., & Åhman, M. (2025). Grön industripolitik: Behov, möjligheter och risker. Produktivitetskommissionen.

Bataille, C., Stiebert, S., Algers, J., Li, F., & Alfare, M. (2024). Triggering Investment in first-of-a-kind and early near-zero emissions industrial facilities. Columbia University Centre for Global Energy Policy.

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As I finalise this thesis, I have realised how previous experiences were essential for me ending up where I am today. A special thanks to Patrick Mokre for long formative chats in the streets and bars below the Empire State Building. Also, thanks to Magnus Marsdal who both sharpened my pen and let me spend the lockdown years to study the ins and outs of industrial policy from my messy desk on Torggata.

I would not have been able to get through these intense years without the support from my dear friends. Will – whose arrival in Copenhagen has been an intellectual energy injection, Jacob – who remains the most loyal of sherpas, Sofie – always focused on the duty to win, Anton – whose generous mood can lift any spirit. And all the friends who have supported me and showed up when it matters. Thank you.

Finally, thank you to my family. To my parents Bo and Anne, who have always believed in me and showed me how simple kindness and curiosity can take you far in the big world out there. To my wife Johanne, who has let me pursue late-night meetings and lots of travelling, time and again listened to my frustrations about academia, endured many hours of deep sighs and loud hammering on the keyboard, and still remained the light of my life. I cannot thank you enough.

Abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
BTE	Barriers to exit
CAPEX	Capital expenditure
CBAM	Carbon border adjustment mechanism
CCS	Carbon capture and storage
DR	Direct reduction
EAF	Electric arc furnace
ETS	Emissions trading scheme
H	Hydrogen
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
LCOS	Levelized cost of steel
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
Mtpa	Million tonnes per annum
R&D	Research and development
ROCE	Return on capital employed
SOE	State-owned enterprise
TIE	Theory of innovative enterprise
WACC	Weighted average cost of capital

Introduction

> “There is a war between the ones who say there is a war and the ones who say that there isn't't”
>
> Leonard Cohen, 1974.

This thesis is written in an era of compounding crises. As the covid-19 pandemic receded, it left scrambled supply chains and disrupted trade flows, contributing to a historic rise in inflation. Russia’s weaponisation of energy ahead of the invasion of Ukraine, and the sanctions imposed by the West in response further diminished the supply of energy, pushing inflation even higher. Along these acute crises, geopolitical rivalry is motivating trade “wars” and trade “deals”, further disrupting trade and supply chains, risking the livelihoods of workers and communities across the globe. Underlying and intensifying these human conflicts is the climate crisis, which has caused record heatwaves on land and at sea, droughts, forest fires, storms and floods (Jones, 2025; Millard, 2025; Mooney, 2025a, 2025b; Mooney & Bernard, 2025; Mooney & Bhandari, 2024).

These compounding crises of climate, geopolitics, energy and inflation make the topic of this thesis – which is industrial policy for the decarbonisation of steelmaking – more, not less important. The steel industry is one of the largest emitters of greenhouse gases, producing nearly 10 percent of global annual emissions (International Energy Agency, 2019). It is therefore imperative to cut these emissions as rapidly, and persistently as possible in order to halt the rise in global temperatures and extreme weather events. The steel sector is also energy-intensive, making competitiveness highly contingent on energy supply and costs (Algers et al., 2025; Draghi, 2024). Domestically produced clean power can reduce fossil energy import dependencies but depends on the availability of large quantities of low-cost electricity. At the same time, the steel industry is a strategic sector, producing inputs for a variety of large downstream sectors such as the infrastructure, energy, housing, automotive, defence and industrial equipment sectors (Bataille, 2019). Thus, decarbonizing the steel sector could significantly impact global emissions, industrial competitiveness, and geopolitical dependencies.

When I started my studies of steel decarbonisation at the division for Environmental and Energy Systems at Lund University, I expected to spend the next four years in a secluded corner of academia. This is also what attracted me to the PhD after some years at a thinktank with regular moments in the heat of public debate. Instead, several national and international debates have been concerned with industrial decarbonisation and provided intellectual fodder for this research. First, the debate on the "de-risking state", i.e. the practice to conduct industrial policy through the subsidisation of private investment has been an inspiration (Gabor, 2021). Then, the debates on the merits of "Bidenomics" (Bulfone et al., 2024) – named after the green industrial policy of US President Biden in particular through the passage of the Inflation Reduction Act (Reynolds, 2024). The report on European competitiveness by former president of the European Central Bank and Italian prime minister Mario Draghi (Draghi, 2024) again brought industrial decarbonisation into the limelight. Finally, the Swedish debate on the merits of steel decarbonisation (see e.g. (Andersson et al., 2021; Henrekson & Sandström, 2023)) raised questions of the role of clean power and state involvement in industrial development. That these debates have spanned journal articles, op-eds, reports, podcasts and social media, shows how industrial policy has become a hotly contested political and academic issue across jurisdictions. As a consequence, rather than slow persistent development of my own research and thinking on the topic, these debates and political developments in Asia, North America and Europe have highly informed this thesis.

Personally, I have been motivated by the ambition to understand *how* the interplay of social and technical factors can enable the decarbonisation of a strategic and emission-intensive sector like steel. The steel industry is a complex and global large technical system where the coordination of multiple components is essential for its continuous functioning (Hughes, 1987). Technically, energy sources – fossil or renewable – and facilities – such as various types of furnaces, electrolysers, and storage facilities and infrastructure – all shape the potential steelmaking processes and thus the potential for change. Allocating and coordinating those resources, however, is a *social* process where decisionmakers plan and allocate resources to decarbonisation over time. Therefore, this thesis aims to contribute to a more sophisticated understanding of the political economic processes necessary for a rapid and persistent decarbonisation of the steel industry.

Why green industrial policy for the steel industry?

Steel decarbonisation is about eliminating the use of fossil fuels from steelmaking. Motivations to do so, however, can be manifold, where stopping climate change is just one among others such as reducing fossil fuel imports, increasing the value of exports, product differentiation and increased value added, plant modernisation or the reduction of local air pollution. Four key trends have driven the adoption of green industrial policy in the steel sector: the rise of China as an industrial powerhouse, the rise of renewable energy as a low-cost, geographically abundant energy source, deindustrialisation and social decline in former industrial regions in major economies, and the growing threat of climate change-driven disasters. In the following section, I briefly explain why green industrial policy for the steel industry has been a response to these concurrent trends.

In recent decades, China has grown into a major steelmaking power. The country increased steel production from 128 million tonnes of steel in 2000 to 1018 million tonnes in 2022. The Chinese industrial model, where investment is made based on top-down targets and profitability is a second-order concern has given rise to a structural overcapacity in steelmaking, with global steelmaking capacity at 2472 mtpa in 2024 but consumption at in the same year at 1870 mtpa (OECD, 2025). Global capacity utilisation is therefore at a mere 76 percent, pressuring steel prices across the world. The growth of China is therefore pressuring Western governments to respond by protecting domestic industries. Western governments have motivated support for a domestic low-carbon steel industry with the dominance of China in the global steel industry, and the high emissions of Chinese production (European Commission, 2023; Reynolds, 2024). The EU has introduced a Carbon Border Adjustment Mechanism in addition to the domestic ETS to penalise emissions in imported products (European Commission, 2021). Governments beyond the EU have used emissions to motivate tariffs on Chinese steel (Friedman, 2021; Podesta, 2024), as have US and EU steelmaking associations done in their lobbying efforts (Eurofer, 2024; Steel Manufacturers Association, 2024). The growth of steelmaking in China has therefore been an important factor in creating a political willingness to use green industrial policy for the steel industry.

The second trend I want to highlight is the rise of renewable energy as a low-cost, geographically abundant source of energy. From 2010 to 2024, the levelized cost of energy (LCOE) of wind and solar has fallen by two-thirds and nine-tenths respectively (IRENA, 2025). With the rise in interest rates since the covid pandemic, the fall in costs has been somewhat arrested but again picked up momentum (International Energy Agency, 2025). As renewable energy costs fall, the potential for energy-intensive industry to transition to renewable energy sources is becoming increasingly attractive. In the book *The Price is Wrong*, Brett Christophers shows how the falling cost of renewable energy does not in and of itself lead to a transition away from fossil fuels (Christophers, 2024). Rather, he shows that it is profitability – not cost – that drives the deployment of renewable energy, and that profitability is not certain enough for rapid deployment. However, Christophers does not discuss how falling costs of renewables can improve the profitability of *downstream* low-carbon projects using renewable energy. A growing number of policymakers, steelmakers and mining firms are investing in the use of renewable energy to power operations, partially for the competitive potential in future "green steel" markets (Bataille et al., 2024), and partially for the strategic benefits of decoupling industrial prices from global fossil fuel prices (see e.g. (Draghi, 2024)). Recent academic research has gone further and suggested that as energy is a significant cost for energy-intensive industry, it is likely that there will be a trend where renewable-rich regions attract or "pull" investments in industries such as steel (Devlin et al., 2023; Samadi et al., 2023; Verpoort et al., 2023). The falling cost of renewables has been an enabler of profitable non-fossil steelmaking that firms and policymakers seek to exploit.

The third trend is the process of deindustrialisation and social decline in former industrial regions across Europe and North America. 18 000 jobs have been lost in the EU steel sector in 2024, in addition to the 90 000 jobs lost since 2008. According to the European steel industry association Eurofer, another 300 000 direct jobs and 2 300 000 indirect jobs are currently at risk (White et al., 2025). In their book *Rust Belt Union Blues*, Lainey Newman and Theda Skocpol show and explain political frustrations rising in the wake of deindustrialisation in the former steelmaking region of Western Pennsylvania (Newman & Skocpol, 2023). With a combination of interviews, union membership data, and a creative collection of data on the number of union halls, union locals, and bumper stickers at parking lots outside steel mills, Newman and Skocpol show how industrial decline has driven political shifts with major effects on federal US politics. In the 2024 election, both Republicans and Democrats therefore pushed for various types of steel-oriented industrial policy, particularly focusing on tariffs and green modernisation respectively (Waldman, 2024). Similar dynamics are seen in Europe, Canada and Australia, where green modernisation of steelmaking and associated reindustrialisation has been part of electoral pitches at national and regional levels (Crawley, 2022; Fildes, 2025; Packroff, 2024). The French National Assembly recently passed a motion to nationalise and decarbonise ArcelorMittal assets which was supported by the CGT union (AFP, 2025). Green industrial policy for the steel industry has been a method for governments and parties across the world to claim to boost industrial production and reinvigorate deindustrialised towns and regions.

The fourth trend is the rise of climate change as a real threat to human society. 1980-2008, there was only one year where the United States suffered nine or more billion-dollar weather and climate disasters, and the average number of such disasters per year was five. Every year since – save 2010 – has had nine or more billion-dollar such disasters. Since 2020, the number of billion-dollar disasters has averaged 23 per year (National Centres for Environmental Information, 2025). In the EU, average annual costs of extreme weather events amounted to €44.5 billion between 2020 and 2023 – two and a half times higher than between 2010 and 2019 (Hancock, 2025). The EEA estimates that industrial supply chains are directly exposed to climate risks, in particular heatwaves and droughts (European Environmental Agency, 2024b). Heatwaves increase electricity demand and reduce the efficiency of electricity production and transmission. Forest fires risk infrastructure such as power transmission and transport. According to the EEA, the drought of 2018 shut down transport at the river Rhine, forcing German steel manufacturer Thyssenkrupp to reduce production by an estimated 200 000 tonnes due to a lack of supplies. The shut-down is estimated to have reduced German GDP by 0.2 percent. As I write these words, unprecedented rainfall has wiped out rail tracks in mid-Sweden, cutting deliveries for the Swedish steel, forestry, and chemical industries (Isberg, 2025). Despite recent political defeats of the climate movement, industrial firms, state bureaucracies and broader segments of the political spectrum are therefore increasingly under pressure to mitigate and adapt to climate change.

These four concurrent political-economic trends drive a rise in the use of industrial policy for the decarbonisation of the steel industry over the past decade. Studying steel decarbonisation has therefore been a lens through which I have aimed to understand larger dynamics in contemporary capitalism.

Aim

The aim of this thesis differs from common approaches in the energy system and political science literature on decarbonisation and green industrial development. Hence, the aim is not to model a decarbonised steel system by 2050 and draw conclusions on the necessary steps to get there, as is common in contemporary energy system studies (see e.g. (Li et al., 2022; Watari et al., 2023)). Neither is the aim to critique the lack of action on decarbonisation and provide a theory of why action is lacking, or analyse the motivations or processes that have led up to the passage of a policy, both which are common in contemporary political science (see e.g. (Breetz et al., 2018; Meckling & Karplus, 2023; Schmid et al., 2019; Tilsted, 2024). Rather, the aim is to understand what has been the role of policy in the *really existing* development of low-carbon steelmaking – both on the technology development and deployment side – and how it can influence industrial decarbonisation, as well as what are the limitations of such policy on its own terms.

Therefore, the thesis is structured around the research question *in what way is green industrial policy shaping the decarbonisation of the steel industry?* This research question allows me to analyse green industrial policy for steel from multiple angles. In the papers, I have in turn broken down this wider research question into the following sub-questions:

> A) How do endogenous strategic, organisational, and financial conditions affect the decarbonisation of incumbent industrial firms?
>
> B) How does the relationship of energy costs and industrial policy affect the decarbonisation of steelmaking?
>
> C) Why are policies and approaches of deliberate decline necessary for the decarbonisation of steelmaking?

With these sub-questions, I have been able to look into green industrial policy at three distinct and complementary levels; the firm level, the comparative domestic policy level, and a global market level. This thesis adopts an empirical approach, focusing on existing developments in industry and policy. Indeed, focusing on ongoing policy developments within steel decarbonisation has also meant that the thesis includes a close study of a major well-known policy program – okay, it's the *Inflation Reduction Act* – that has now been rescinded. However, the empirical focus does not mean that the thesis does not use theory or contributes to the development of theory. The thesis is informed by theories of innovation, green industrial policy, and industrial development, and contributes to theories of innovative enterprise, competitiveness and deliberate decline. These insights are further discussed in the results section of this thesis frame.

The thesis consists of five papers, each of which studies an element of green industrial policy for the steel sector, plus this summary. In this summary, I explain how the five papers relate to and complement each other. Paper I is a review of the literature on steel decarbonisation where my co-authors and I present the recent changes in the literature and what that means for trajectory of industrial transformation. In Paper II, I conduct a close process-tracing of the strategic decisions within the HYBRIT joint venture firms that were necessary for the development of the first major hydrogen-based steelmaking pilot plant in the world. Two studies – Paper III and Paper IV – connect theory from the economics of energy and international trade. These papers engage with the "renewables-pull" hypothesis, where access to low-cost renewable energy will pull investment in energy-intensive production. In Paper III: Competition and climate policy – my co-authors and I make the case that this is a new edition of a recurring argument in economics: that economic specialisation follows from endowments of natural resources giving rise to comparative advantages, and that this specialisation is benevolent in that it enables global trade to leverage optimal low-cost production sites. We nuance this view by arguing for the centrality of fiscal capacity and industrial experience. In Paper IV we continue this work, by analysing a wider set of locations, value chain configurations, and policies, and their respective effect on the cost of low-carbon steelmaking. Paper V makes the case that the particular characteristics of the steel sector such as durable assets, high closure costs, long economic legacies, and local employment effects give rise to high barriers to exit that block the closure of unprofitable firms and contribute to steel overcapacity. We combine literatures on phase-out and barriers to exit in the steel sector and review low-carbon steel projects to find that there is a lack of closures corresponding to new low-carbon plants. Therefore, for a sector-wide uptake of new low-carbon steel assets, previous fossil-based assets require dedicated policies encouraging their deliberate decline.

Research process

This thesis is an outcome of the Circular and Sustainable Steel Transitions (CAST) project, supported by the Swedish Energy Authority. The research project aims to increase the understanding of how the emergent fossil-free steel system can become commercially viable and diffuse internationally. This aim is attained by increasing our knowledge about the conditions affecting the pace and extent of a global transition to fossil-free steel production. The research project builds on research made as part of the HYBRIT Research Project 1, which was more focused on technical aspects of the transition.

The aim has a wide scope, and a single PhD thesis cannot cover all the conditions affecting the pace and extent of a transition of a socio-technical system. Due to my interests in the global turn towards green industrial policy, the papers this thesis builds on have therefore taken an increasingly deep look at the role of industrial policy in shaping markets and firm strategies in the steel industry.

The research process for this thesis started by directly building on previous work at the division, primarily led by Valentin Vogl (Nilsson et al., 2021; Vogl, 2023; Vogl et al., 2021; Vogl et al., 2023). This work analysed the technical conditions of phase-outs in the steel industry and the need for such phase-outs in line with carbon budgets. The paper first written for this thesis (Paper V) therefore studied the role of phase-outs in the global steel transition and the geopolitical frictions arising from global overcapacity. In order to increase the granularity of the study, I thereafter turned towards policy mapping and techno-economic modelling of existing policies for a low-carbon steel transition (Papers III and IV). At the same time, my supervisors and I started working on a review (Paper I) that could synthesise our view of the ongoing steel transition and the new questions that are arising around the conditions for deep decarbonisation. Finally, to go even deeper into the processes that have shaped really existing steel decarbonisation projects, I chose to inquire about the conditions for innovation within the firms that have led the early, leading steel decarbonisation project HYBRIT (Paper II). As a collection of papers however, I have chosen to situate them in a different order than the research process, starting with the review framing the work, moving from the firm level of transitions, through a comparative domestic policy level, ending at the global market level. This reversed order better reflects how the subject should be approached. By first explaining the conditions for an industry-wide socio-technical transition and firms' decisions when navigating a transition before reaching the domestic policy and global market level, we can better understand policy and industry systems.

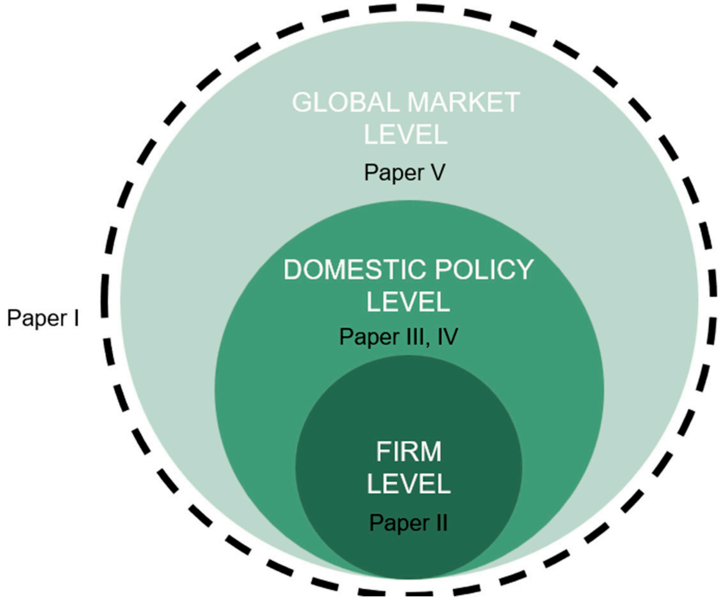

Figure 1: Situating the papers.

Delimitations

"Steel" is a word covering multiple types of products with different qualities and forms. It can also be produced in multiple production routes. Conventionally, steel production is divided into two categories, depending on the main metallic input. Steel can be made from scrap which is low-cost and relatively easy to melt into new steel products although limited in quantity and quality (Watari et al., 2023). Steel made in this route is usually used for long products primarily in the construction sector. Steel can also be made from "virgin" iron ore, which allows greater control of metallurgical purities usually required for producing flat products traditionally used in the automotive sector. This latter form of steel made from iron ore is called "primary" steel and is more emission-intensive than the scrap-based "secondary" route. This is because oxygen must be taken out of the iron ore to produce iron, which is today conventionally done through the addition of carbon in a blast furnace (BF). The chemical process leads to the production of carbon dioxide. Scrap on the other hand can be melted into new steel in an electric arc furnace (EAF) which is powered by electricity, and therefore easier to decarbonise through the deployment of clean power. Hence, this thesis focuses on the decarbonisation of primary steelmaking, although it should be mentioned that new technological configurations allow for increased blending of scrap and iron, and a merge of the two routes.

A second delimitation is the closely connected choice of energy and technology. Most of the papers constituting this thesis focus on the emergent hydrogen direct-reduction electric arc furnace (H-DR-EAF) steelmaking route, although papers I and V discuss other technology choices. The reason is that this route is currently the most prominent route of choice for low-carbon steelmaking projects around the world (Vogl et al., 2023). A transition away from the traditional blast furnace-basic oxygen furnace (BF-BOF) route to the H-DR-EAF route requires new furnaces to be built and a closure of the old ones, rather than retrofitting existing sites with new technology, for example carbon capture and storage (CCS) technology. Such a switch also requires large amounts of new clean energy, and in this thesis, I focus on renewable (solar and wind) energy. The reason is that these technologies have low costs across the globe and strong complementarities with hydrogen-based steelmaking through energy storage. That transformative, rather than incremental, change produces new potentials and challenges for policymaking.

A third delimitation is that this thesis primarily focuses on green industrial policy for the steel industry in the EU and the US. Paper II is a case study of industrial policy in Sweden, and Paper III is a comparative study of policy mixes in the EU and the US. Living in the EU and being part of a network of researchers mainly based in the EU and the US, my work has mainly been informed by developments in these jurisdictions, which is like to produce an attention bias. While papers I, IV and V have a global outlook they are limited by this attention bias. Paper II is a case study of Sweden on the role of SOEs, however most SOEs in the sector are in Asia, and particularly in China (OECD, 2018). Paper III compares policies in the EU and the US. This bias may shape the insights and conclusions drawn from this research.

Theoretical approach

The political economy of green industrial policy

The research for this thesis has been conducted in the spirit of a relatively recently emerging generation of interdisciplinary applied research on green industrial policy, see for example (Aiginger & Ketels, 2024; Aiginger & Rodrik, 2019; Bataille et al., 2018; Breetz et al., 2018; Bulfone et al., 2023; Ferrannini et al., 2021; Juhász et al., 2024; Mazzucato & Rodrik, 2023; Meckling, 2021; Meckling & Allan, 2020; Meckling et al., 2017; Nilsson et al., 2021; Trollip et al., 2022; Wade, 2018; Wesseling et al., 2017; Åhman & Nilsson, 2015; Åhman et al., 2017). This literature uses a mix of qualitative and quantitative methods to study questions such as for example how recent geopolitical changes or domestic political changes and coalitions affect the conditions for industrial policy, how policymakers' approach industrial policy, or sectoral aspects of industrial policy. This approach is fundamentally different from studies that approach the issue of transitions from the perspective of what ought to be done on the basis of climate targets, justice and historical responsibilities, or from social and political impacts (see for example (Ban & Hasselbalch, 2024; Holmberg et al., 2024; Li et al., 2025; Newell et al., 2022; Tilsted et al., 2023)). While such studies are important, this thesis approaches green industrial policy from the perspective of what *is* being done and what does that say about the potentials and limits of green industrial policy. This is not to affirm the world as it is, but rather to base this research on the recognition that any attempt at a transition will have to depart from these conditions.

While the aim is within the realm of applied policy studies, the thesis both draws on and contributes to theoretical development. The theoretical foundation for this work is the assumption that carbon lock-in shapes economic activity and development (Seto et al., 2016; Unruh, 2000). Carbon emissions are an outcome of how global economies have developed over time based on infrastructures, industries and materials that require fossil fuels or produce process emissions in their production or use (D'Costa, 1999; Florida & Kenney, 1992; Hughes, 1987). Innovation dynamics are therefore important, as the development of new technologies can further entrench current practices or enable a transition away to new systems (Auty, 1991; Dosi et al., 1997; Grubb et al., 2002; Pavitt, 1984; Perez, 1983). This literature has a long tradition, dating back to Schumpeter who developed the theory of "creative destruction" where new innovations render existing systems obsolete

(Schumpeter, 1994). I would also like to highlight the early contribution of Paul Sweezy in explaining how profits drive innovation (Sweezy, 1943). Given that economic activity remains overwhelmingly tied to carbon emissions, innovation in new infrastructures, production techniques and technologies and materials are necessary for future economic activity without carbon emissions. Reaching climate targets and decarbonising energy-intensive industries such as the iron and steel sector therefore requires change in the form of a transition; a breakout of carbon lock-in at a sufficient pace to avoid catastrophic climate change (Nilsson et al., 2021; Wesseling et al., 2017; Åhman et al., 2017).

Regardless of such climate imperatives, industrial activity is primarily controlled by firms who seek to maximise profits (Copley, 2024; Lazonick, 2014; Silva, 2017). Competition renders deviations from profit maximisation unsustainable as firms would then lose their market position to rivals. The low cost of fossil fuels and the advanced stage of development of highly emitting infrastructure and technology renders unsupported change unprofitable (Christophers, 2024; Gabor, 2021; Nilsson et al., 2021). The critical actor that can induce change at the required speed, scope and scale is therefore the state. The state has historically been and is currently an actor shaping economic activity in a multitude of ways, ranging from innovation and deployment of new technologies to investment in infrastructure to the phase-out and closure of unsustainable practices (D'Costa, 1994; Evans, 1995; Markard, 2011; Rogge & Johnstone, 2017). The state can reduce the cost of new low-carbon technologies through subsidies or increase the cost of high-emission technologies via regulation and fees (Grubb et al., 1995; Grubb et al., 2021). The state has historically similarly supported industrial development and catch-up in for example East Asian economies, through supportive industrial policy such as subsidies, state-ownership, strategic investments, and coordination of supply chains (D'Costa, 1994; Evans, 1995; Lane, 2025). The US state has played a major role in supporting innovation through various support and coordination schemes (Wade, 2017). In the EU, government subsidies for low-carbon energy supported deployment of technology, with spillover effects across the world (Meckling, 2018).

Despite the need to address emissions, climate targets do not necessarily motivate states to introduce policies. Instead, policy is highly sensitive to other domestic and international political pressures arising from political coalitions and/or geopolitical competition. Such pressures can follow from how new technologies make entire sectors "decarbonisable", whereby firms may change their political strategy from opposition to cooperation on climate policy (Kupzok & Nahm, 2024; Meckling & Strecker, 2022). Workers and voters also pressure policymakers depending on whether they see positive or negative outcomes from green industrial policy development (Breetz et al., 2018; Bulfone et al., 2023; Mayfield et al., 2023). Competition from foreign industries capturing a growing market share within given sectors may lead to strong pressures on policymakers to respond (Aiginger & Ketels, 2024; Allan & Nahm, 2024; Reynolds, 2024). It is therefore central to understand green industrial policies as a product of political economy – not climate targets alone.

In Paper I, which is a theory-agnostic review paper, my co-authors and I explain how steel decarbonisation has become less an issue of optimising energy and materials use in existing assets, and increasingly an issue of system change. This increases complexity and makes the above questions of political economy essential for steel decarbonisation. How do then such political economy constraints – firm behaviour, international competition and domestic politics – shape the conditions for green industrial policy? To answer this question in any meaningful way, we need a more granular level of theoretical abstraction. The research questions of the thesis concern the conditions for innovation in incumbent firms, the relationship between energy costs and policy for the decarbonisation of steelmaking, and the role of deliberate decline for a transition of the steel industry. Let us discuss the theoretical space of each in turn.

Firm behaviour and innovation

Paper II lies within the theoretical space of firm-level innovation. Firms are social organisations, governed by executives who allocate resources for innovation based on expectations of future profitability. A large literature studies socio-technical transitions at the system level where firms are key agents (Geels et al., 2017; Kushnir et al., 2020; Wesseling et al., 2017; Zolfagharian et al., 2019). The transitions literature studies how innovations develop and can transform the socio-technical configurations of various industries over time. There are many case studies of historical and contemporary examples of such transitions, and the interplay of system components (Karakaya et al., 2018; Normann, 2015; Verbong & Geels, 2007). However, the internal dynamics of firms that constitute key parts of such systems remain understudied. There is an emergent literature on the effect (and limit) of environment, sustainability and governance (ESG) targets, science-based targets and similar frameworks for firm behaviour (Tilsted et al., 2023; Zhou et al., 2022). However, while this literature can provide a critique of the gap between claims and actions within firms, more research is needed on how changes *within* firms have enabled the development of low-carbon technologies and a move away from unsustainable practices. This thesis attempts to study why key firms in the Swedish steel industry did change their strategic orientation and chose to allocate resources for an industrial transformation.

The paper applies the Theory of Innovative Enterprise (TIE), which is a theoretical framework for the study of firm innovation developed by a group of scholars around William Lazonick (see e.g. (Hopkins & Lazonick, 2024; Lazonick, 2014, 2023; Lazonick & Mazzucato, 2013; O'Sullivan, 2000; Palladino, 2020)). As there are differences in behaviour and strategic orientation between private and state-owned firms, the paper also discusses theoretical insights from studies of state-owned firms and their role in decarbonisation, such as (Benoit et al., 2022; Bulfone et al., 2023; Steffen et al., 2022; Tõnurist & Karo, 2016). This paper makes a theoretical contribution by applying the TIE to state-owned and decarbonising firms and asking how state-ownership can affect firm decarbonisation strategy. It finds that incumbent firms that have made real investments in the development of low-carbon steelmaking have had to align their strategy and financial targets with decarbonisation, over profit distribution.

The renewables-pull effect

A second theoretical space for this thesis, applied in Papers III and IV concerns the "renewables-pull hypothesis". This hypothesis argues that energy produced via renewables is seeing falling costs but is less tradable than coal and oil. Therefore, regions with strong renewable potential will become competitive industrial locations for energy-intensive industry where energy is a major cost. Such energy-intensive industries will therefore relocate away from traditional industrial hubs such as central Europe, northern United States and east Asia to renewable-rich areas such as the Middle East and Australia. Multiple studies have been published that estimate the renewables-pull effect (Devlin et al., 2023; Gielen et al., 2020; Samadi et al., 2023; Verpoort et al., 2023), discuss how countries position themselves in relation to such competitive pressures (Eicke & De Blasio, 2022), as well as geopolitical and social effects of such relocation (Trollip et al., 2022). Some studies discuss the factors that may mitigate the renewables-pull effect, such as policy interventions and variations in infrastructure development (see for example (Samadi et al., 2023; Schneider, 2022; Verpoort et al., 2023)). This literature builds on a long debate in economics on the nature of comparative advantages derived from natural resources, social institutions or class structures (Johnson, 1988; Klein & Pettis, 2020).

However, this literature does not engage with the literature on industrial location with roots from long before the development of cost-competitive renewable energy. Multiple papers have been published that specifically look at the industrial location of the steel industry over time, and how this has been shaped by a multitude of factors, such as various forms of industrial policy – for example in the case of South Korea – as well as trade policy, the flexibilities of facilities, and labour costs (Auty, 1991; Bain, 1992; D'Costa, 1994; Florida & Kenney, 1992; Moore, 1996; Walker & Storper, 1981). While the renewables-pull literature makes a strong case that the development of low-cost renewables will create a pull effect on investment, this one-sided focus on renewables and use of methodologies based on cost-modelling lead to incomplete conclusions on international competitiveness. In our studies, we have tried to show how even on its own terms, the renewables-pull hypothesis is not as conclusive when subsidies are included as a single form of policy intervention. By including existing subsidies in the US and the EU in a in model of cost-competitiveness, as well as making simple assumptions that similar policies could be introduced across jurisdictions, we find that policy is another factor that should be included in such modelling. We also find that such modelling of the renewables-pull effect is sensitive to assumptions on other cost factors, such as labour costs. Therefore, theories of competitive advantages need to include more factors than natural resources.

Deliberate decline

A third theoretical space used in Paper V concerns the deliberate decline – or phase-out – of unsustainable practices in industry (Rinscheid et al., 2021; Rosenbloom & Rinscheid, 2020; Vogl et al., 2021). There is an emergent critique of the transitions literature, that the world is in fact not seeing any energy transition away from fossil fuels yet, but instead seeing energy addition – that renewable energy is added op top of total fossil fuel use (Christophers, 2024; York & Bell, 2019). While studies show that the cost difference of emission-intensive and low-carbon production is not only shrinking, but actually in favour of low-carbon production (as for renewable energy) it is important to not implicitly assume any rational organisation of production, where market forces simply lead to a transition away from fossil-based production. In the steel industry, the irrationality of production has been a problem for multiple decades, not only for decarbonisation, but for profitability (Copley, 2024). The steel industry has suffered from structural overcapacity and unprofitable underutilisation of assets for decades, even prompting the establishment of high-level political forums such as the OECD Steel Committee and the G20 Global Forum on Excess Steel Capacity to try to improve coordinated management and reduce overcapacity. These attempts at reducing overcapacity have failed (OECD, 2025). Therefore, it would be wrong to assume that any automatic rational organisation (and transition) of the global steel industry would follow from the introduction of cost-competitive low-carbon production.

Paper V therefore engages both the studies on the technical potential of phase-outs in the steel industry (Agora Industry et al., 2024; Vogl, 2023; Vogl et al., 2021), barriers to exit in the steel industry (Deily, 1988; Deily & Gray, 1991; Rimini et al., 2020), as well as the literature on policies for deliberate decline. Deliberate decline represents the ‘flipside’ of innovation and development of new low-carbon technologies and instead concerns conditions for and effects of policy-driven closures of emission-intensive production and consumption. Policies can lower economic and political barriers to exit by subsidising the demolition of assets, environmental clean-up of sites and retirement of workers, and by enabling alternative industrialisation for workers and communities dependent on emission-intensive sites for employment. Such deliberate decline can provide strong incentives for new innovation as firms seek to find new sources of revenue, giving rise to the concept of “exnovation” (Arne Heyen et al., 2017; David, 2017; Rogge

& Johnstone, 2017). However, the potential for policy-driven closures is also constrained by technological and political factors. Industries tend to resist change unless technological alternatives exist or the sector has already advanced in its transition (Kupzok & Nahm, 2024; Meckling & Nahm, 2019; Meckling & Strecker, 2022).

Theoretical complementarities and differences

The theoretical space of the various papers are complementary, due to the various levels at which determinant processes for the steel industry operate. While these different theoretical approaches are associated with particular ontological assumptions, they are not in conflict with one another but rather focus on different aspects of industrial transitions and change. The renewables-pull literature has no theory of the firms it assumes will make investments based on an optimisation of cost structures. Nor does it have any theory of emission reductions in a sector characterised by overcapacity. Correspondingly, the theory of innovative enterprise is not concerned with sectoral decarbonisation and the deployment of technologies across geographies. Therefore, when studying the decarbonisation of the steel sector, I have opted to engage with different theoretical frameworks depending on the level of analysis. This approach enables a more comprehensive study of the social process that is steel decarbonisation.

At the firm level, this thesis finds that firms balance investments in low-carbon innovation and deployment with profit distribution to shareholders and that the imperative to distribute profits is not compatible with such major investments. While policymakers try to incentivise firms to invest in low-carbon production by providing subsidies for such investment, they are likely to be limited by whether firms see how that affects their ability to distribute profits. Other options exist, as policymakers can induce investments in low-carbon production more directly in state-owned firms, by changing the strategic and financial targets of such firms. Such changes might even be more effective than subsidies.

Second, while firms and policymakers have made some efforts to invest in low-carbon steelmaking, this is not the same as reducing emission-intensive steelmaking. In fact, while various forms of subsidies can induce investment in new technologies and low-carbon production, such support has tended to increase total steelmaking capacity. Historically, specific policies to penalise trade, or support the closure of obsolete technologies have been necessary to close steelmaking assets. However, such policies do not constitute any meaningful part of contemporary steel decarbonisation policy.

Situating the papers

The theoretical insights from each paper complement each other. Paper I situates steel decarbonisation within a frame of system change. Paper II develops the TIE framework for decarbonisation of industrial firms. This paper shows how firms allocate resources for innovation, and how radical decarbonising innovation conflicts with the typical sectoral focus on incremental cost-cutting innovation in pursuit of profits. The paper stops short of explaining the role of external conditions of policy and energy costs that can shape the conditions of profitable investment in low-carbon steel. This is instead done in papers III and IV. The relationship between these papers is important, as it covers both external conditions for investment and how such investment aligns with the pursuit of profit. These socially determined conditions – government policy and firms' pursuit of profit – nuance and complicate results from studies finding the "optimal" location for low-carbon steelmaking (e.g. (Devlin et al., 2023; Li et al., 2022; Samadi et al., 2023)).

Finally, building on the Schumpeterian notion of "creative destruction" (Schumpeter, 1994), paper V goes beyond the *creative* issue of how to build low-carbon steelmaking of the previous papers, and instead discusses the *destructive* side of industrial transitions, which is the corresponding closure of existing emission-intensive plants. Previous technology-oriented research on the phase-outs and closure of blast-furnaces (e.g. (Deily, 1988; Deily & Gray, 1991; Vogl et al., 2021)) have provided insights on the barriers to closures, and how the reinvestment cycles relating to relining of blast furnaces are opportunities where these barriers to closures are lower. However, this research has not been put in the context of overcapacity and an expansion of low-carbon steelmaking capacity. Our study therefore contributes with a conceptualisation of how the lack of closures limit the long-term viability of the steel transition and situates it within a geopolitical frame.

Table 1: The research questions, theoretical space and concepts of the five papers.

Paper	Research question	Elements of main RQ addressed	Theoretical space	Concepts
Paper I: Steel decarbonisation: From optimisation to transformation	How has recent technological change enabled shifts in academic and policy approaches to steel decarbonisation?	Framing.	Theory-agnostic review paper.	Carbon lock-in, industrial transformation, value chain reconfigurations, overcapacity.
Paper II: The innovative state-owned enterprise	How did endogenous factors affect the development of the HYBRIT low-carbon steelmaking project? How can the social conditions for innovative enterprise inhibit or enable the decarbonisation of energy-intensive industry?	*How do endogenous strategic, organisational, and financial conditions affect the decarbonisation of incumbent industrial firms?*	Firm governance, innovation studies.	Theory of the Innovative Enterprise, innovation policy, industrial transitions.
Paper III: Competition and climate policy in the steel transition	What is the relative cost effect of energy and existing policies along the low-carbon steel supply chain in the EU and the US?	*How does the relationship of energy costs and industrial policy affect the decarbonisation of steelmaking?*	Renewables-pull hypothesis. International competition.	Geo-political competition, comparative advantage, climate policy, renewables-pull hypothesis.
Paper IV: Renewables pull and strategic push – What drives hydrogen-based steel relocation?	How large difference in LCOS can emerge for different configurations of H-DRI-EAF based steel value chains? How sensitive are conclusions on the renewables pull effect to varying assumptions on key techno-economic variables and other strategic considerations?	*What is the relationship of energy costs and industrial policy in the decarbonisation of steelmaking?*	Renewables-pull hypothesis. International competition.	Geo-political competition, climate policy, renewables-pull hypothesis, value chain configurations.
Paper V: Phase-in and phase-out policies in the global steel transition	What are barriers to exit (BTE) for conventional steelmaking plants? How are policymakers addressing BTEs as part of industrial transitions?	*Why are policies and approaches of deliberate decline necessary for the decarbonisation of steelmaking?*	Phase-outs and deliberate decline.	Phase-outs, deliberate decline, overcapacity, barriers to exit, phase-ins.

A note on the limits of this approach

The steel industry is a socio-technical system composed of both technical and social elements. A single thesis cannot cover all technical and social elements, and therefore some key elements of the system have been excluded from the study. These are for example political elements such as coalitions that affect policy developments within given jurisdictions and their internal dynamics. Political processes are drivers of policy, and green industrial policy is therefore a product of political processes within specific national contexts. This thesis however focuses on existing policies and does not explain political processes that enabled them or can change policy in the future. Another limit with this approach is that the development of new technologies that can enable production of low-carbon steel but are currently at early development levels are not studied in the thesis. These are for example direct electrolysis, developed for example by the firm Boston Metals (Agora Industry et al., 2024). Such technologies have the potential to shape the future of steelmaking but are at the moment at such early development levels with minor implications for industrial policy and commercial-scale steelmaking.

Research methods

The subject of industrial transitions can be studied through a number of disciplines. I have been fortunate to study at the highly interdisciplinary Lund University division for Environmental and Energy Systems Studies – which empowers its students to utilise several different methods and approaches – and to be able to collaborate with researchers at the Stockholm Environment Institute. This has enabled me to develop both qualitative and quantitative skills that I have employed where relevant.

In order to study green industrial policy for the steel sector from various perspectives, I have chosen to employ a number of methods. These methods and the theoretical frame used are shown in table 2.

Table 2: The research methodology, type of data and data source, and data analysis of the five papers.

Paper	Type and source of data	Application and data analysis
Paper I: Steel decarbonisation: From optimisation to transformation	Various types of literature, including IPCC reports, academic journal articles, NGO reports, estimates from consultancy firms.	Literature review.
Paper II: The innovative state-owned enterprise	Meeting notes, speeches, internal presentations, email correspondence accessed from the Swedish Government Offices. Corporate annual reports, and press releases. Interviews. EU R&D Industrial Investment Scoreboard.	Coding of keywords and process tracing. Semi-structured interviews.
Paper III: Competition and climate policy in the steel transition	Policies announced on US government and EU commission websites. Wage data from UNIDO and from United Steelworkers websites. CAPEX, energy cost estimates, and cost equations from academic journal articles.	Policy mapping, techno-economic modelling.
Paper IV: Renewables pull and strategic push – What drives hydrogen-based steel relocation?	Estimates and cost equations from academic journal articles, IEA, and grey literature. UNIDO wage data.	Literature review. Techno-economic modelling.
Paper V: Phase-in and phase-out policies in the global steel transition	Green steel projects from the LeadIT Green Steel Tracker data set. Policies announced on government websites and reported in grey literature. Interviews.	Project review and analysis, policy mapping, semi-structured interviews.

Paper I is a review of the academic and grey literature on steel decarbonisation. The aim was to show change in academic approaches to steel decarbonisation over the past decade, and therefore we started with a review of the chapters on Industry in the IPCC assessment reports (AR) five and six from 2014 and 2022. We thereafter included literature since the cutoff date for IPCC AR 6, in October 2021 to include development in the literature since. As part of our literature search, we included literature referenced in the IPCC chapters, as well as later works by referenced authors.

Qualitative case study

Paper II employs a qualitative methodology, where the primary data was internal documentation of correspondence, strategic discussions, annual meetings and other documents across the government and the two state-owned firms LKAB and Vattenfall, accessed from the Swedish Government Offices (SGO) via the principle of public access to information. It is a study of the innovation project HYBRIT, which was launched in 2016. In order to delineate the relevant period, I chose to set the decision to move on the project with an industrial-scale demonstration plant in Gällivare as the end year studied, as the project at that point was moving into a scaling and deployment phase. I chose to include two years prior to the launch of the project in order to capture relevant circumstances ahead of the launch. In discussion with staffers at the SGO, the material requested was narrowed-down to key documents on meetings concerning strategy, industrial collaboration, economic targets, and the development of the HYBRIT-project. This process produced 1300 pages of documents. This material was searched for discussions on strategic, economic, and sustainability targets, the distribution of profits, and investments in new clean power and/or new HYBRIT facilities. This archival material has then been triangulated through four semi-structured interviews with former members of the board and executive staff at SSAB and Vattenfall. Desk research of annual reports, press releases and newspaper articles provided additional insights on the timeline of decisions and events.

This qualitative approach enables analysis of strategic decisions at the corporate level. This is a rare material, as such direct access is rarely accessed beyond what is shared as public information or through interviews which has the limitation that not all considerations are shared in public, and as explanations of strategic decisions can be skewed in interviews. This material covers discussions as they were at the time, which provides a unique insight in considerations made by firms as they innovate and adapt strategies to decarbonisation targets. Industrial policy is to a large degree about shaping firm behaviour to reach desired goals. This methodology allows for the study of what trade-offs firms face as they adapt to new cost structures, policy incentives and competitive pressures, which is central for the effectiveness of industrial policy. However, this is a single-case-study. Therefore, the methodology does not allow for direct comparisons with other cases with different political and/or ownership conditions. Conclusions should therefore be limited to how the firms and policymakers navigated constraints to decarbonisation in the specific case.

Policy mapping and techno-economic modelling

Paper III combines qualitative and quantitative methods, through policy mapping with techno-economic modelling. The policy mapping used US government and EU commission websites to map subsidies along the low-carbon steel supply chain. These were compiled and used in a techno-economic model of the cost of low-carbon steelmaking across four jurisdictions, Ohio and West Virginia in the US, and Spain and Germany in the EU. The US jurisdictions were chosen to reflect two geographically close jurisdictions in the US with similar renewable energy potentials, but where labour costs are different as steelworkers in Ohio are unionised but not steelworkers in the right-to-work state of West Virginia. The EU jurisdictions were chosen to include Spain with strong low-cost renewable energy potential, relatively low wages, and new low-carbon steel projects, and Germany which is the largest steelmaker in the EU, relatively high wages and poorer renewable energy potential. Data on subsidies and labour costs were included in our model along with data on capex, energy costs for each location, and costs of operations and maintenance.

This paper aims to combine methods. Policy mapping is a method that enables analysis of policy frameworks within given jurisdictions that can both help explain the policy landscape that firms navigate, as well as the strategic approaches of policymakers. In order to more comprehensively capture how policy frameworks shape the conditions for firms to develop in a desired way, this mapping exercise is combined with a quantification of support and costs in given locations. We can thereby analyse and compare the relative importance of various policy interventions across jurisdictions and locations with different energy and labour costs. This quantitative methodology builds on the techno-economic modelling done in the literature on the "renewables-pull effect" and industrial relocation but adds a thorough analysis of the role of policy in augmenting such pull effects.

Paper IV also engages with the literature on the "renewables-pull" hypothesis and therefore includes a close study of the assumptions in the existing literature. It covers assumptions on resources, energy costs, labour costs and transportation costs, and – as in Paper III – introduces subsidies into the model. This paper looks at a larger number of locations than Paper III, as well as various configurations of low-carbon steel supply chains, i.e. both cases where all production is done at one site, and where the different segments of production are dispersed across various locations. This paper uses the same model as in Paper III but inquires different sites and transportation costs. It does not use policy mapping but instead makes assumptions based on existing subsidies to illustrate the potential of subsidies relative to other cost components. It therefore produces a richer analysis of how various value chain configurations and policy interventions can alter the cost-competitiveness of low-carbon steelmaking across locations.

Project review, policy mapping and interviews

Paper V starts with the literature on sector-specific barriers to exit and inertia and empirically reviews policies and low-carbon steel projects in top steelmaking jurisdictions and quantifies the number of low-carbon steel projects that replace, augment or add to existing capacity. The project analysis is based on the LeadIT Green Steel Tracker dataset. This dataset includes investment announcements for near-zero emission primary production of iron and steel and includes a methodological protocol for the selection of projects (see (Vogl et al., 2023)). For the study of policies, we conduct a document analysis compiling information from scholarly publications, reports from international organizations such as the IEA and the OECD, and private consultancies, as well as official government publications aiming to review the major relevant policies affecting steel decarbonisation. To triangulate the results from the document analysis, and as well to guide further desk research, eight semi-structured, open-ended interviews were conducted with steel experts across the four major steelmaking jurisdictions China, the European Union, the United States, and India. The policy study is delimited to these top four jurisdictions due to their large share in global steelmaking.

While the policy landscape is rapidly changing and the low-carbon steel sector remains emergent, this methodology produces a snapshot of low-carbon steel projects, whether they have depended on policy support, and whether they lead to emission reductions by replacing existing emission-intensive production. The methodology does not enable analysis of whether the projects will increase steel overcapacity, or whether there may be closures in the future. But it does show that the development of new low-carbon steel projects and the closure of existing emission-intensive plants are often two separate decisions, which allows for an analysis of the separate processes of phasing-in new assets and phasing-out old assets.

Combining methods

Collectively, these methods complement each other to produce a more comprehensive analysis of industrial policy for the decarbonisation of steelmaking due to the different levels at which crucial processes are operating. People in executive management make strategic, organisational and financial decisions based on their assessment of options and expectations for the future. While the outcomes of these decisions can be known through investment decisions and projects that can be analysed ex post, the methodology in Paper II captures more of their assessments and expectations for the future. This is important for understanding the importance of external factors such as subsidies, energy costs and labour costs. Papers III and IV develops the techno-economic modelling of various locations cost-competitiveness, by adding comprehensive policy mapping to these studies. This gives a richer view of the external conditions facing firms as they judge whether to invest in low-carbon production. And finally, the methodology of Paper V captures the relationship of low-carbon steel projects (and policy support for these) and the reduction in fossil-based production. While the combination of methods provides a richer account of steel decarbonisation in this time, there are of course limitations with this methodological approach. The first and most obvious one is the empirical object of study, which is ongoing policy developments. That limits the conclusions that can be drawn, as trends are emergent, policies can be rescinded, and the full consequences are yet to be seen. I have tried to be careful with the conclusions and limit them to emergent trends and tendencies and allowing for potential shifts in the future, and theoretical insights on policy aims and firm behaviour. Another methodological limitation of the thesis is the use of techno-economic modelling, where results are heavily dependent on assumptions and transparency is essential. Here, my co-authors and I have tried to be highly transparent with the material, and in Paper IV we conduct a thorough review of other modelling, present their assumptions and are also highly transparent with our assumptions. A third methodological limitation is the number of interviews used in papers II and V. However, these interviews are used for triangulation of other data sourced in policy mapping and archival material. Second, the interview data in both papers concern a limited number of policies and decisions in firms in contrast to other papers that for example research social experiences. A large number of interviews is likely to have led to data saturation for the subject matter.

Findings

The findings of this research are presented in detail in the five appended papers. Paper I is a review of the literature on steel decarbonisation which situates the rest of the papers within a larger shift towards transformation as an emergent strategy for steel decarbonisation. Below is a summary of the findings in papers II-V followed by a discussion of how these relate to the overarching research question, as well as the implications of this research.

Firm level: Strategies for transitions

The steel industry is a capital- and infrastructure-intensive industry, dominated by firms with long legacies and established partnerships with upstream and downstream firms. The sector is therefore characterised by a high degree of inertia (Pavitt, 1984; Sánchez & Hartlieb, 2020; Wesseling et al., 2017). Breaking out of carbon lock-in in industry would require innovation for a deep transition away from fossil energy and greenhouse gas emissions altogether rather than the traditional sectoral focus on cutting costs (Algers & Åhman, 2024; Vogl et al., 2021). However, as Milton Friedman said “business is the business of business” – i.e. the purpose of firms is to maximise value for shareholders, and the environmental impact of firms is a social concern that lies beyond the scope of shareholder value. Shareholders will disinvest if a firm makes large investments that will require a reduction of dividends without a probable boost of future profitability. Why would any business choose to invest in low-carbon innovation when costs are high and potential benefits are low?

In Paper II, I investigate the strategic, organisational and financial changes made by three firms that are investing in the transition of their operations. As innovation at the firm level is an essential process for industrial decarbonisation, more research is needed on how conditions within the decarbonising industrial firm enables or obstructs green industrial policy. In Paper II, I therefore analyse a rare case of radical decarbonising innovation in the steel industry, i.e. the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project. Publicly launched in 2016, the HYBRIT project is a joint venture between Swedish state-owned mining company LKAB, state-owned utility Vattenfall, and steelmaker SSAB – in turn partially owned by LKAB. The HYBRIT project aims to transition all of LKAB’s iron ore production and SSAB’s steelmaking to the hydrogen-based direct reduction electric arc furnace (H-DR-EAF) route, using hydrogen derived from clean electricity. To analyse the internal conditions that enabled the development of this innovation project, I use the theoretical framework the Theory of Innovative Enterprise (TIE).

The study finds that the two SOEs were able to make these strategic changes due to the owner's commitment to decarbonisation. As strategic control within Vattenfall and LKAB is exercised in a dialogue between the executive management and the owner, it is the Swedish government's prioritisation of long-term decarbonisation over profit maximisation that moves the needle on the final strategic choices made. LKAB is a major owner in SSAB, and its role as the largest shareholder in the company gives it significant – albeit not full – control of the downstream company. Organisational integration within and across the three companies is complex, and difficult to fully analyse through the archival material used for this study. The joint venture firm HYBRIT was set up in order to enable stronger coordination across the three firms, and LKAB increased their ownership stake in SSAB in order to ensure integration across firm strategies. Vattenfall made changes to their own R&D division in order to deliver on a renewables-oriented strategy, which led them to coordinate industrial development with energy-intensive industry. Finally, the SOEs LKAB and Vattenfall made changes to their economic targets to enable greater investment in decarbonisation and innovation. LKAB reduced the dividend targets and Vattenfall changed the targets for Return on Capital Employed (ROCE). These changes facilitated a financial commitment to decarbonization within the firms.

Table 3 below stylises how strategic control, organisational integration, and financial commitment have been structured within and across the three companies.

Table 3: How strategic control, organisational integration, and financial commitment is organised within and across the three companies Vattenfall, LKAB, and SSAB, as well as the joint venture HYBRIT.

	Vattenfall	LKAB	SSAB	HYBRIT
Strategic control	Operational strategic control lies with executive management; government sets long-term economic, social, and sustainability targets. Executive incentives are aligned with government, by being stable and invariable.	Operational strategic control lies with executive management; government sets long-term economic, social, and sustainability targets. Executive incentives are aligned with government, by being stable and invariable. Purchase of shares in downstream SSAB.	Operational strategic control lies with the executive management; shareholders have control over executive management. Executive incentives are partially tied to economic performance and partially to share prices. Increased ownership stake by LKAB.	The three firms have representatives on the Board.
Organisation al integration	Creation of a dedicated division for industrial decarbonisation internally in Vattenfall. Absorption of learning on hydrogen storage from the HYBRIT pilot plant.	Expansion of activities into the downstream iron reduction step with the demonstration plant in Gällivare. Absorption of learning from hydrogen-direct reduction from the HYBRIT pilot plant.	Using EAF experience from the US operations to build and operate EAFs in Sweden and eventually Finland. Ensuring necessary steel grades and qualities can be produced at the HYBRIT pilot plant.	Joint venture HYBRIT Development backed by Vattenfall, LKAB, and SSAB with members of the Board from all three companies enabling learning from HYBRIT into the mother firms.
Financial committment	Lowering of ROCE targets to enable investment in decarbonisation.	Changes to the economic targets within LKAB loosening dividend, profitability, and debt targets. Support of 3.1 billion SEK from the Swedish Energy Authority and €143 million from the EU innovation fund for the demonstration plant in Gällivare (Algers, 2024).	Ambiguous. Large investments announced leading to negative shareholder pressure.	Joint venture funded by equal equity from the three companies. Support of 528 million SEK for the iron reduction pilot plant, 72.4 million SEK for the hydrogen storage pilot (The Swedish Energy Agency, 2022), and 22 million SEK for a pre-feasibility study (The Swedish Energy Agency, 2020).

This early and radical innovation project was enabled through changes in corporate strategy facilitated by government ownership of key firms and a political commitment to climate targets. However, for the project to stay on course and lead to deployment of commercial-scale plants, it is pivotal that strategy, organisational integration and financial commitment remains effective and aligned with long-term decarbonisation targets.

Domestic policy level: Policy within resource constraints

The rapid growth in renewable energy generation is a major transformation of the productive capacity of human society. Powering industry by fossil fuels from the Earth's lithosphere has made industrial development dependent on geographically locked energy sources. By harvesting the power of the sun, either directly through solar power or indirectly via the sun's heating of air creating wind power, industrial production can instead be powered by an energy source with a completely different geographical distribution. This has led to a rise in academic studies of how this new geographical distribution of energy can lead to new competitive advantages in areas with strong renewable energy sources, called the "renewables-pull effect" (see for example (Devlin et al., 2023; Samadi et al., 2023; Verpoort et al., 2023)). This literature argues that a transition of energy-intensive industry towards renewable energy will drive a relocation of industry towards new locations.

Climate and competitiveness in the US and the EU

In two studies – Paper III and Paper IV – my co-authors and I nuance this view. "Harvesting" even the power of the sun is fundamentally a process requiring both labour and technology. The availability and cost of these factors should be included in analyses of cost-competitiveness of industry powered by renewables. Green industrial policy in the form of subsidies and loans and guarantees can significantly alter costs across supply chains and accelerate deployment of low-carbon production technology. However, policy is a product of politics, and therefore policies are vulnerable to political changes. Policymakers have tried to address such vulnerabilities and increase the political support for green industrial policy by creating incentives for better labour outcomes. At the same time higher labour remuneration may affect the competitiveness of production and policymakers must therefore navigate both political and competitive constraints.

To study how subsidies can alter the cost-competitiveness of low-carbon steelmaking, we map and quantify subsidies across the supply chain for low-carbon steel in the US and the EU. In figure 2 we map subsidy intervention points across the supply chain to show how many, and different policies exist across these jurisdictions.

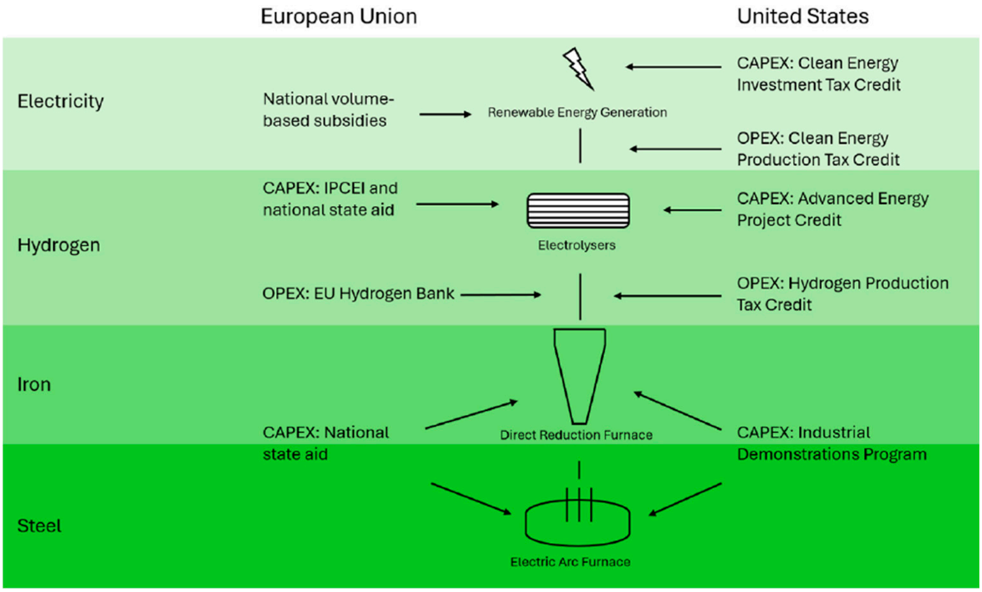

Figure 2: Subsidy intervention points along the supply chain for low-carbon steel in the EU and the US.

We compare the contribution of natural resources, labour, and subsidies to the cost of low-carbon steelmaking across the four cases, in figure 3 below, showing costs and cost components per tonne of steel across our four cases. The stacked bar to the left in each subplot shows the unsubsidised cost components of H-DR-EAF steel, while the blue bars in the waterfall show the cost reductions from various subsidies resulting in final subsidised cost on the right-hand side. Due to the structure of subsidies targeting hydrogen production, we have separated hydrogen into its own cost component.

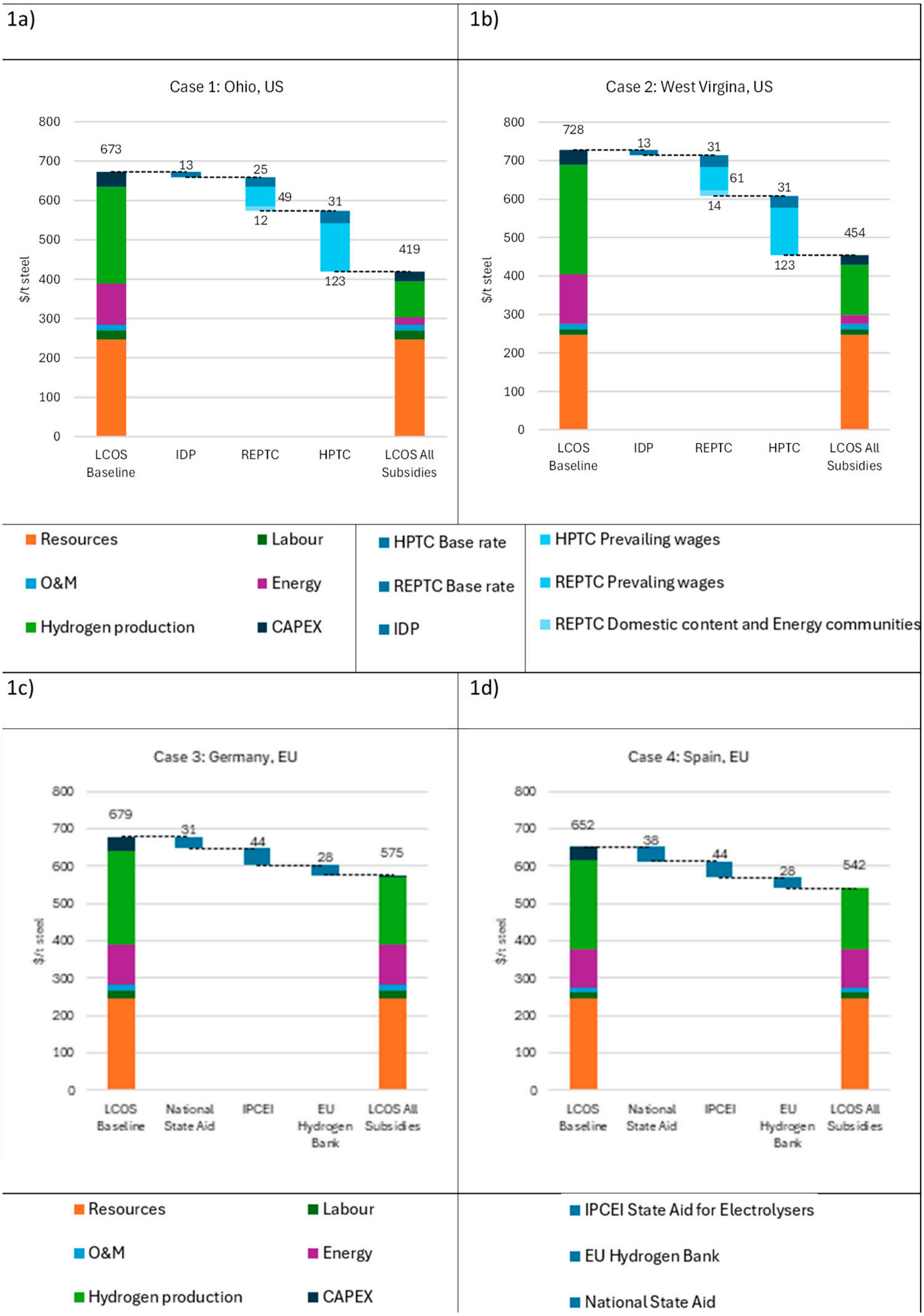

Figure 3: Costs and subsidies for low-carbon steel across the US states Ohio and West Virginia and the EU member states Spain and Germany.

Subsidies significantly reduce the cost of low-carbon steelmaking in the EU and even more so in the US. The impact is larger than either the cost differentials for energy or for labour in the selected cases. However, in the EU subsidies at the national and EU level are not allowed to be "stacked" and therefore real cost reductions are more limited than shown in the figure. Labour cost differentials contribute little to the cost differentials across the four cases. These results do not show the final price of a tonne of steel, as we do not include rolling to finished goods, and there are additional cost components such as employer, energy, and emission taxes, pensions, and labour protection costs which will increase the cost of steelmaking and can potentially alter cost relations. The above exercise shows, however, how cost differentiators related to subsidy regimes, labour costs, energy costs, and the cost of other resources measure against each other.

The US and EU possess the fiscal capacity to support the development of new low-carbon steelmaking technologies. The size of the subsidies could enable these jurisdictions to take a market share in the low-carbon steel market early on, locking-in steelmaking over time as new facilities, infrastructure and skills are established and discourage a large-scale relocation of the steelmaking industry. The implication for policy is that if fiscal capacity is a larger potential cost differential than renewable energy across countries, the speed of global deployment may be determined more by the willingness to use that fiscal capacity through industrial policy, rather than simple natural endowments. However, several EU firms have recently stopped or postponed their steel decarbonisation plans citing a lack of clean hydrogen and sufficient subsidies (Hancock et al., 2025). In the US, the whole policy programme has been withdrawn. Fragmentation in the EU and unpredictability in the US is blocking sector-wide diffusion beyond initial projects.

Cost differentials and policy interventions across the globe

In Paper IV, we expand our view to include more geographies and supply chain configurations. Reviewing the existing renewables-pull literature, we find significant variations in estimated levelized cost of low-carbon steel (LCOS). We identify five techno-economic components that can drive such large differences in LCOS and therefore affect how steel value chains can be reconfigured. These are the cost of renewable energy and hydrogen production, the cost of transport, the cost of labour, energy costs and integration benefits including assumptions on process design, and differences in weighted cost of capital (WACC). Policy interventions are also important factors that can affect industrial localisation. There are two main rationales for subsidising low-carbon steelmaking: maintaining and protecting an existing domestic steel industry, and/or increasing domestic value added by moving up the value chain producing steel.

In the H-DRI-EAF route, integration benefits across the ironmaking and the steelmaking steps are weaker than in the BF-BOF route, while benefits of colocating ironmaking with hydrogen production are stronger. Therefore, this technological set-up enables a separation of various steps of the production route, where the energy-intensive ironmaking step can be co-located with renewable energy resources, and iron can be shipped to steelmaking sites elsewhere. We elaborate on five plausible archetypical configurations of the H-DRI-EAF value chain (See figure 4). The aim is to have a purposeful sample of cases that illustrates all the possible configurations through representative cases of possible low-carbon steel value chains in 2030.

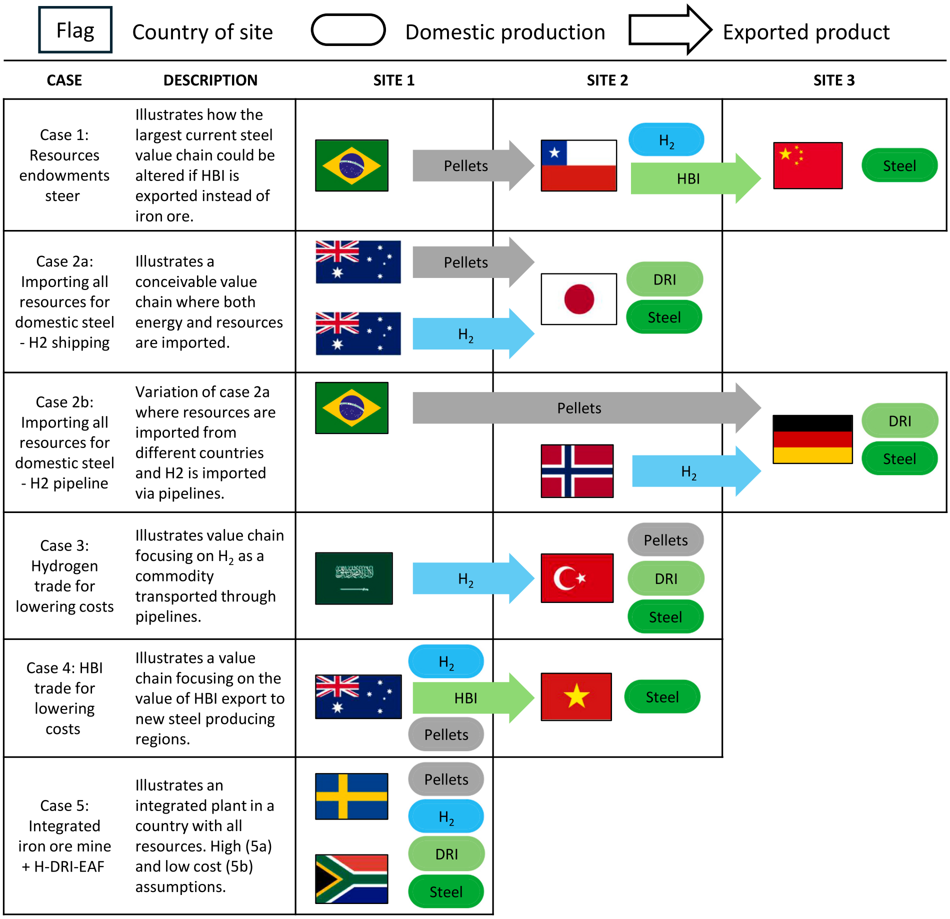

Figure 4: Illustrative supply chain configurations for low-carbon steel, showing production country, commodity and trade relations.

Our results suggest that the renewables pull effect is weaker for steel than suggested in previous studies. Conclusions on the renewable-pull effect are highly sensitive to assumptions of the cost of energy, labour, and hydrogen transport, as well as subsidies. There are also factors counteracting the renewables pull-effect. Most studies do not include differences in WACC which further countervails the effect for various locations. Low renewable energy costs make other costs relatively more important, which is generally not recognised in the current renewables pull-literature.

Our analysis spans the full range of high and low costs cases and shows that while techno-economic analysis is important, it is also insufficient for explaining how value chains may be reconfigured. Results on cost competitiveness are significantly altered when assuming policy interventions to lower energy and capital costs. Policymakers therefore have tangible options to influence decision on retaining domestic production for strategic reasons. A low-carbon steel transition will be accelerated by better access to low-cost renewable energy, though policy interventions can alter costs across supply-chain configurations. While H-DRI-EAF likely remains more costly than BF-BOF steel by 2030, cost differentials are not too large for policy interventions to tip the scale towards a transition to a low-carbon steel industry in both higher and lower energy cost regions.

Global market level: Decarbonisation under overcapacity

The above sections focus on how policymakers can and are supporting the development and deployment of low-carbon steelmaking. In Paper V we instead look into the sector-specific barriers that undermine such a deployment of new low-carbon facilities and a sector-wide transition. The steel sector has for a long time been under pressure due to structural overcapacity that puts downward pressure on steel prices, thereby increasing the gap between steel prices and low-carbon steelmaking costs. Current overcapacity in the steel sector has been associated with the rise of China as a global hub for steelmaking producing a typhoon of steel on global markets. This overcapacity negatively affects the financial health of steelmaking firms just as they should invest in new low-carbon assets.

Sunk costs, the 'lumpiness' of large steelmaking investments, and the social embeddedness of steelmaking in local communities create sector-specific inertia and path dependency. These inhibit the closure of plants, contribute to overcapacity and undermine the financial viability of new low-carbon steelmaking assets. Deliberately lowering barriers to exit and phasing-out emission-intensive plants would therefore support a transition of the steel industry by reducing overcapacity and associated price-pressures and encourage investment in new low-carbon innovation through processes of ‘exnovation’ (David, 2017). Policies for deliberate decline could therefore play a major role in the transition of the steel industry.

However, policies today tend to focus on supporting low-carbon projects no matter whether such low-carbon projects replace conventional steelmaking. To assess the relationship of new low-carbon steel projects and the closure of conventional steel plants, we conducted a study of existing low-carbon steel projects in the LeadIT Green Steel Tracker (Vogl et al., 2023). Of the 36 projects included in the analysis, public funding could be identified for 16 of them. In 20 cases, public funding could not be established. Identified policy support includes direct capex subsidies, loans from public development banks, and green credit guarantees. As much as 42% of green steel projects are new plants that will add to existing primary capacity. For example, while the HYBRIT project in Sweden is associated with the planned closure of blast furnace capacity, the Stegra low-carbon steelmaking site will add another 5 mtpa of capacity to Sweden's current total of 6 mtpa. Policymakers are therefore subsidising projects to enter a market with structural overcapacity rather than supporting the closure of emission-intensive assets. This risks leading to new low-carbon projects merely adding capacity. Without policies to lower exit barriers and accelerate the closure of emission-intensive plants, low-carbon steel will lack market space, and the price gap between conventional and low-carbon steel will persist. Coordination of concurrent phase-outs of emission-intensive assets and phase-in of low-emission steelmaking may contribute to a more rapid transition of the steel industry and ease frictions associated with global steel excess capacity.

Discussion: Rising to the challenge?

> "There is a growing acceptance of fragmentation, and — maybe even more troubling — I think there's a growing sense that ours may not be the best fragment to be associated with."

- Lawrence Summers, 2023.

The progress of steel decarbonisation

Four years is a long time in this era of compounding crises. When I started this research, the ambitious Inflation Reduction Act did not exist but there was real momentum towards higher ambitions and more policy for industrial decarbonisation across the globe. As this research comes to a close, the Inflation Reduction Act also does not exist, and momentum for industrial decarbonisation is slowing down across the West. The implications of this research are therefore different than assumed at the outset. Initially this research was aimed at understanding future limits of existing policy regimes, and why policy will remain important for steel decarbonisation. At the end however, this research rather exhibits the political limits of industrial policy and decarbonisation in the West. Financial Times columnist Alan Beattie has described the US response to Chinese leadership in low-carbon technologies as failing a new "Sputnik moment" where technological leadership by a geopolitical rival is leading to withdrawal rather than renewed efforts (Beattie, 2025). He is correct in assuming that governments outside China could and should accelerate the deployment of low-carbon technology. Initial support in the form of strategic development and subsidies has enabled early advances in innovation and deployment of low-carbon steel in the EU, but now the development has stalled, and projects have been paused or cancelled with fragmented responses across member states and the Commission. The Inflation Reduction Act could have kick-started projects in the US and enabled political buy-in, but the passage and roll-out was too slow to lead to any meaningful change before withdrawal by the next administration. Global steel decarbonisation is hampered by this lack of policy consistency over time, a lack of coordination across jurisdictions, and a lack of comprehensive green industrial policy spanning whole supply chains.

The research in this thesis and state of steel decarbonisation in the EU and US suggests that catching up with the industrial prowess of China will require a much more forceful approach beyond existing subsidies and other forms of support. Western governments cannot force private firms to make investments that will squeeze dividends. Nor can they allocate renewable energy from new clean power projects to energy-intensive industry while remaining committed to a "level playing-field" for power consumers, and decentralised electricity systems. Without better political sustainability and longevity of policy support, and stronger coordination across jurisdictions, geographies and supply chains, even ambitious and costly initiatives like the ones studied in this thesis are falling short in reaching their own targets.

The implication is that rapid steel decarbonisation will require more than clever policy mixes. Without political sustainability of decarbonisation policy and with fragmented political systems, even generous subsidies have failed to induce investment at the desired scale. While most low-carbon steel projects have been announced in the EU (Vogl et al., 2023), China has overtaken both the US and the EU in industrial electrification (Stylianou et al., 2025) and in green hydrogen deployment (Yang et al., 2025). According to Eurometal, the Chinese state-owned firm HBIS has already sold 20 000 tonnes of "hydrogen-based green steel" to the EU (Eurometal, 2025). Chinese firms are conducting a major push to invest in low-carbon production around the world, and the government is in various ways supporting them in developing production in developing countries with strong renewable energy potential. A recent report found that Chinese investment in the Global South is – adjusted for inflation – equivalent to the US Marshall Plan that rebuilt Europe after the Second World War (Xue & Larsen, 2025). This push could lead to a reduction in the use of fossil fuels and – if it continues over time – upend the global energy order. It would be all too familiar if European governments and firms lead a regulative and innovative push for steel decarbonisation, only to cede the initiative to Chinese state-owned firms. Future research should look more into the details of Chinese industrial policy and how coordination, and subsidisation of low-carbon steelmaking in China is progressing and what this means for the global transition of the steel industry.

Historical comparisons can help us understand contemporary challenges. Several academics have called for a "Green New Deal", which refers to the major US investment plan the New Deal of the 1930s (see e.g. (Galvin & Healy, 2020; Green & Healy, 2022; Mazzucato, 2021)). The EUs "Green Deal" refers to the same historical precedent, and Joe Biden called himself a modern heir to President Franklin D. Roosevelt who was the architect of the New Deal (Alter, 2020). If modern policymakers find inspiration in the New Deal, how do their policies compare to the real, historic, New Deal? In total, the New Deal programmes have been estimated at 40.1 percent of GDP, while the original Biden plans were estimated to $6 trillion, or 27.8 percent of GDP (Dupor, 2021). These were however whetted down in Congress to a fraction of the sum. The energy investments of the Inflation Reduction Act were estimated at $369 billion of federal spending – or 1.7 percent of GDP – which aimed to crowd in a larger amount of private spending. As the programmes have been rescinded by the current administration, the final size of the investment stimulus is even smaller. The EU, however, is not even close to the expenditure in the US. Eurostat recently shared that private investment in climate change mitigation reached 0.55 percent of GDP in 2023 – up from 0.45 percent in 2005, but down from 0.6 percent of GDP in 2021 (Eurostat, 2025).

Profits, politics and geopolitical competition

The theoretical approach to green industrial policy for the steel industry in this thesis starts with the premise that the industry is a strategically important, energy-intensive industry, producing globally traded industrial goods, dominated by large, incumbent firms with strong links to upstream and downstream sectors. These sector-specific characteristics mean that green industrial policy for the steel industry relates to a complex set of political economic constraints at multiple levels – the firm level, the domestic policy level and the global market level. At the first level, firms try to maximise value for shareholders. As decarbonisation requires large investments in new facilities that will reduce available resources for shareholders, there is a trade-off between shareholder value maximisation and decarbonisation. At the domestic policy level, policymakers can shape the cost structures of steelmaking and support a transition of the steel industry but are constrained by a combination of natural and fiscal factors. While natural resources are an important cost factor, they are not the sole determinant for investments in low-carbon industry. At the global market level, the collective actions of various firms and governments lead to turbulent imbalances in steel demand and capacity, giving rise to political and economic frictions. The lack of coordinated phase-outs of emission-intensive assets and development of low-carbon steelmaking will inhibit wider steel decarbonisation. This thesis therefore argues that research on industrial decarbonisation needs more careful attention to the interplay of constraints across each distinct level.

This thesis also makes a contribution at each level. It finds that incumbent firms' strategies and resource allocation are critical to decarbonizing sectors like steel. While previous research finds that innovation systems are important for decarbonising innovation (Karltorp et al., 2024; Kushnir et al., 2020), and strong natural resources can provide strong signals for deployment of technology (Devlin et al., 2023; Gielen et al., 2020; Verpoort et al., 2023), the internal dynamics and trade-offs within incumbent firms deserves more research. This thesis shows the ways in which green industrial policy has accelerated the innovation and deployment of low-carbon steelmaking. Natural resources such as iron ore of relevant quality and renewable energy potential are relevant but insufficient for explaining where and when low-carbon steel projects have emerged. Instead, industrial strategy and financial support have been key enablers of steel decarbonisation projects. Therefore, a change in governance policy in Swedish state-owned firms has had major implications for the entire steel industry, by inducing innovation and creating spillovers for the wider industry. Countries that want to increase the competitiveness of low-carbon steelmaking vis-à-vis other countries and fossil-based steelmaking are constrained not only by energy costs, but also by fiscal capacity. Rich economies are therefore in a better position to advance steel decarbonisation rather than solely renewable-rich economies. But policy-driven decarbonisation of steelmaking is vulnerable to domestic and international political conflicts. Hence, energy system studies need to pay more attention to the political economy of industrial transitions – not just in the abstract but in the limitations arising from concrete policy and industrial changes. This thesis therefore contributes a richer understanding of the web of real constraints for low-carbon investment decisions beyond what has been given by previous studies of industrial policy ambitions such as (Aiginger & Ketels, 2024; Reynolds, 2024; Veugelers et al., 2024), the renewables-pull effect such as (Devlin et al., 2023; Lopez et al., 2023; Samadi et al., 2023; Verpoort et al., 2023), and socio-technical transitions (Bataille et al., 2018; Nilsson et al., 2021; Vogl et al., 2018; Wesseling et al., 2017; Åhman & Nilsson, 2015; Åhman et al., 2017).

While policy has played a major role in the development of new low-carbon steel projects, less is done to lower barriers to exit, and phase out emission-intensive production. This is unsurprising, given the political constraints for shutting-down production, but given how the steel industry is characterised by overcapacity and underutilisation, policy-driven closures would be essential for realising real emission reductions and to ensure that new low-carbon projects replace rather than add to existing steelmaking capacity. The studies mentioned above focus on innovation, development and deployment of low-carbon steelmaking, but have not looked into the closures of emission-intensive assets. Such studies exist but tend to focus on the technical potentials for phase-outs and how to reduce the cost of closures, and minimise stranded assets (see for example (Agora Industry et al., 2024; Vogl, 2023; Vogl et al., 2021). In our study, we find that new low-carbon steel projects are in aggregate increasing steelmaking capacity and not complemented with a corresponding number of closures. We also find that the lack of closures of emission-intensive assets has been a persistent problem in the steel industry, contributing to structural overcapacity and that historically, policy support has been necessary for the closures of underutilised or inefficient assets. However, such policy support does not yet constitute any meaningful part of steel decarbonisation policy, and for steel decarbonisation to work on required timelines, careful consideration of how to increase the pace of closures is necessary.

Conclusion

> "The only thing we have to fear is fear itself—nameless, unreasoning, unjustified terror which paralyzes needed efforts to convert retreat into advance."
>
> Franklin D. Roosevelt, 1932.

Green industrial policy for the steel industry is engendered by the aim to boost industrial competitiveness, mitigate greenhouse gas emissions, reduce fossil fuel import dependencies, and reindustrialise post-industrial societies. Over the past years, several ambitious attempts have been launched in multiple jurisdictions, including the US and the EU. This thesis investigates their role for the decarbonisation of steelmaking at three levels of analysis: the firm-level, the level of domestic policy and at the level of global markets. To do so, I have conducted the studies based on three overarching research questions. How do endogenous strategic, organisational, and financial conditions affect the decarbonisation of incumbent industrial firms? How does the relationship of energy costs and industrial policy affect the decarbonisation of steelmaking? And why are policies and approaches of deliberate decline necessary for the decarbonisation of steelmaking?

As the crises of climate change and geopolitical rivalry intensify, this thesis shows how green industrial policy has accelerated the decarbonisation of the emission-intensive and strategically important steel industry. It finds that early innovation in Sweden was enabled by a strategic, organisational and financial commitment to decarbonisation in state-owned firms which has led to innovation spillovers across the wider steel industry. Second, subsidies in the EU and the US have created a strong push for low-carbon steel projects in these jurisdictions, although a lack of coordination and political fragmentation in the EU and lack of political sustainability in the US has led to project withdrawals and a slowdown in decarbonisation. Thirdly, barriers to exit limit the closure of existing emission-intensive assets, which leads to overcapacity and price pressures that undermine the transition of the industry. Sector-specific barriers to exit require targeted approaches of deliberate decline that can enable more rapid transition of the steel sector through the closure of existing emission-intensive assets, and a reduction of steel overcapacity.

By developing our understanding of these socio-technical processes in the steel industry, this thesis makes a small contribution to support the global effort to convert the current moment of social and climate-political retreat into advance.

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Steel decarbonisation in the early 21st century

This thesis investigates the role of green industrial policy for the decarbonisation of steelmaking at three different levels of analysis: the firm, domestic policy and global market levels. By applying theoretical insights from the literatures on innovation, energy systems, and green industrial policy, this thesis argues that ambitious industrial policy initiatives are critical enablers of the emergent transformation of steelmaking. These initiatives have not only been motivated by sustainability targets, but also by geopolitical competition. Policy achievements are constrained however by barriers to exit, political fragmentation, discontinuity, and a lack of coordination.

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