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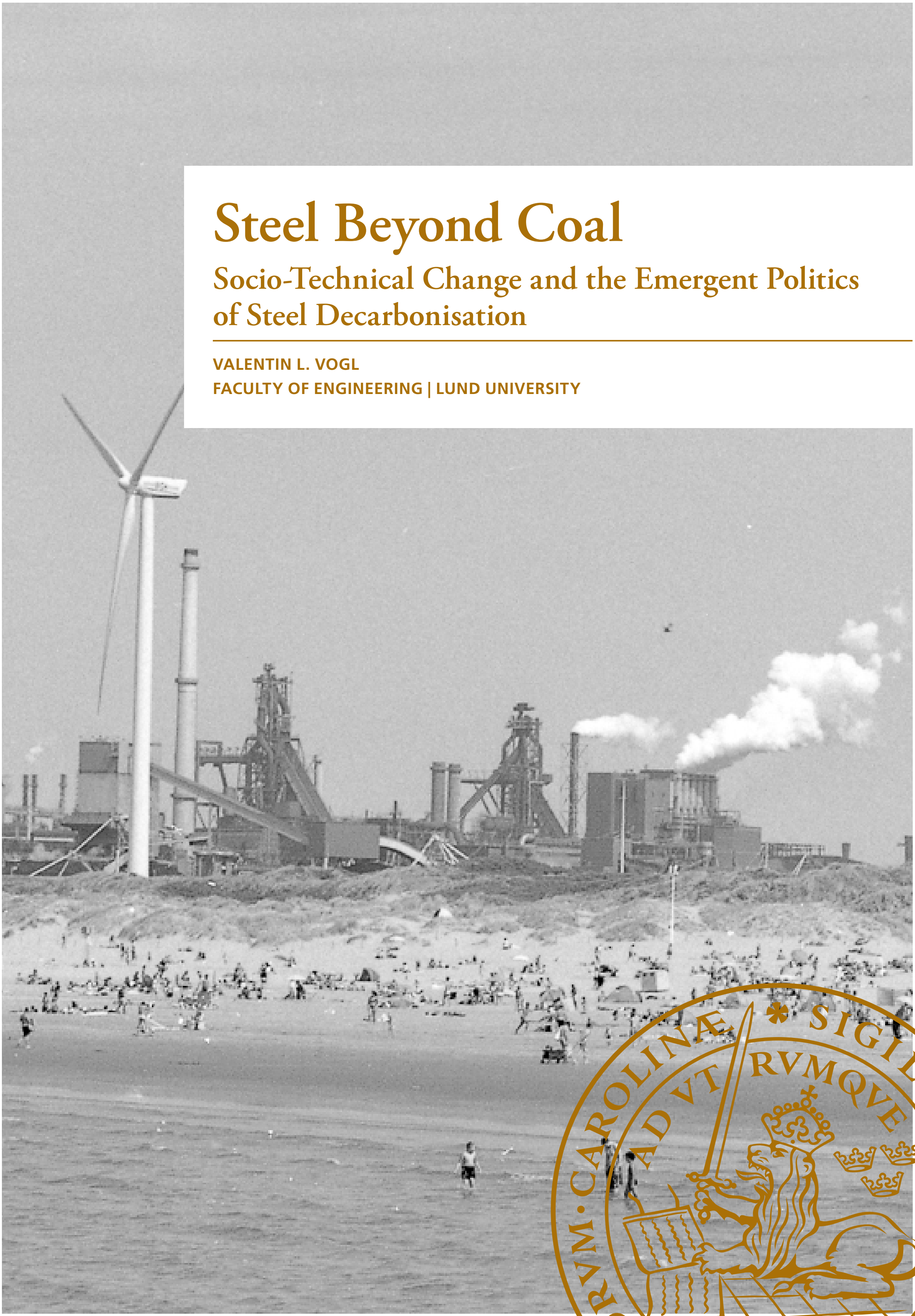

Steel Beyond Coal

Socio-Technical Change and the Emergent Politics of Steel Decarbonisation

VALENTIN L. VOGL

FACULTY OF ENGINEERING | LUND UNIVERSITY

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LUND
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Steel Beyond Coal – Socio-Technical Change and the Emergent Politics of Steel Decarbonisation

Abstract

The steel industry is responsible for 8% of all anthropogenic greenhouse gas emissions and is the second largest user of coal after the power sector. The main emission source in steel production is the blast furnace, which converts iron ore and metallurgical coal into pig iron that is then further refined into steel. Past efforts to reduce emissions from steel have focussed on increasing energy efficiency and developing carbon capture and storage technology, while continuing to use coal. These efforts have so far had little success and as a result the steel sector remains locked into coal. However, things are beginning to change. In the aftermath of the Paris Agreement, several European steelmakers announced they would close their blast furnaces and replace coal with renewable energy in their mills. Their announcements mark the beginning of a change of mind in the steel sector. Since then, many of the largest steel companies in the world have announced similar plans to abandon the blast furnace production route. This raises several questions. What has enabled this sudden shift to hydrogen and why is it happening now? And furthermore, how can this shift be interpreted in light of the urgency of decarbonisation and wider transformations towards sustainability?

In this thesis, I study the transition from coal to renewable energy in steel production. I show how the Paris Agreement and its imperative to decarbonise the economy is pushing the blast furnace to its technical and economic limits. What is more, renewable energy is becoming cheaper and more technologically mature, which allows steel producers to resurrect the century-old idea of electrifying steel production. In the four papers included in this thesis I study both the steel industry's lock-in into fossil fuels and different ways to escape this lock-in through policy measures, phase-out politics and innovation. In the thesis summary, I connect the findings in the papers theoretically through a socio-technical transitions perspective. Such a transition, I argue, is already in the making today in diverse instances of an emerging politics of steel decarbonisation, from confrontations around coal mine projects, blast furnace relinings, hydrogen production and trade projects, and green industrial policy. The findings of this thesis are part of a larger conversation on transformations towards sustainability, in which the engagement of civil society is a crucial factor that can make decarbonising primary steel production become a force for sustainability.

Keywords: steel, coal, climate change, decarbonisation, socio-technical transitions, sustainability

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Valentin L. Vogl

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To my grandparents,
and to Pauli.

Popular science summary

The steel industry is responsible for 8% of all anthropogenic greenhouse gas emissions and is the second largest user of coal after the power sector. The main emission source in steel production is the blast furnace, which converts iron ore and metallurgical coal into pig iron that is then further processed into steel. Past efforts to reduce emissions from steel have focussed on increasing energy efficiency and developing carbon capture and storage technology, while continuing to use coal. These efforts have so far had little success and as a result the steel sector remains locked into coal. However, things are beginning to change.

In the aftermath of the Paris Agreement, several European steelmakers announced they would close their blast furnaces and replace coal with renewable energy in their mills. Their announcements mark the beginning of a change of mind in the steel sector. Since then, many of the largest steel companies in the world have announced similar plans to abandon the blast furnace production route. This raises several questions. What has enabled this sudden shift to hydrogen and why is it happening now? And furthermore, how can this shift be interpreted in light of the urgency of decarbonisation and wider transformations towards sustainability?

In this thesis, I study the transition from coal to renewable energy in steel production. I show how the Paris Agreement and its imperative to decarbonise the economy is pushing the blast furnace to its technical and economic limits. What is more, renewable energy is becoming cheaper and more technologically mature, which allows steel producers to resurrect the century-old idea of electrifying steel production. In the four papers included in this thesis I study both the steel industry's lock-in into fossil fuels and diverse ways to escape this lock-in through policy measures, phase-out politics and innovation. In the thesis summary, I connect the findings in the papers theoretically through a socio-technical transitions perspective. Such a transition, I argue, is already in the making today in diverse instances of an emerging politics of steel decarbonisation, from confrontations around coal mine projects, blast furnace relinings, hydrogen production and trade projects, and green industrial policy. The findings of this thesis are part of a larger conversation on transformations towards sustainability, in which the engagement of civil society is a crucial factor that can make decarbonising primary steel production become a force for sustainability.

Populärvetenskaplig sammanfattning

Industrin är en av de största utsläpparna av växthusgaser och en stor användare av fossil energi. Enbart stålindustrin står för 8% av alla mänskligt orsakade klimatutsläpp och är dessutom den näst största konsumenten av kol efter elsektorn. Tidigare insatser för att minska utsläppen av växthusgaser från stålproduktion har fokuserat på energieffektivisering och på att utveckla teknik för koldioxidinfångning och lagring för att på så sätt fortsätta kunna använda både kol och industrins beprövade masugnstekník. Dessa insatser har hittills inte lyckats sänka stålindustrins utsläpp nämnvärt. Nu börjar dock saker och ting att hända.

Kort efter Parisavtalet tillkännagav flera europeiska ståltillverkare att de på sikt skulle sluta använda kol, stänga ner sina masugnar och ersätta dessa med ny teknik som i stället använder vätgas från förnybar energi. Dessa tillkännagivanden markerade början på ett mentalitetsskifte inom stålindustrin där man ifrågasätter masugnens framtid. Dessa tillkännagivanden har följts av flera andra stora stålföretag i världen som valt samma strategi. Denna utveckling leder till flera frågor. Vad har möjliggjort detta snabba mentalitetsskifte och varför händer det nu? Och hur kan detta skifte tolkas i ljuset av den akuta klimatkrisen och inte minst tolkas i en större omställning mot hållbarhet?

I min avhandling studerar jag omställningen från kol till förnybar energi inom stålsektorn. Jag visar hur Parisavtalets krav på snabba och på långtgående utsläppsminskningar pressar masugnstekniken över vad som är tekniskt och ekonomiskt rimligt att åstadkomma. Detta, tillsammans med att priset på förnybar el sjunkit drastiskt, har gjort stålproduktion baserad på förnybart attraktivare än kolbaserad masugnsteknik med koldioxidavskiljning. I de fyra artiklar som inkluderas i denna avhandling så studerar jag både stålindustrins historiska inlåsning till att använda kol och olika möjliga vägar för att bryta och undkomma denna inlåsning via styrmedel och strategier som stödjer både utfasning av fossilt och innovation mot förnybart. I sammanfattningen (kappan) så binder jag samman artiklarna teoretiskt med ett större socio-tekniskt omställningsperspektiv. Jag hävdar att en sådan stor omställning redan är på gång på flera fronter idag med exempel på flera kontroverser kring till exempel nya kolgruvor, renoveringar av masugnar, vätgasprojekt, och framväxten av en ibland ifrågasatt grön industripolitik. Denna avhandling ska ses som en del i en större debatt som pågår om samhällets omställning mot hållbarhet. Ett engagemang från civilsamhället är en viktig förutsättning för att säkerställa att stålindustrins väg mot klimatneutralitet även blir ett bidrag till de bredare hållbarhetsmålen.

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List of publications

This thesis is based on four publications, referred to by their Roman numerals:

I. Vogl, V., Åhman, M. and Nilsson, L.J. (2018) ‘Assessment of hydrogen direct reduction for fossil-free steelmaking’, *Journal of Cleaner Production,* 203, pp. 736-745. Available at: https://doi.org/10.1016/j.jclepro.2018.08.279.

II. Vogl, V., Åhman, M. and Nilsson, L.J. (2020) ‘The making of green steel in the EU: a policy evaluation for the early commercialization phase’, *Climate Policy,* 21(1), pp. 78-92. Available at: https://doi.org/10.1080/14693062.2020.1803040.

III. Vogl, V., Olsson, O. and Nykvist, B. (2021) ‘Phasing out the blast furnace to meet global climate targets’, *Joule,* 5(10), pp. 2646–2662. Available at: https://doi.org/10.1016/j.joule.2021.09.007.

IV. Vogl, V. (2022) ‘The forgotten fossil fuel: Exploring the politics of phasing out metallurgical coal’ [U*nder review*].

Author contributions

I am the lead author of all four publications included in this thesis and was involved in all stages of the research process. In *Paper I,* all authors contributed to the conceptualisation, analysis, writing and editing stages, whereas the flowsheet development, data collection and modelling were primarily my contribution. In *Paper II,* all authors contributed to method development, analysis, writing and editing, whereas the taxonomy was largely my own contribution. In *Paper III,* all authors contributed to the conceptualisation, methodology design, validation and investigation of results, article writing, and proofreading, whereas the formal analysis and visualisation was primarily my contribution. I am the single author of *Paper IV.*

Other relevant publications

During the course of this PhD several other related studies were published:

Peer-reviewed studies

Kushnir, D., Hansen, T., Vogl, V., and Åhman, M. (2020) ‘Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study’, *Journal of Cleaner Production*, 242, pp. 118185. Available at: https://doi.org/10.1016/j.jclepro.2019.118185.

Arens, M., Åhman, M., and Vogl, V. (2021) ‘Which countries are prepared to green their coal-based steel industry with electricity? - Reviewing climate and energy policy as well as the implementation of renewable electricity’, *Renewable and Sustainable Energy Reviews*, 143, pp. 110938. Available at: https://doi.org/10.1016/j.rser.2021.110938.

Nilsson, L.J. *et al.* (2021) ‘An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions’, *Climate Policy*, 21(8), pp. 1–13. Available at: https://doi.org/10.1080/14693062.2021.1957665.

Åhman, M., Arens, M., and Vogl, V. (2022) ‘International cooperation for decarbonizing energy intensive industries: the case for a Green Materials Club’, in M Jakob (ed.) *Handbook on Trade Policy and Climate Change*. Elgar Handbooks in Energy, the Environment and Climate Change. Cheltenham: Edward Elgar.

Jakob, M. *et al.* (2022) ‘How trade policy can support the climate agenda’, *Science*, 376, pp. 1401–1403. Available at: https://doi.org/10.1126/science.abo4207.

de Leeuw, G. and Vogl, V. (2022) ‘Scrutinising commodity hype in imaginaries of the Swedish green steel transition’ [*Submitted manuscript*].

Conference papers

Nilsson, L.J., Åhman, M., Vogl, V., and Lechtenböhmer, S. (2017) 'Industrial policy for well below 2 degrees Celsius: The role of basic materials producing industries', *Paper presented at 9th LCS-RNet annual meeting.* Warwick, UK, 12-13 September.

Vogl, V., Rootzén, J., and Svensson, O. (2019) 'A just transition towards a coal-free steel industry: perspectives from labour', *Paper presented at 14th Nordic Environmental Social Science Conference*. Luleå, Sweden, 10-12 June.

Vogl, V. and Åhman, M. (2019) ‘What is green steel? - Towards a strategic decision tool for decarbonising EU steel’, *ESTAD proceedings*: *4th ESTAD.* Düsseldorf, Germany, 24-27 June.

Vogl, V. (2022) ‘The forgotten fossil fuel: barriers and leverage points in phasing out metallurgical coal’, *Paper presented at the ECPR General Conference*, Innsbruck, Austria, August 22-26.

Other publications

Åhman, M. *et al.* (2018) *Hydrogen steelmaking for a low-carbon economy*. EESS report no 109 and SEI working paper WP 2018-07. Lund and Stockholm, Sweden.

Arens, M. and Vogl, V. (2019) 'Can we find a market for green steel?', *Steel Times International*, 43(4), pp. 59-63. Available at: https://www.steeltimesint.com/issues/view/may-june-2019.

Åhman, M., Arens, M., and Vogl, V. (2020) 'International cooperation for decarbonizing energy intensive industries – Towards a Green Materials Club: A working paper on sectoral cooperative approaches'. IMES Report no. 117. Lund: Miljö- och energisystem, Lunds universitet.

Vogl, V. (2021) ‘Einseitige Stahlvisionen: EU-Industriepolitik aus der Perspektive der Energiegerechtigkeit’, *Kurswechsel*, 4/2020, pp. 75–86.

Vogl, V. *et al.* (2022) *Green Steel Tracker.* Available at: www.industrytransition.org/green-steel-tracker (Accessed: 12 December 2021).

Vogl, V. (2021) ‘Why Europe doesn’t need Cumbria’s coking coal’, *Inside Track*. Available at: https://greenallianceblog.org.uk/2021/02/09/why-europe-doesnt-need-cumbrias-coking-coal/ (Accessed 27 October 2022).

Tilsted, J.P., Vogl, V., and Voldsgaard, A. (2021) 'Det er en udpræget misforståelse, at CO2-afgifter alene kan drive omstillingen', *Klimamonitor*. Available at: https://miljoogklima.dk/debat/art8104056/Det-er-en-udpr%C3%A6get-misforst%C3%A5else-at-CO2-afgifter-alene-kan-drive-omstillingen (Accessed 12 December 2022).

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Sonesson, Teis Hansen and others who will hopefully condone my forgetfulness for their help and advice.

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Abbreviations

BF/BOF	Blast furnace/basic oxygen furnace
CBDR-RC	Common but differentiated responsibilities and respective capabilities
CCfD	Carbon contracts for difference
COP	Conference of the Parties
CCS	Carbon capture and storage
DRI	Direct reduced iron
EAF	Electric arc furnace
EU ETS	European Union Emission Trading System
HBI	Hot briquetted iron
H-DR	Hydrogen direct reduction
IPCC	Intergovernmental Panel on Climate Change
NER300	New Entrants Reserve funding programme in the EU
ULCOS	Ultra-Low Carbon Dioxide Steelmaking
UNFCCC	United Nations Framework Convention on Climate Change

Units

$GtCO_2eq$	Billion metric tonnes carbon dioxide equivalent
Mt	Million metric tonnes

1 Introduction

Climate change is one of the central concerns of societies in the early 21st century. At the time of writing, human activities have caused planetary temperatures to increase by 1.25 °C (Matthews and Wynes, 2022) and annual global emissions are yet to peak. In 2019, 59 ± 6.6 billion tonnes of carbon dioxide equivalent ($GtCO_2eq$) were emitted globally (Dhakal *et al.*, 2022, p. 4), with highly unequal emission levels between countries and socio-economic classes (ibid., p.2-4 & 2-5). The largest greenhouse gas emitters are energy production (34%), industry (24%), agriculture, forestry and other forms of land use (22%), transport (15%), and buildings (5.6%) (ibid.). These sectors are interconnected, for example through energy demand in industry driving emissions in the energy sector. Hence, if indirect emissions are included the industry sector is the single largest sectoral emitter, accounting for one third of all anthropogenic greenhouse gas emissions (Bashmakov *et al.*, 2022, pp. 16–17). What is more, industry is both the fastest growing sector in terms of emissions and expected to decarbonise slower than other sectors (ibid., pp. 16). This makes industrial decarbonisation a particularly pressing challenge to address.

This thesis is concerned with the largest industrial emitter of greenhouse gases: iron and steel production. The recent Sixth Assessment Report by the IPCC presents a review of assessments of greenhouse gas emissions from iron and steel production. These range between 3.6 and 4.2 $GtCO_2eq$ for the years 2019 and 2020, of which 2.5 Gt are direct emissions from iron and steel production (Bashmakov, 2021; Bashmakov *et al.*, 2022, pp. 19 & 21). The main emission source in iron and steel production is the use of metallurgical coal in blast furnaces (Wang *et al.*, 2021), although other sources within and outside the steel mill (e.g. coal mine methane) are not to be neglected (see *Paper IV*). Since 2000, iron and steel production has been the industrial sector with the fastest growing emission levels (Bashmakov *et al.*, 2022, p. 18). This is a dilemma not just for industrial decarbonisation, but for the entire project of climate action. Steel is an important material in many people's lives today. Globally, its main applications are in infrastructure, construction, machines, and transport (Worldsteel, n.d.), and it is furthermore a material heavily used in both renewable and fossil energy technologies, as well as in climate adaptation infrastructures such as flood protection and measures against sea level rise. As such, slow action on steel decarbonisation has the macabre consequence that infrastructures for climate change mitigation and adaptation will have to be built with steel made with fossil fuels.

It needs to be acknowledged at this point that the term steel describes a vast diversity of different products, each with their own histories, geographies, and impacts throughout their supply chains. Not all steels are equal, just as not everyone benefits from steel in the same way and some hardly benefit at all. Steel use[1] per capita levels differ strongly between different parts of the world and between countries (Worldsteel, 2020), as well as between different socio-economic classes within countries (Stede *et al.*, 2021), although evidence for the latter is still limited. Neither is the impact of steel purely positive. Weaponry, fences, local air pollution, and land grabbing are all part and parcel of steel today, just as are wind turbine towers, railway infrastructure, bicycles, and cutlery. Claims of steel being essential to our lives should thus be met with care and nuance (see *Paper IV*). After all, it is largely the values (Kalt *et al.*, 2019), institutional structures (Foster, 1999), and material conditions of a society that decide the magnitude and distribution of the burdens and benefits of technology. This is the case for iron and steel production as for other technologies, from smartphones to chemical distillation.

Concerns over greenhouse gas emissions from iron and steel production emerged in the 1990s out of previous efforts to reduce the energy consumption in response to the energy crises of the 1970s. Early climate change mitigation efforts in the iron and steel sector were concerned with profitable energy efficiency improvements and incremental technological change (Worrell, Price and Martin, 2001; Pardo, Moya and Vatopoulos, 2012; Arens and Worrell, 2014). From the early 2000s onwards, the World Steel Association[2] had been coordinating an international programme to promote innovation in what were called ‘breakthrough technologies’ (IPCC, 2005, p. 137). In the short and medium term particularly, such breakthroughs were expected to come from the application of carbon capture and storage (CCS) technology to existing coal-based steel production facilities.

Under the auspices of Worldsteel, several regional steel federations embarked on research and development efforts to advance CCS alongside other technologies. In the EU and elsewhere, progress on scaling up CCS technology was nonetheless slow, with several factors inhibiting progress. The main reason for the very modest advances of CCS in light of the urgency of mitigation is the issue of carbon leakage, i.e., the threat by industry to relocate if subjected to a unilateral carbon price. However, no evidence of carbon leakage could be found either at the time (Branger, Quirion and Chevallier, 2017) or today (Grubb *et al.*, 2022), which is partly due to the fact that sectors such as iron and steel were shielded from paying the full price of carbon (ibid.). This shielding came at the cost of reducing the effectiveness of the existing carbon pricing scheme, which itself was supposed to be the main driver for

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[1] These numbers refer to ‘true steel use’. The difference between apparent and true steel use is that the latter takes so-called indirect trade of steel into account, which describes trade of products that contain steel (Worldsteel, 2022)

[2] In 2003 the World Steel Association was still called International Iron and Steel Institute (IISI). Toady, it is also known as Worldsteel.

CCS development. The plight for blast furnace CCS was further exacerbated by the 2008 financial crisis and the suboptimal design of funding schemes for scaling up CCS technology (Åhman, Skjaerseth and Eikeland, 2018). The final straw for European steel CCS efforts pre-Paris came in 2012, when the single CCS demonstration project in the pipeline at the time was cancelled due to 'technical difficulties' (Focraud, 2012). In 2011 still, the European Commission had positioned CCS in its low carbon roadmap as the number one technology for the steel sector for the years past 2035 (European Commission, 2011).

By 2015, the year the Paris Agreement was successfully negotiated at COP21 of the UNFCCC, blast furnace CCS had not yet been demonstrated anywhere in the world. The Paris Agreement, among other things, incorporates and promotes the idea of net-zero emissions. It also presents a change to the architecture of international climate collaboration from allocating mitigation responsibilities to promoting regular enhancements to voluntary mitigation pledges (Bernstein and Hoffmann, 2018). The cementing of the idea of net-zero in the Paris Agreement marks an important turning point, insofar it signals to global markets that emission reductions are no longer sufficient, but that eventually greenhouse gas emissions will need to be eliminated (Falkner, 2016). Throughout this thesis, this is how I use *decarbonisation*: as the imperative to radically reduce and eventually eliminate greenhouse gas emissions, which owes its force to the Paris Agreement. The idea of decarbonisation implies that all sectors of society bring their greenhouse gas emissions at least close to zero, and, if possible, beyond to become emission sinks in the future (Anderson and Peters, 2016; Rogelj *et al.*, 2019, see also *section 2.1*). The temperature goals of Article 2 of the Paris Agreement and the emissions gap between planned efforts and what is needed to achieve the Paris goals (UNEP, 2022) thereby function as a yardstick to inform the pace of the decarbonisation process. In its aftermath, many countries, companies, and other organisations responded to the Paris Agreement by adopting their own net-zero targets, including many steelmakers and steel-producing states.

The Paris Agreement acts as the starting point for this thesis. By 2015, the promise of blast furnace CCS had not yet been realised and the iron and steel sector seemed firmly caught in a state of carbon lock-in (Unruh, 2000). It was thus surprising when in the wake of the Paris Agreement, several European steelmakers announced plans[3] to abandon not only CCS but the blast furnace entirely in favour of an alternative ironmaking technology based on renewable hydrogen. Since then, the shift to hydrogen in industry plans has gained momentum, with many of the largest steel companies on the planet setting net-zero targets and announcing similar intentions (Agora Energiewende, 2022; Vogl *et al.*, 2022). These developments

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[3] HYBRIT was announced in April 2016 (Moström, Lindqvist and Hall, 2016). Salzgitter and voestalpine announced projects to produce of green hydrogen in September 2016 (Salzgitter AG, 2016), and February 2017 (voestalpine, 2017), respectively. These were followed by a series of announcements to replace blast furnaces with direct reduction technology, including large steelmakers ThyssenKrupp, ArcelorMittal, and Tata Steel Europe (Vogl *et al.*, 2022).

raise several questions: What has enabled the shift from CCS to hydrogen and why is it happening now? And furthermore, how can this shift be interpreted in light of the urgency of decarbonisation and wider transformations towards sustainability?

1.1 Aim

The aim of this thesis is to understand how primary steel production can be decarbonised in line with the targets of the Paris Agreement. I understand steel *decarbonisation* as the imperative to radically reduce and eventually eliminate greenhouse gas emissions from iron and steel, which originates out of the Paris Agreement. Decarbonisation thus stands in contrast to earlier less ambitious and less stringent efforts aimed at bringing about mere *emission reductions*. In order to meet this aim, the presentation of the research in this thesis is structured along three research questions:

1. What does the imperative of decarbonisation imply for primary steel production?
2. How can the decarbonisation of primary steel production be advanced?
3. How can the decarbonisation of primary steel production be aligned with transformations towards sustainability?

This thesis consists of four papers and this summary text which in Swedish we call *kappa*. The four papers investigate different aspects relating to the topic of steel decarbonisation. With the *kappa* I connect the papers by adding a theoretical perspective based in an understanding of decarbonisation as a socio-technical transition. The main argument developed in the *kappa* is that a socio-technical approach to steel decarbonisation is needed to understand how decarbonising primary steel production can be aligned with the targets of the Paris Agreement. I show that this is the case since the Paris Agreement increasingly challenges the idea of *fixing* the emissions problem of primary steel production through carbon capture and storage. Instead, the imperative of decarbonisation, in conjunction with progress on renewables increasingly necessitates a socio-technical transitions approach to climate change mitigation in primary steel production. Theoretically, I understand transitions to mean qualitative shifts in the composition of socio-technical systems, which are brought about through the two analytically distinct and interlinked processes of destabilisation and reconfiguration.

The *kappa* adds a theoretical frame to the four papers of this thesis by situating them within an overall socio-technical transition. The papers each investigate different aspects of the transition process. The first two studies concentrate on the process of reconfiguration. *Paper I* investigates the functioning of an alternative production process at the heart of one potential version of a reconfigured steel system by studying the techno-economics of the hydrogen direct reduction process. *Paper II*, in turn, evaluates policy approaches to scaling up low-carbon technology as part of the reconfiguration process. The latter two studies of this thesis are concerned with the destabilisation of the existing socio-technical system. *Paper III* investigates the temporality of reproduction of the core element of the current coal-based socio-technical system, the blast furnace. *Paper IV* finally compares different perspectives on phasing out metallurgical coal, of which the destabilisation of the coal-based socio-technical system is one.

1.2 Delimitations

Before proceeding, I want to draw some boundaries for this study. The research presented here focusses on greenhouse gas emissions related to iron and steel. The connection between steel decarbonisation to other pressing social and ecological challenges of our times are discussed in *section 6.3*. I further focus on socio-technical change in primary steel production, i.e., the production of steel from iron ore rather than from steel scrap. Steel recycling presents one of the main pathways to decarbonisation and its potentials and limits are discussed in *sections 2.2* and *6.3*. Besides recycling, non-technological and demand-side approaches are crucial to meeting climate targets and those have been analysed in detail by others (see section 2.2). *Section 6.3* furthermore discusses the relationship between primary steel and steel decarbonisation more generally. Finally, a certain attention bias for decarbonisation efforts using renewable energy and developments in Western Europe must be acknowledged. I discuss issues of positionality in *section 4.1.*

1.3 Thesis outline

The remainder of this thesis is structured as follows. The next chapter sets the scene for papers and *kappa* by providing the necessary context to studying the decarbonisation of primary steel production. It describes the role of the Paris Agreement as a starting point for steel decarbonisation and reviews the state of steel production and associated greenhouse gas emissions globally, as well as the main previous efforts to address it. In *chapter 3,* I present the theoretical framework that guides the *kappa* and connects the four papers of this thesis. *Chapter 4* describes the main ideas that guided my research process and presents the main methods used in the papers. *Chapter 5* summarises the papers and situates them within the theoretical framework. In *chapter 6*, I discuss the three research questions based on the findings of the papers and my theoretical framework. The final chapter concludes with a summary of the main findings.

2 Contextualising steel decarbonisation

This section sets the scene for the remainder of the thesis by describing the point of departure for the project of steel decarbonisation. First, I provide an overview of the main ideas in the Paris Agreement that are relevant to this thesis. I then review the state of primary steel production today and the main sources of associated greenhouse gas emissions. Finally, I provide a brief historical account of attempts to ‘fix’ steel’s carbon problem through carbon capture and storage.

In this thesis, I use *decarbonisation* to denote the forceful idea of radically reducing and eventually eliminating greenhouse gas emissions, which owes its force to the Paris Agreement. Decarbonisation describes both the state of an emission-free socio-technical system and the practice of working towards this goal. Others have distinguished understandings of decarbonisation based on back-casting and exploration (Börjeson *et al.*, 2006; Bernstein and Hoffmann, 2018), and between decarbonisation as the eliminating of carbon either as *emissions* or in the form of *fossil fuels.* Rockström et al. (2017), for example, define decarbonisation as the eliminating of global CO_2 emissions in line with the 2 °C goal. For Hildingsson, on the other hand, decarbonisation describes 'deep reductions in the *carbon intensity* of modern economies and societies', which are brought about by 'transformative social change' (Hildingsson, 2014, p. 19, my emphasis). My focus here is on emissions rather than fossil fuels or the carbon intensity of the economy. However, as I show in *section 6.1*, these two largely overlap in the case of decarbonising primary steel, since the imperative to decarbonise fundamentally challenges the viability of using fossil fuels to produce iron and steel.

2.1 Paris Agreement

The Paris Agreement (United Nations, 2015) is an international climate treaty under the United Nations Framework Convention on Climate Change (UNFCCC). It was formally accepted at the 21st Conference of the Parties (COP) in Paris in December 2015 and entered into force in November 2016. The Paris Agreement followed the Kyoto Protocol as the main international treaty on fighting climate change. It covers decisions on a wide range of matters regarding climate change, including mitigation, adaptation, loss and damage, and climate finance. Article 2 states the general ambition of the Agreement. It

> aims to strengthen the global response to the threat of climate change … including by … [h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. (United Nations, 2015, Art. 2)

These targets are to be pursued under the principles of equity and of common but differentiated responsibilities (for climate change) and respective capabilities of different Parties to the treaty (CBDR-RC). The CBDR-RC principle was first articulated in the UNFCCC, but the Paris Agreement changed its meaning, in particular by de-emphasising the categorical approach to differentiation countries responsibilities and capacities based on Annexes (Bodansky, 2016). In simple terms, the CBDR-RC principle implies that rich countries with large cumulative historic emissions and other responsibilities for climate change must take the lead in its mitigation. The Agreement further stresses the role of sustainable development, the eradication of poverty, and differing national circumstances as important contextual factors in its implementation.

In response to the Paris Agreement, a large body of climate modelling and scenario research has evolved to inform the implementation of the enshrined temperature goals. Some key concepts in these influential studies in international climate politics are carbon budgets, net-zero emissions, temperature overshoots and residual emissions. In the following, I will briefly explain each of them and how they are relevant to iron and steel decarbonisation.

- **Carbon budgets** are frequently used to quantify the emissions that would lead to warming of 1.5 and 2°C respectively starting from current levels[4]. By the beginning of 2023, these budgets are 380 and 1,230 $GtCO_2eq$ respectively (50% chance of meeting targets, Friedlingstein *et al.*, 2022), with considerable uncertainties regarding, among others, climate and earth system responses as well as future emissions of non-CO_2 climate forcers (Rogelj *et al.*, 2019). Carbon budgets are useful concepts to take stock of global overall mitigation ambitions, but breaking down carbon budgets to the sectoral or national levels is contested and value-laden (see below).

- **Net-zero:** Article 4 of the Paris Agreement specifies that in order to meet these objectives, the Parties to the Agreement aim to reach a peaking of global greenhouse gas emissions as soon as possible, and a balance between sinks and sources of anthropogenic greenhouse gases in the second half of this century. This balance of sinks and sources is often referred to as net-

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[4] In 2020 global average temperature was 1.1°C higher than pre-industrial levels.

zero emissions or carbon neutrality (Rogelj *et al.*, 2019). Most large steel producing countries and many of the largest steel companies in the world have set their own net-zero target by the time of writing (Vogl *et al.*, 2022).

- **Temperature overshoot:** The temperature target of Article 2 is referred to as a long-time temperature goal within the Agreement. This leaves space for a temperature overshoot, i.e. global average temperatures surpassing 1.5 and 2 °C in the medium term. The concept of *peak warming* describes the cumulative emissions until net-zero is achieved (Rogelj *et al.*, 2019). The ideas of temperature overshoot and peak warming allow to, in theory, exhaust and surpass carbon budgets up to the point of reaching net-zero, and to compensate this excess by sustaining a period of net-negative emissions in the future. Some have criticised the ideational shift from strict carbon budgets to net-zero for inducing *mitigation deterrence, i.e.* a discouraging of present-day climate action in favour of hopes for future negative emission technologies (McLaren, 2016; Markusson, 2022).
- **Residual emissions:** Besides peak warming, the extent to which negative emissions will be necessary to achieve the Agreement's long-term temperature goal also depends on the level of residual emissions (Luderer *et al.*, 2018)**.** The concept of residual emissions describes those greenhouse gas emissions that are technologically, economically or politically 'hard-to-abate', and that continue to exist even beyond the point in time of net-zero emissions. This means that any residual emissions will need to be compensated by negative emissions once the carbon budget is exhausted. However, the definition of what qualifies an emission source to be considered difficult or impossible to abate leaves ample room for debate and is inherently political.

The Paris Agreement has been hailed a diplomatic success (Dimitrov, 2016; Falkner, 2016) and marks a turning point in international climate negotiations (Bodansky, 2016). In particular, it represents a shift in the architecture of international climate collaboration from allocating mitigation responsibilities to a more polycentric approach based on regular enhancements to voluntary mitigation pledges (Jordan *et al.*, 2015; Bernstein and Hoffmann, 2018; Depledge, 2022). In response to the ratification of the Agreement, many countries, sub-national actors such as cities, as well as companies and other organisations have adopted their own net-zero targets. As of September 2022, 88% of global greenhouse gas emissions were covered by a net-zero target, with target years of most net-zero targets ranging between 2040 and 2070 (Climate Action Tracker, n.d.). What is more, governments have begun to pass on deep decarbonisation requirements to single sectors and industries. The European Commission, for example, speaks about an intended 'transition of Europe's industry to climate-neutrality' (European Commission, 2020a, p. 14). In response, many iron and steel companies and industry federations have followed suit by communicating roadmaps laying out how net-zero can be achieved (Eurofer, 2019; JISF, 2021; POSCO, 2022; Vogl *et al.*, 2022).

While carbon budgets and climate scenarios provide a yardstick for global mitigation efforts, net-zero targets do so for single nation states, cities, or companies. However, breaking down carbon budgets or national climate targets to the respective contribution of single economic sectors involves a series of normative value judgements. Climate scenarios, for example, are typically built around optimising the cost-efficiency of mitigation pathways (Raupach *et al.*, 2014; Steininger *et al.*, 2015). Normative choices include the extent to which pathways rely on future technological developments and how fairness is conceptualised to determine the distribution of mitigation efforts between richer and poorer countries. This means that under the Paris Agreement, the pace and distribution of mitigation efforts in a single sector such as iron and steel production is ultimately a political matter and cannot logically be derived from the Agreement's long-term temperature goals. Instead, the pace and level of decarbonisation of single sectors becomes a continuous political struggle that is informed by the respective global emissions gap (UNEP, 2022), i.e. the gap between necessary reductions and current commitments. An alternative to the intricacies of determining sectoral carbon budgets (Steininger *et al.*, 2020) is to compare sectoral with national and global emission trajectories, allowing to identify leading and laggard sectors, which can serve as the basis for the 'naming and shaming' that is built into the architecture of the Paris Agreement (Falkner, 2016).

The necessary pace for the decarbonisation of steel it thus essentially a normative and political matter. At the time of writing of this thesis, a public debate over whether the 1.5 °C has finally been blown is being held. This and other factors suggests that steel should decarbonise at least at the same pace as the economy on average. These factors include the uncertainties and potential large land uses of yet-to-be-developed negative emissions technologies (Carton, 2019) and the relatively higher availability of mitigation options, especially on the demand side if compared to sectors such as petrochemicals, cement, or agriculture (Allwood *et al.*, 2011; Allwood and Cullen, 2012; Cooper-Searle, Livesey and Allwood, 2018). The temperature overshoot debate furthermore implies that the iron and steel sector might not only have to eliminate greenhouse gas emissions from its operations but become a net-negative emitter thereafter (Tanzer, Blok and Ramírez, 2020).

2.2 Iron and steel production

Steel is one of the most used materials by humans today. In its most basic form steel is an alloy made of iron and carbon. The material properties of steel can be varied widely by adding other metals, so-called alloying elements such as nickel, chromium, manganese, and molybdenum. Although alloys of iron and carbon have been widely used for at least three millennia (Smil, 2016), recent decades have seen an unprecedented increase in global iron and steel production. Between 1950 and 2018, global steel production increased ninefold (see Figure 1) as a consequence of two periods of rapid growth in steel production (Worldsteel, 2007, 2022). Between 1950 and 1980, output more than quadrupled due to growing steel industries in industrialised and industrialising countries such as Soviet Union, the US, Japan and several European countries (D'Costa, 1999, see also *Paper III*). The 1980s and 1990s saw a turbulent restructuring of steel production with steel industries on the decline in the US, Japan, and later in the aftermath of the disintegration of the Soviet Union. It also saw growth in new markets such as South Korea, Brazil and, most notably, China (ibid.). After the year 2000, the emergence of China as the world's biggest steel producer resulted in another doubling of global steel production within two decades. Besides China, the largest steel producers today are the European Union, India, Japan, the US, Russia, and South Korea. The general upward trend of steel output since 2000 has been interrupted only by the 2008-2009 financial crisis as well as the Covid-19 outbreak in 2020. Today, approximately half of global steel production and two thirds of global blast furnace capacity is located in China (see *Paper III*).

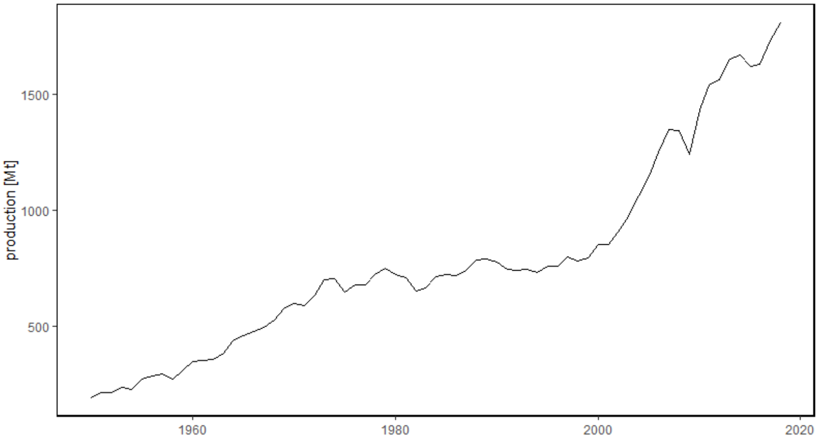

Figure 1

Global steel production production 1950-2020. Data from Worldsteel (2007, 2021).

Steel production routes

Steel can be made from two different raw materials, either from iron ore or from steel scrap. The production of steel from iron ore is commonly referred to as primary steel production, while the recycling of scrap to make new steel is called secondary production. As would be the case with any continuously growing commodity market, primary production has outweighed secondary production historically. In 2018, 70% of metallic input into steel production was iron ore, while 30% was scrap (IEA, 2020). The life cycle of steel begins as raw materials in the mine. Iron ore, metallurgical coal, alloy ores and other inputs to the steel production process are extracted and further processed before they are converted into steel. The main stages of the steel production process are ironmaking, steelmaking, casting, rolling and forming. Iron- and steelmaking can be considered the heart of the production process, since it is these stages that chemically transform raw materials into steel, consume most energy and are the biggest source greenhouse gas emissions (see next section). Two technological routes dominate iron- and steelmaking today, the blast furnace-basic oxygen furnace (BF/BOF) route, and the electric arc furnace (EAF) route. Although the terms primary production and BF/BOF route, as well as secondary production and EAF route, are often used interchangeably, this is not fully precise. In practice, scrap is also used in primary production and virgin iron might be used in secondary production, respectively. While many steel mills will fit into one of these two stylised production routes, a large variety of technology configurations has co-evolved with regional circumstances, increasing industry specialisation and fragmentation of the market into thousands of grades.

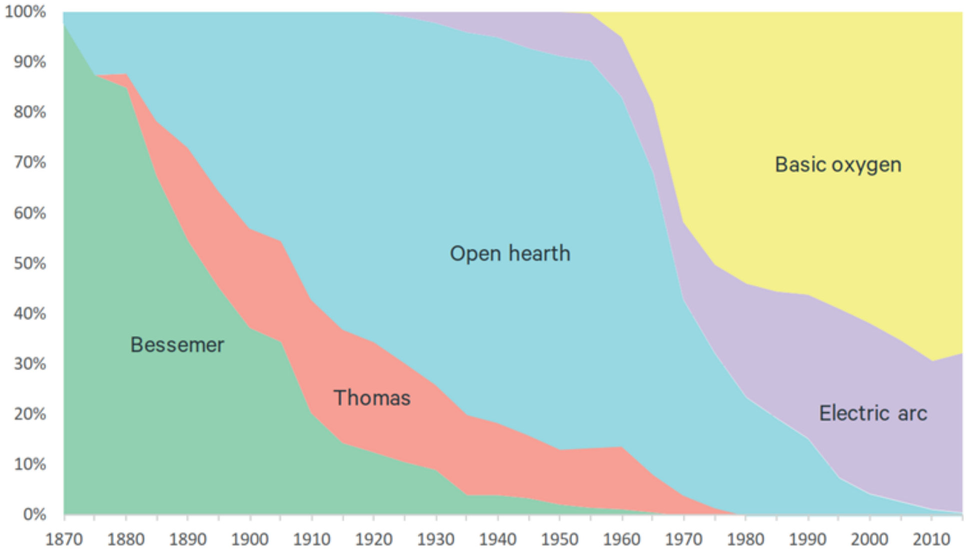

Figure 2

Historic technological changes of steelmaking processes in the global steel industry. Adopted from Åhman et al. (2018) based on work by Jernkontoret, Jalkanen and Holappa (2014) and on data by Worldsteel.

The BF/BOF route is the most common way to make steel today, with 71% of all steel made through this route globally in 2021 (Worldsteel, 2022). The basic oxygen furnace is a rather recent invention and only diffused widely after 1960. Figure 2 illustrates the pace and magnitude of four major shifts in steelmaking technology from the late 19th century to today. The open-hearth furnace, the dominant steelmaking process since the early 20th century, was almost entirely replaced by the more cost-effective basic oxygen furnace within 25 years from 1960 onwards. Roughly at the same time, so-called mini mills specialised on scrap recycling in electric arc furnaces rapidly diffused into markets that were previously served by large integrated steel mills (Madar, 2012). Similarly fast diffusion rates could be observed for continuous casting technology (D'Costa, 1999).

While steelmaking and to some extent casting has seen similar technological shifts, the blast furnace has persisted as the main technology for ironmaking for centuries. The oldest European blast furnace dates back more than 800 years, with even earlier examples operating on similar technological principles found in Japan and China (Smil, 2016). However, the blast furnace process has changed significantly over time. In particular, the size of blast furnaces has increased by more than an order of magnitude since pre-modern times (ibid.). Early blast furnaces were dependent on regional charcoal supply, which was difficult to transport over long distances (Ducoing and Olsson-Spjut, 2021). This and their dependency on water wheels to power the blasts (Smil, 2016) required small-scale, decentralised iron production located close to rivers. Only the emerging use of coal of fossil origin allowed blast furnaces to be scaled up, and this alongside technological innovations such as the hot blast, the steam engine and coal-fired puddling and rolling (Smil, 2016) and changes in the control over the means of production facilitated the centralisation and scaling up of blast (Svensson, 2022). As part of this restructuring process steel mills started to become bigger and more integrated. Integration here refers to the placement and interconnection of different parts of the steel production process in the same location in order to use energy-rich off-gases and by-products from one process step in another. Examples of such integration are the combustion of off-gases from blast furnace, basic oxygen furnace and coke ovens in the downstream rolling and forming operations, and the use of coke oven by-products such as coke breeze in the sinter plant.

The EAF route is the second most used way to make steel today, corresponding to 29% of global steel production[5]. Electric arc furnaces melt scrap and primary iron through applying a strong electric current. EAFs are often at the core of so-called mini mills, which are smaller and less integrated than the typical BF/BOF steelworks. Although electric arc furnace technology has been around for a century already, only the decades since 1970s saw continuous growth in global EAF capacity. Factors contributing to this growth were both technical and social: the increasing availability of scrap, technological development to produce higher qualities of steel through EAFs, the higher locational flexibility of mini mills versus

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[5] This number includes steel made in induction furnaces, which is a comparatively small amount and thus neglected here.

integrated mills, and the non-unionisation of the workforce in the US, where mini mills were pioneered (D'Costa, 1999).

Increasing the recycling of steel scrap in electric arc furnaces is one of the main strategies to reduce greenhouse gas emissions from iron and steel production. Steel recycling has a much lower energy consumption than primary steel production and mostly consumes electricity rather than coal. In tandem with measures to reduce overall steel demand (see below), large potentials exist to increase share of steel recycling in steel production. Work by Material Economics (2018) has for example shown that the EU could meet up to 85% of its steel demand by 2050 through secondary steel production if circularity potentials are fully tapped and copper levels in steel stocks managed. The accumulation of impurities such as copper and tin in steel scrap stocks, however, limits the potential contribution of steel recycling to emission reductions in the steel sector (Daehn, Cabrera Serrenho and Allwood, 2017). Copper typically enters the steel metabolism at the end of life of products that contain steel alongside copper wires, such as car engines, machinery, and other appliances (ibid.). Today, the separation of copper from steel at the end of life of such products is often not done due to its high labour intensity and associated costs (Daehn, Serrenho and Allwood, 2019). Once in the steel, copper contamination then leads to metallurgical problems in steel rolling where it limits the formability of the steel product (Daehn, Cabrera Serrenho and Allwood, 2017). Accordingly, different steel goods have different copper tolerances, with reinforcing bars on the upper and flat products on the lower end of the range (ibid.). While different solutions to steel's copper problem have been identified, a lack of progress on this front risks to lead to a serious accumulation of copper in the global steel stock, which effectively makes it unusable and thus restricts its potential contribution to decarbonisation.

Since EAFs can melt both primary iron and scrap, EAF steel production does not necessarily coincide with secondary production. The most common types of primary iron used in the EAF are sponge iron and pig iron[6]. The use of sponge iron in arc furnaces is a common practice in the industry today, while the use of pig iron in EAFs is not as common. Globally, 8% (114 Mt) of all iron produced was sponge iron in 2021 (Worldsteel, 2022), with Iran and India as the two dominant producers globally. The more common gas-based direct reduction method is practiced in gas-rich countries such as Iran, while coal-based direct reduction is primarily found in India where coal is abundant but has too high ash contents to be used in blast furnace ironmaking (IEA, 2020). A crucial difference between direct reduction and the blast furnace from a decarbonisation perspective is the aggregate phase of the product. While a blast furnace produces liquid pig iron, a direct reduction furnace yields a solid product commonly referred to as sponge iron[7]. The solid form of sponge iron

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[6] Pig iron, or hot metal, describes the high-carbon product of the blast furnace.

[7] Sponge iron is the product of the direct reduction process. It is also called direct reduced iron (DRI). Sponge iron can be further processed into hot briquetted iron (HBI) in order to enable

allows for the transportation of iron compared to the liquid form of pig iron when leaving the blast furnace. This difference in aggregate phase largely explains why it is readily exported today (Midrex, 2021), while the export market for pig iron amounts to only a tiny fraction of total production (Worldsteel, 2022).

Energy use in steel production

Coal is the main energy source for the BF/BOF route and thus also in today's iron and steel production globally. The iron and steel sector consumes a sixth of all coal globally (IEA, 2019, see also *Paper IV*). Coal used in iron and steel production is referred to as metallurgical coal, or met coal in short. Coal has three main purposes in the steel production process (Díez, Alvarez and Barriocanal, 2002). First, it is used as a fuel to supply heat to a variety of furnaces. Second, it is used as a chemical reactant to convert iron ore into iron and iron carbides in the blast furnace. Here, coal's carbon reacts with oxygen present in iron ore in a series of exothermic chemical reactions. Third, coal in the form of coke is used for its mechanical properties in the blast furnace. Coke is produced through the coking process, in which coking coal is heated in absence of oxygen, leading to a partial melting and resolidifying when it cools down. The product from this process is called coke and has a remarkably high mechanical stability that is essential to ironmaking in modern blast furnace ironmaking (see *Paper IV*). In particular it is its high compressive strength that makes the inside of the blast furnace permeable for the reactive gases that are present in the ironmaking process (Díez, Alvarez and Barriocanal, 2002; Smil, 2016). Since this material property is unique to coking coal, modern large blast furnaces cannot be operated without coke of fossil origin (Suopajarvi *et al.*, 2017). Energy-rich off-gases from the blast furnace, but also from coke ovens and basic oxygen furnaces are used in integrated steel mills to provide energy to other process steps or combusted in nearby power plants to generate electricity (IEAGHG, 2013). Other significant energy uses in global steel production are electricity, which is the main energy input to the EAF route, and natural gas, which is used as a fuel in both main production routes (IEA, 2019).

2.3 Greenhouse gas emissions from steel

Carbon dioxide and methane are the main two greenhouse gases associated with iron and steel production. Figure 3 illustrates the total greenhouse gas emissions from iron and steel per main source since 1900. While the main source of CO_2 is the production of iron and steel, methane emissions occur mainly as a by-product of

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long-term storage or long-range transport. This is necessary to mitigate the tendency of sponge iron to oxidise and explode.

metallurgical coal mining. Direct CO_2 emissions are generated through using fossil fuels as both energy carriers and chemical reactants in iron and steel production. Further indirect emissions arise due to the use of electricity generated from fossil fuels in electric arc furnaces as well as from upstream and downstream emissions, for example in mining or manufacturing. Hasanbeigi (2022) report total[8] CO_2 emissions from iron and steel production of 3.6 Gt in 2019, of which 3.1 Gt are related to the BF/BOF production route and the remaining 0.5 Gt are mostly due to the use of electricity from fossil fuels.

The use of metallurgical coal is the main source of CO_2 emissions in iron and steel production and furthermore one of the main energy-related sources of anthropogenic methane emissions. Only rough estimates exist today for methane emissions from metallurgical coal mining, which includes coal production from both coking coal and non-coking coal deposits (see *Paper IV*). The International Energy Agency's Methane Tracker Database (IEA, 2022) estimates coking coal methane emissions to be at 12 Mt (0.4 $GtCO_2$eq, see *Paper IV*). Actual global coal mine methane emissions, however, might be significantly higher, since this estimate does not account for emissions from non-coking coals and because of potentially serious underreporting of coal mine methane (see *Paper IV*). Wang et al. (2021) have shown cumulative emissions of 147 $GtCO_2$eq from iron and steel production since 1900. More than 90% of these emissions came from primary steel production, with 58 $GtCO_2$eq alone from blast furnace ironmaking. These numbers in turn are likely to be underestimates, since the authors did not consider emissions related to metallurgical coal, such as the coking plant or upstream coal mine methane in their calculations (Wang *et al.*, 2021).

Iron and steel is the largest emitter in the industrial sector and emissions from iron and steel production have been growing faster than in any other large industry (Bashmakov *et al.*, 2022, p. 18). Due to the rapid expansion of global steel production since 2000, in particular in China, greenhouse gas emissions from iron and steel increased more than in any previous period in history (ibid.). Consequently, the previously increasing share of secondary production has been declining in the past two decades (Wang *et al.*, 2021). Furthermore, the emissions intensity of iron and steel production has remained relatively constant since 1995 since improvements in process efficiency have been offset by overall growth of primary production (Wang *et al.*, 2021). In addition, efficiency improvements in both primary and secondary steel production have slowed significantly (Wang *et al.*, 2021). The International Energy Agency finds the potential for further emission reductions through efficiency measures in current production processes to be limited to 20% under their Sustainable Development Scenario (IEA, 2020).

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[8] This number includes indirect *CO_2* emissions from electricity use. Bashmakov et al. (2022) find direct *greenhouse gas emissions* of 2.5 Gt for 2020, and Bashmakov (2021) estimates scope 2 greenhouse gas emissions from iron and steel 1 Gt and scope 3 as 0.6 $GtCO_2$eq.

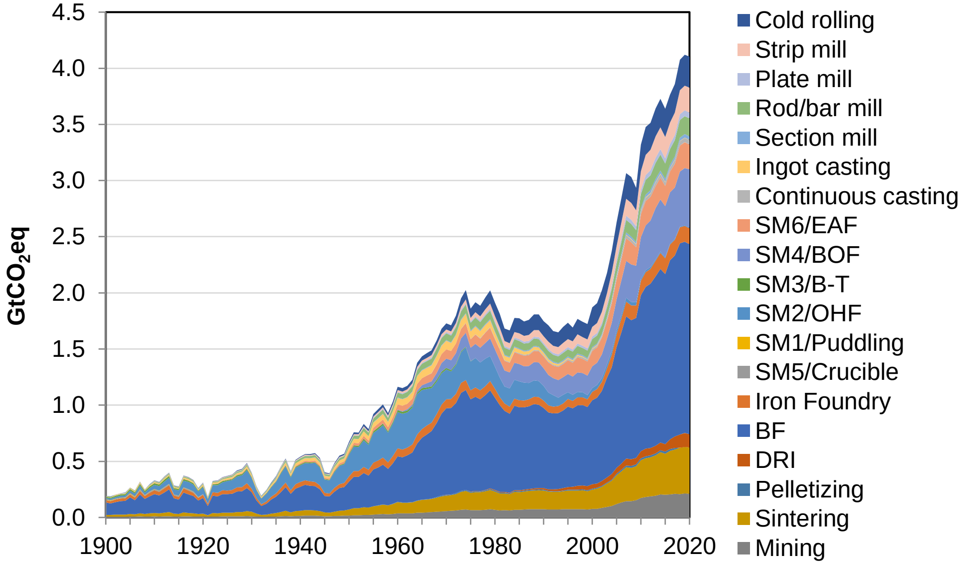

Figure 3

Greenhouse gas emissions (Scope 1, 2 and 3) from iron and steel production for main sources since 1900. Data includes emissions from iron ore mining, transport of iron and steel products, and from production of raw materials (lime, oxygen, compressed air, other industrial gases, metallurgical additives). Data excludes emissions from metallurgical coal, limestone and dolomite mining. The abbreviation SM refers to different steelmaking technologies. Adapted with permission from Bashmakov (2021).

2.4 Pre-Paris emission reduction strategies

This section provides an overview of efforts to reduce greenhouse gas emissions in iron and steel production up to the Paris Agreement. It reviews the main innovation and technology development projects and describes the main technological pathways pursued at the time. In particular, coal and CCS-based technologies were at the centre of debates on emission reductions in iron and steel production right up to the Paris Agreement. Hydrogen direct reduction, on the other hand, was not a major consideration for steel producers, although elements of the hydrogen-based method were already present, with the earliest roots dating back to the beginning of the 20th century.

Emission reduction efforts in iron and steel production originated from energy savings concerns. Energy efficiency became a central concern for the iron and steel industry during the energy crises of 1970s (Birat, 2001). While oil and gas prices tripled, the price of coal increased by 30% in the decade after 1973 (Gretz, Korf and Lyons, 1991). Accordingly, the iron and steel industry started to implement energy efficiency measures, leading to large improvements in energy consumption in both primary and secondary production in the same period (Manning and Fruehan, 2001).

The issue of iron and steel's contribution to global warming increased in prominence in the years around the new millennium. In an early contribution, Forrest and Szekely (1991) raise the issue of global warming and review options such as energy efficiency, process optimisation and increasing recycling, as well as coal-based alternatives to the blast furnace. Others problematised the focus on coal-based production and advocated for steel made from renewable energy. Eketorp (1989) reviewed options to replace coal with electricity and vice versa, and together with his colleague Pei Wen Guo discussed 'the challenging possibility of a futuristic steel plant based on 100% electricity and hydrogen reduction' (Eketorp, 1989, p. 261). These speculations originating out of Sweden built on a longer tradition of domestic efforts in electrifying iron and steel production. Already 80 years before, the first electric blast furnace had begun industrial-scale operation and by 1933, a total of nine electric blast furnace were operational in Sweden (Stålhane, 1933). These furnaces ran on electricity and charcoal, but the technology eventually stumbled over too excessive costs of electricity (ibid.). The idea of electrifying steel production, however, survived and was picked up again in the context of climate change mitigation. In another early contribution, Gretz et al. (1991) argue that the increasing concern over the steel industry's carbon dioxide emissions would naturally lead it towards considering hydroelectric hydrogen[9] in the future:

> [T]he present thrust of [coal-based] technological development in the steel industry does not appear to offer prospects of a solution to its problem of CO_2 emissions, and a changeover to hydrogen technologies seems almost inevitable. (Gretz, Korf and Lyons, 1991, p. 692)

Around the turn of the millennium, steel using hydrogen direct reduction technology was made on a commercial scale in a steel mill in Trinidad and Tobago. The plant had a capacity of half a million tonnes of hot briquetted iron production and operated only briefly between 1999 and 2001 when it ran into economic difficulties (Nuber, Eichberger and Rollinger, 2006; Lang, Haimi and Köpf, 2022). The plant on Trinidad was the first and hitherto only commercial steel mill in the world to run on pure hydrogen. Its operation was based on the Circored process, which at its core has a fluidised bed reactor (Nuber, Eichberger and Rollinger, 2006). Despite its short-lived existence, the Trinidad plant seems to have sparked some imagination:

> In regions where an abundant and inexpensive source of natural gas (or hydrogen) exists, gas-based direct reduction of iron followed by melting in an EAF can provide a cost-competitive alternative to quality steel products. (Manning and Fruehan, 2001, p. 38)

In 2003, the International Iron and Steel Institute (IISI), nowadays called Worldsteel, launched a global initiative to coordinate research and development

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[9] Hydroelectric hydrogen here refers to hydrogen made through electrolysis using hydropower.

efforts on emission reduction strategies in various parts of the world. The CO_2 Breakthrough Programme, established through 'unanimous agreement by the IISI membership', set itself the aim to 'explore opportunities to radically reduce CO_2 emissions' (IPCC, 2005, p. 137). The initiative coordinated existing emission reduction efforts by the steel industries in the EU, US, in Canada, South America, Japan, South Korea, China and Australia (Quader *et al.*, 2015). Under this global umbrella, the European ULCOS project aimed to develop primary production technologies that would reduce emission intensity by 50%. ULCOS was launched in 2004 and ran until 2010. A second phase to the project was planned but never realised. ULCOS resulted in a selection of four technological paths for further research. Three of these four paths were premised on the continued use of fossil carbon with carbon capture and storage (blast furnace, smelting reduction and direct reduction), whereas the final technology pathway was based on the direct electrification of ironmaking through either low- and high-temperature electrolysis of iron ore. However, the ULCOS technology selection did not include hydrogen-based steel production. With the financial crisis hitting the sector hard, these initiatives lost most of their momentum and plans for ULCOS II were shelved. A blast furnace CCS demonstration project in Florange in France was cancelled (Focraud, 2012) despite being shortlisted for EU funding under the NER300 programme (European Commission, 2012). The other technologies have since not moved beyond pilot stage[10]. Similar technologies were in focus in 'breakthrough programmes' around the world. In Japan, the COURSE50 initiative focussed on the development of energy-efficient technology. In particular, the project aimed to convert off-gas from the coking process into hydrogen and to inject it into the blast furnace (Cavaliere, 2022). In the US, efforts led by the American Iron and Steel Institute (AISI) investigated the development of different direct electrification technologies for ironmaking (Quader *et al.*, 2015). In Korea, steel producer POSCO pursued efforts in both carbon capture and hydrogen production and in Brazil and Australia, emission reduction efforts focussed on biomass (ibid.).

In the years after the financial crash, the European steel industry was still largely focussed on blast furnace carbon capture and storage. In its 2013 roadmap, the European steel federation Eurofer concluded that

> [t]he maximum CO2 emission reduction achievable by the EU steel industry by 2050 compared to 1990 levels would be about 60% (Eurofer, 2013, p. 52)

Although hydrogen direct reduction (and smelting reduction) is mentioned in the roadmap, this technology was dismissed as it was thought to come 'at the expense of huge amounts of energy' (Eurofer, 2013, p. 50). In 2014, a comparative

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[10] Today, one demonstration plant capturing carbon dioxide from primary steel production based on direct reduction technology exists in Abu Dhabi. However, the captured gas is not stored permanently but used for enhanced oil recovery (Somers, 2022).

evaluation of innovative technologies for steel production by Fischedick et al. (2014) reinvigorated the prospects of electrifying steel production. The evaluation compared blast furnace-based production (with and without CCS) with hydrogen direct reduction (H-DR), based on the Circored process that had been trialled in Trinidad, as well as electrowinning technology. The study found that electrified steel production could economically outperform the traditional blast furnace-based route already between 2030-2040. Responding to these findings, Smil critically commented that ‘most notably, and not surprisingly, the German team of authors assumed a mass penetration of inexpensive wind and solar electricity’ (Smil, 2016, p. 218).

3 A socio-technical perspective on steel decarbonisation

In this chapter I describe my theoretical points of departure for studying steel decarbonisation. I develop my theoretical framework around the concept of socio-technical transitions, which I understand as a qualitative shift in the composition of socio-technical systems. This shift is brought about by a dual process of destabilising carbon lock-in and reconfiguring socio-technical systems. Transitions in turn intersect and come together with processes of change in other domains of society to produce larger transformations. I use the theoretical framework to connect the papers in *section 5* and discuss the research questions in *section 6*.

3.1 Socio-technical systems

This thesis is concerned with the decarbonisation of iron and steel production. In this thesis summary, I use the concept of socio-technical systems as the main unit of analysis (Rip and Kemp, 1998). Socio-technical systems are heterogenous ensembles of artifacts, infrastructures, knowledge, capital, norms and discourses, to name a few (Geels, 2004, 2005), which are coordinated around a particular system goal (Hughes, 1987). Socio-technical systems thus include and bring together elements traditionally studied in the technical and social sciences. By appreciating heterogeneity, the socio-technical systems approach emphasises the more-than-technical nature of technology (Savaget *et al.*, 2019).

Analytically, the steel socio-technical system can be abstracted around the system goal of steel production. Depending on the focus of a given study, steel production here might refer to steel of specific quality and quantity linked to a concrete spatial and temporal context. Here, I am mostly concerned with the types of steel produced today in integrated steel mills on a global level, although in *Paper II*, I adopt an EU focus. The global steel socio-technical system includes a variety of physical steel mills and adjacent infrastructure, transport-related infrastructures, and flows of feedstock, energy, and waste, as well as specific institutions, discourses, knowledges and identity categories. Some of the central actors reproducing and transforming the global socio-technical system are large integrated steelmakers (e.g. Baowu, ArcelorMittal, POSCO), governments, business associations (e.g.

Worldsteel), the largest iron ore and met coal and alloy miners (e.g. BHP, Vale, Rio Tinto), the main technology suppliers (e.g. SMS group, Primetals, Midrex, Tenova), as well as trade unions and their federations.

Socio-technical systems are one of several similar concepts that emphasise the social character of technology. The concept owes its roots to earlier contributions in innovation and technology studies (Savaget *et al.*, 2019, p. 884) such as dominant design (Utterback and Abernathy, 1975), technological paradigms (Dosi, 1982), and technological regimes (Nelson and Winter, 1985). Similar concepts to socio-technical systems include large technological systems (Hughes, 1987), configurations that work (Rip and Kemp, 1998), and techno-institutional complexes (Unruh, 2000). Although the exact definitions of these concepts vary, they share the intention to overcome an understanding of technology as a mere tool or artifact through emphasising the social, immaterial, and relational nature of technology. Hughes's (1987) large technological systems, for example, are comprised of technical and social components, their characteristics emerge from their interconnectedness, and they are both socially constructed and society-shaping. Rip and Kemp's (1998) 'configurations that work' draw on Hughes but have a narrower focus. They emphasise that although technologies might appear as tools, they contain the skills to design, maintain and change them. Unruh defines techno-institutional complexes as 'complex systems of technologies embedded in a powerful conditioning social context of public and private institutions' (2000, p. 818).

3.2 Carbon lock-in and socio-technical transitions

Today's socio-technical systems that serve the purpose of producing steel and other basic materials have co-evolved with and currently depend on the ample availability of cheap fossil fuels. However, more than having co-evolved, these systems structurally defy efforts to wean them off fossil fuels. In other words, socio-technical systems are locked into fossil carbon (Unruh, 2000). Climate change and other social and ecological issues present fierce challenges to fossil fuels and the social systems dependent on and organised around them. Consequently, the last two decades have seen a surge of scholarly work on socio-technical transitions to sustainability, or transitions, in short. This scholarship has among other things been investigating how transitions out of fossil fuels and into more sustainable social practices occur. The by now vast field of sustainability transitions has emerged from innovation studies and offers different theoretical frameworks and understandings of transitions such as the multi-level perspective, technological innovation systems, or strategic niche management (Köhler *et al.*, 2019).

For the purposes of this thesis summary it would be overburdening to fully adopt one of these frameworks. Instead, I will outline the main ideas on transitions that I have found useful in analysing industrial decarbonisation. I understand socio-technical transitions as qualitative shifts (Svensson and Nikoleris, 2018) from one socio-technical system configuration to another. By qualitative shift I mean that a change to one or several core elements of the socio-technical system must occur in order for a transition to happen. This qualitative shift can be brought about through the two interconnected and largely simultaneous processes of destabilisation and reconfiguration. Destabilisation aims to loosen the carbon lock-in of the incumbent system in order to weaken the stability of those core system elements that are at the root of the problem, in this case the emission of greenhouse gases. Reconfiguration then aims to reorganise the relations laid bare by the removal of core components around new and different elements. This analytical abstraction of transitions as dual processes is common in the transitions field and has its roots in Schumpeter's notion of creative destruction (Kivimaa and Kern, 2016).

In its original formulation, carbon lock-in was defined as the result of 'a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale' (Unruh, 2000, p. 817). The source of lock-in furthermore was furthermore attributed to 'interlocking technological, institutional and social forces' (ibid.). Here I draw on Unruh's original notion and regard the stability of socio-technical systems as originating from the co-evolvement of system elements. As socio-technical systems evolve, elements become increasingly coordinated with each other in a process of system optimisation. It is through this process that elements come to be designed with other system elements in mind. In other words, the elements of socio-technical systems become increasingly internally related (Ollman, 1971; Svensson, 2021) to each other as the system evolves. Modern blast furnaces, for example, are designed with the availability of coking coal in mind, rolling mills are planned assuming the use of blast furnace off-gases, and car designs are premised on the use of steel products with specific quality characteristics fine-tuned through decades of integrated steel production. It follows that carbon lock-in is a particular kind of stability that describes the inertia of socio-technical systems in light of efforts aimed at decarbonising them.

Destabilising and reconfiguring

The carbon lock-in of a socio-technical system thus originates in the ways fossil fuels are inscribed in other elements of the system. In order to loosen and 'escape' (Unruh, 2002) carbon lock-in then, it is necessary to identify, destabilise and eventually reconfigure these 'fossil relations'. I understand destabilisation as the task of identifying through which mechanisms core elements are stabilised and then creatively finding ways to weaken those fossil relations. In efforts to phase out coal, such ways are for example protest, the promotion of anti-coal norms, divestment, and litigation (see *Paper IV*). These strategies destabilise coal insofar as they contribute to eroding its social licence to operate (Blondeel, 2019), drying up funding streams, setting legal precedents, inspiring institutional change, and shaping public opinion. Furthermore, they can prepare the grounds for targeted phase-out policies.

For a transition to occur, the socio-technical system must furthermore be reconfigured around alternative elements. Reconfiguring essentially describes the task of making socio-technical configurations work again (Rip and Kemp, 1998) by creatively and strategically combining remnants of the old system with new components. The system goal is central to reconfiguration. In order to reconfigure a socio-technical system towards decarbonisation (see below), the fulfilling of the system goal must be ensured or the goal itself reconfigured. The prior is the case if, for example, the new system can produce exactly the same steel as the old, the latter if demand for steel changes in order to accommodate the new system. Reconfiguration can include the quest for finding innovative solutions to system integration problems or the alignment of the new socio-technical system with other transitions. Again, in the example of the power sector, the variability of renewable electricity presents a barrier to socio-technical systems change insofar as power grids need to be designed to accommodate variable loads. By linking up the renewables transition with the electrification of other sectors such as mobility or industry, the problem of variable loads can be mitigated by using the latter as load balancing actors.

Destabilisation and reconfiguring are both concepts used in transition studies, although in slightly different ways. Turnheim and Geels define destabilisation ‘as the process of weakening reproduction of core regime elements’ (2012, p. 35). Their notion is similar to my use of the concept but grounded in structuration theory (Giddens, 1986) and the concept of the regime (Rip and Kemp, 1998; Geels, 2004; Smith, Stirling and Berkhout, 2005). Here, I follow recent realist contributions that attribute the stability of socio-technical systems to the interrelations of its components instead of the shared rules that characterise the regime concept (Sorrell, 2018; Svensson and Nikoleris, 2018; Svensson, 2021). My use of reconfiguration is similar to Geels’ (2002) original notion of technological transitions as processes of changing of sociotechnical configurations. Others have used reconfiguration as a phase of the development and decline of large technical systems (Sovacool, Lovell and Ting, 2018).

3.3 Transitions and transformations

The interplay of socio-technical transitions with change in other social systems is at the heart of the debate over transitions and transformations towards sustainability. The concepts of transition and transformation are used to denote a variety of ideas within and between different literatures and are sometimes used interchangeably, at other times hierarchically ordered or even in contradiction to each other (Child and Breyer, 2017). Eckersley (2021), citing Linnér and Wibeck (2019), uses transition to denote a change from one state to another, while transformation refers to a change in shape or form. In this understanding, transformations are to be understood as larger and more thorough changes to society than socio-technical transitions. Similar to Eckersley's 'great green *transformation*' that has its roots in Polanyi (1944), Schot and Kanger (2018), refer to the 'radical change, not only in socio-technical systems but also in the meta-rules driving their evolution' as a second deep t*ransition*.

Here, I understand transitions to describe the destabilisations and reconfigurations of single (socio-technical) systems, while transformations connotate larger qualitative changes involving multi-system co-evolutionary change. Socio-technical systems are useful analytical abstractions and as such highly entangled with a large number of other systems, some of which might undergo transitions or transition-like processes of change at the same time. In this understanding, it is the interactions between different transitions that produce the unruly, emergent, and surprising outcomes that are sometimes attributed to transformations (Leach, 2010; Stirling, 2014). This stands in contrast to more explicitly normative perspectives on transformations. Stirling (2014), for example, distinguishes transitions and transformations based on the types of knowledge, governance, and actors and their power relations involved. Transitions in this understanding are top-down, instrumental, and government and incumbent-led projects mostly aimed at technological change. Transformations, on the other hand, are understood as bottom-up innovations in social practices including but not limited to technology. As such they include a rich diversity of embodied knowledges and subaltern interests and can lead to unruly political realignments that challenge incumbent structures (Stirling, 2014). However, such attempts to distance such concepts normatively are easily challenged by the dominant coalitions co-opting potentially dangerous ideas (Newell, 2019). A 2019 report by the International Energy Agency, for example, is titled 'Transforming Industry through CCS', and the European Commission is being lobbied by industry-friendly reports suggesting 'industrial transformations' based on the precepts of profitability and economic growth (HLG-EII, 2019; Material Economics, 2019). In contrast to such normative distinctions then, transitions and transformations are here understood as occurring on different levels. Transformations are the product of interacting transitions, and these interactions might produce the surprising, unruly and emergent outcomes that characterise past and ongoing social transformations. This, however, does not reduce the importance of subaltern interests and the diversity of embodied knowledges in processes of transformation.

4 Research approach and methods

In this section I describe the main ideas that guided my methodological and empirical choices. In the first part I discuss the idea of critical problem solving and its relevance to my research. I further reflect on some of the main themes that shaped the process leading to this thesis, including transformative learning, collaboration, reflexivity, and interdisciplinary research. In the second part of this chapter, I describe the main qualitative and quantitative methods used in the four papers.

4.1 Research approach

The research presented here co-evolved with my conviction that fundamental *social transformation* is necessary in order to confront pressing socio-ecological crises and to provide a decent living for all within the reproductive capacities of the planet (Haberl *et al.*, 2011; Patterson *et al.*, 2018; Newell, 2019; Eckersley, 2021). The research done as part of this thesis aims to contribute to the transformations needed. It hopes to do so by presenting an analysis of how primary steel can be decarbonised in line with the Paris targets and by reflecting over the limitations and the risk of problem shifting inherent in focussing on primary steel production.

My wish to align transitions with transformations towards sustainability echoes what Robyn Eckersley has termed ‘situated and critical problem solving’ (Eckersley, 2021). Eckersley defines its aim as to ‘identify the next best transition steps with the greatest transformative potential’, with ‘next best’ referring to ‘the politically possible next steps’ (2021, p. 256). Critical problem solving aims to transcend Cox’s (1981) dichotomy of problem-solving and critical theory. Problem solving according to Cox ‘takes the world as it finds it’ (Cox, 1981, p. 128) and aims to make it run smoothly at the risk of reifying existing social, power, and institutional relations. Critical theory, in contrast, aims to problematise those relations by studying their historical and political development (ibid.). To overcome these supposedly incompatible poles, Eckersley suggests an approach to ‘problem solving in the service of transformation’ (2021, p. 256). Based on Eckersley’s work, I interpret critical problem solving to include commitments to transformative learning, to collaborating widely and to aiming to empower collaboration partners and working in a reflexive and interdisciplinary manner. In the following I discuss each of these aspects and illustrate how they have shaped the research process.

Transformative learning

Coming from an engineering degree, it seemed reasonable to approach this PhD project through problem-solving. With each consecutive study, however, the need to question what had been taken as given in earlier studies grew. This challenging of one's own convictions is at the heart of what Karen O'Brien refers to as transformative learning. It is

> the process by which we transform our taken-for-granted frames of reference (meaning perspectives, habits of mind, mind-sets) to make them more inclusive, [less] discriminating, open, emotionally capable of change, and reflective so that they may generate beliefs and opinions that will prove more true or justified to guide action. ((Mezirow and Associates, 2000, pp. 7–8), cited in O'Brien (2012, pp. 672–673)).

The more my skills and understanding evolved over time, the more I felt the need to confront certain assumptions I had previously made. *Paper I*, for example, takes the economic 'playing field' upon which different technologies compete for granted. By doing so it fits neatly within Cox's conception of problem solving (Cox, 1981). In successive papers, however, I adopted a more explicitly political conception of markets as co-constructed (e.g. Mazzucato, Kattel and Ryan-Collins, 2019) in order to transcend the confines of the comparative techno-economic assessment of *Paper I*. Along similar lines, the deeper I got into the topic the more I began to problematise some of my previously implicit assumptions. *Paper III*, for example, reflects upon the limits of inferring past social behaviour in constructing scenarios. By doing so we ended up critiquing the very method of committed emissions accounting that we had intended to use in the paper. In the same vein, the design of *Paper IV* was born partly out of frustration over the inflated attention paid – by me and others – to government policy in industrial decarbonisation research at the expense of the agency of a wider set of actors.

Collaboration and interaction

Collaborations were central to my own process of transformative learning. As this research is inevitably situated, value-coloured and informed by positionality, collaborating widely and interacting with a number of different actors was an attempt to mitigate the biased perception that comes with a certain positionality (white, male, trained engineer in Northern European university) and to 'open up' for other framings and alternative pathways (Stirling, 2008; Leach, 2010). Collaboration and interaction were important for me throughout the stages of developing this thesis and included, beyond other researchers, actors from civil society organisations, industry, grassroots activists, and actors in administration and bureaucracy. These interactions informed the selection of research topics and choice of study designs, and results were brought back and discussed during and after the process of analysis. The collaborations that informed my research to some extent chime with a transdisciplinary approach to research. In its most basic tenets, transdisciplinary can be seen as a commitment to co-creation throughout the research process, involving other actors within as well as outside academia and research institutions. Lang et al. (2012) define three criteria for transdisciplinary research: a focus on societally relevant problems, the enabling of mutual learning with actors inside and outside of academia, and an aim to create solution-oriented, socially robust knowledge useful also beyond an academic context.

One special collaboration deserves to be acknowledged here as it had a strong influence on my research focus and the design of *Paper IV*. From the end of 2020 and throughout the rest of the PhD project, I have closely been following the controversy around the Cumbria coal mine project, a planned metallurgical coal mine near Whitehaven on the west coast of Northern England. The mine proposal rests on the dubious claim of net emission reductions if the coal that otherwise were to be imported would be produced locally. After three rounds of local re-evaluation the decision over the mine was finally elevated to national level in March 2021 (Willis, 2021). From early 2021, I have been collaborating with the local grassroots organisation on the need of metallurgical coal in a future European market, which left me scrambling, as my own understanding of metallurgical coal was terribly scarce. From then onwards, the story goes that the Green Steel Tracker (Vogl *et al.*, 2022) came just at the right time to be defended in cross examination during the public inquiry by an engaged Swedish professor. Six days before submitting this thesis, the Secretary of State in charge of the mine decision eventually greenlighted the project, causing an uproar among civil society, climate researchers, and some politicians. But you never know with this mine, and certainly the anti-mine faction's arsenal of met coal phase-out strategies (see *Paper IV)* is not yet used up.

Reflexivity

Transparent reflexivity over scope and multi-system interactions is a central component of systems analysis (Leach, 2010). All system analysis involves framing, which includes both decisions over the system that is studied such as elements, scale, key relationships and boundaries, and subjective judgements pertaining to interests, values and positionality (ibid.). A socio-technical systems perspective on reducing greenhouse gas emissions from production, as adopted here, will identify particular dynamics and lead to certain recommendations for action. However, a focus on greenhouse gas emissions and production could, if pursued in an unreflexive manner, be blind to other social and ecological issues, or could obscure demand-side approaches. Since decarbonisation efforts will invariably impact other pressing issues such as biodiversity, water stress, land conflicts or social inequality, recommendations for policy and intervention should take into account the interconnectedness of these issues. A large-scale transition to renewable hydrogen could for example put stress on freshwater supply and land used to generate renewable electricity. Throughout my work, I tried to pay attention to the interlinkages between different processes of change.

Interdisciplinarity

I started this research with the intuitive conviction that studying climate change mitigation in heavy industries cannot be effectively done from within a single academic discipline, but that it requires an interdisciplinary approach (see e.g. Bhaskar *et al.*, 2010). The research making up this thesis thus crosses traditional disciplinary boundaries and draws on insights from a diverse set of academic fields. Parts of the research in this thesis were presented at conferences or public seminars in the fields of engineering, energy studies, environmental social science, sustainability transition studies, science and technology studies, political science, and regional studies. Such an interdisciplinary approach to research has its challenges (Castán Broto, Gislason and Ehlers, 2009). Different disciplines and strands within those come with particular ontological and epistemological commitments that require careful attention and attuning by the interdisciplinary researcher (Svensson, Khan and Hildingsson, 2020). Furthermore, different disciplines are characterised by using different definitions and conceptual approaches (Castán Broto, Gislason and Ehlers, 2009), which can present substantive entry barriers to researchers wishing to cross into them. Interactions with supportive colleagues within other departments at Lund University as well as with colleagues during my research visit at the Science Policy Research Unit of the University of Sussex were important enablers for my interdisciplinary research practice.

4.2 Methods

In the following I provide an overview of the methods used in the papers of this thesis. I first describe the data collection process before outlining the main qualitative and quantitative analytical methods that were used in the papers.

Data collection

Both qualitative and quantitative data was used in the process of writing this thesis. Qualitative data was collected from academic papers and grey literature in the form of reports, presentations, news articles, blogs, and web pages, as well as through interviews and observations for *Paper IV*. Quantitative data was compiled from grey literature as well as the Plantfacts dataset for *Paper III*. Searches for academic literature were primarily conducted through the literature databases Web of Science and Scopus and through reference tracing. In some cases, web search engines were used or authors of relevant studies contacted directly to access studies. Grey literature was identified through web-based search and reference tracing. For *Paper IV*, data was recorded in the form of notes from the observation of the public inquiry over the Cumbria coal mine, as well as from background interviews. The interviews served the purpose of guiding the desktop study and the triangulation of findings.

Paper III uses the Plantfacts dataset to construct scenarios for committed emissions accounting (VDEh, 2018). Plantfacts was developed by the German steel institute VDEh (Verein Deutscher Eisenhüttenleute) through surveying a large source of industry publications. A license to the database was acquired as part of the research process. The Plantfacts dataset includes detailed information about the main equipment in steel mills, including locations, nominal capacities, age and various design parameters for different plant types (e.g. sinter plant, coke oven, blast furnace), including references to the sources of this data. In total the dataset covers 36 plant types. Plantfacts captures most capacity in most countries except China, with some capacity also missing in India (Torstensson, 2020). For China, approximately half of the existing capacity is not covered by Plantfacts (see *Paper III*).

Techno-economic assessment

Paper I uses a techno-economic assessment (Grunwald, 2009) to analyse the functioning of a novel steel production process with renewable hydrogen. The assessment is based on material and energy balance calculations of a process design proposed by the author team. The focus of the study is the energy need and the carbon dioxide emissions of the hydrogen-based production process. Other environmental issues are not covered in the assessment. Based on these calculations, a simple cost model is established, which allowed the variation of a wide set of parameters to investigate the production logic of the production process as well as to facilitate later sensitivity analysis. Such simple models have the advantage that the limitations are there for everyone to see and thus become easier falsifiable. More complex, dynamic models might account better for complexity and dynamics, but critical assumptions might be hidden in a ‘welter of complex equations’ (Leach, 2010, p. 20).

The design of the production cost model is informed by previous assessments of different steel production technologies (e.g. IEAGHG, 2013; Fischedick *et al.*, 2014). The production costs are further compared to the costs of the existing dominant production method in integrated steel mills, which were adopted from the literature. Attention has to be paid to the establishment of meaningful system boundaries. In integrated steel mills, significant energy flows are exchanged between the processing stage (iron- and steelmaking) and downstream rolling and forming steps. These flows and their respective economic value need to be taken into account to improve the comparability of the two production processes. The use of literature data on the cost structure of existing integrated production puts clear limitations on the explanatory power of the comparison. The integrated mill used for comparison is largely based on a detailed cost calculation by the IEA Greenhouse Gas R&D Programme (IEAGHG, 2013) for a medium-sized integrated mill in a coastal location in Western Europe. The cost structure thus reflects a European context, both in terms of raw material and energy cost and institutionally in terms of taxes, fees, and exemptions that large industries are subject to in EU countries.

The goal of the techno-economic assessment in *Paper I* is to facilitate a comparison between current and emerging production processes. Such a comparison naturally involves normative assumptions about the future, in particular since the emerging technology (hydrogen direct reduction) had not been deployed commercially by the time of writing. For example, the assessment assumed that power grids are completely decarbonised. Sensitivity analysis of high-uncertainty assumptions is used to account for this uncertainty. A generic model such as the one presented here needs to be translated into respective real-world settings. It might be necessary to adapt assumptions such as the costs for labour or raw materials in order to adapt the model to other contexts. Furthermore, the process design presented in *Paper I* is one of many possible permutations of hydrogen-based steel production, and specific contextual factors might warrant different process configurations.

Policy evaluation

The method employed in *Paper II* is an *ex ante* evaluation of policy instruments along four criteria: effectiveness, feasibility, efficiency, and fairness. The choice of policy instruments is informed by a review of relevant academic and grey literature. The criteria are measured against the policy goal of commercialising low-emission steel production technology in the EU. Instruments relevant to the decarbonisation of steel but which did not primarily target the policy goal in focus of the study are not considered. The criteria used in the analysis are frequently encountered in the policy evaluation literature. Effectiveness denotes the degree to which the policy goal is met and is sometimes referred to as goal attainment (Vedung, 1997; Arvizu *et al.*, 2011; Huitema *et al.*, 2011). Feasibility refers to the possibility of effecting a policy instrument in a given institutional and political context. What we consider political feasibility is consistent with what some authors have called legitimacy (Mickwitz, 2003; Huitema *et al.*, 2011). Efficiency is not used uniformly in the evaluation literature either, with some distinguishing between cost-effectiveness and efficiency (Huitema *et al.*, 2011), or between cost-benefit and cost-effectiveness (Vedung, 1997; Mickwitz, 2003). Fairness is sometimes called equity (Mickwitz, 2003) or finds consideration as distributional equity (Somanathan *et al.*, 2014). Some authors employ different or additional criteria. Mickwitz (2003) for example evaluates the transparency, flexibility, and predictability of a policy.

Scenarios

Scenario analysis is part of the methods in *Papers II and III.* The steel demand outlook scenario in *Paper II* is used to span a space of possible decarbonisation trajectories in which to situate the findings of the policy analysis. It is based on a literature review of scenarios on the future share of secondary production in total steel production in Europe. The minimum and maximum values found through the review are used to span up a range of likely development of secondary steel production. The scenarios that informed this range are themselves normative results of modelling studies insofar as they explored strategic policy decisions towards circularity or decarbonisation under more or less sophisticated cost-efficiency optimisations.

The principal method used in *Paper III* is committed emissions accounting. From 2010 onwards a body of literature formed around emission commitment accounting and the phase-out of coal power and other fossil-fuels (Davis, Caldeira and Matthews, 2010; Davis and Socolow, 2014; Pfeiffer *et al.*, 2018; Cui *et al.*, 2019; Tong *et al.*, 2019). Committed emissions are the cumulative greenhouse gas emissions that are to be expected if current fossil infrastructures continue to operate until the end of their economic lifetime (Davis, Caldeira and Matthews, 2010; Davis and Socolow, 2014). Assumptions considering lifetime and capacity utilisation are crucial to such an analysis (Davis and Socolow, 2014). Committed emissions accounting can be seen as a type of predictive scenario analysis that asks a 'what-if' question (Börjeson *et al.*, 2006). Predictive scenarios typically assume that the structures shaping a particular system, in this case for example the institutional framework the steel industry operates under, remain stable in the temporal horizon of the scenario (ibid.). As such, predictive scenarios are inherently conservative, as they cannot account for transformative change or unprecedented developments. However, predictive scenarios can be used in a transformative manner by showing that a certain goal cannot be met under existing structures. Along these lines, *Paper IV* investigates the cumulative emissions of business as usual in the near future. By doing so, it aims to problematise business as usual and stress the need for more structural change.

Comparisons

Papers I, II and *IV* all use comparisons as part of their methods. *Papers I* and *II* use analytic comparisons, while *Paper IV* shows more similarities with an incorporated (McMichael, 1990) or relational comparison (Hart, 2018). Analytic comparisons deal with distinct cases that are regarded as unconnected within the scope of the analysis (McMichael, 1990). What is typically compared in analytical comparisons are cases treated as ideal types (Hart, 2018). *Paper I* offers a binary comparison between two idealised versions of technologies on the basis of their energy use, carbon emissions and costs. Developments outside the system boundaries that could affect the relative cost balance between the two are outside the scope of the study. *Paper II* follows along similar lines by comparing supply and demand-side policy approaches towards bringing low-emission steel production technologies to commercial use. Different instruments are compared as distinct objects of analysis, but the effect that choosing one approach could have on the feasibility of the other, for instance, is outside the scope of the study.

A second kind of comparisons instead focusses on the interrelations of different parts of a whole that are compared (McMichael, 1990; Hart, 2018). In *Paper IV*, I deploy and compare three theoretical perspectives that all speak to the goal of phasing out metallurgical coal. In the first part of the paper, the perspectives are treated as ideal theoretical types. The second part then opens up to explore the interrelations between perspectives. This approach has similarities with what has been called an incorporated (McMichael, 1990) or relational (Hart, 2018) comparison, which focusses on the interrelation of parts without pre-assuming a whole. In this sense, I do not pre-define the content and properties of ‘phase-out’, but let it emerge as the product of the tree perspectives and their interaction.

5 Results

This chapter summarises the four papers of this thesis and their main findings along with some reflections on the research process. The findings are presented in chronological order as the papers were written. *Paper I* is a techno-economic assessment of a suggested process design for steel production with renewable hydrogen. *Paper II* presents a policy evaluation of supply and demand-side approaches to commercialising low-emission steel production technology. *Paper III* analyses the committed emissions of the global blast furnace fleet based on a scenario built on historical operating patterns. Finally, *Paper IV* explores the politics of phasing out metallurgical coal through an analysis of three distinct theoretical perspectives of deliberate decline.

Figure 4 illustrates the relation between the papers and their position within the theoretical framework. *Paper I* and *II* are concerned with elements of the reconfiguration process, the 'creative' side of the transition, whereas *Paper III* and *IV* study the destabilisation process, the "'darker' side of this creativity" (Holgersen and Warlenius, 2016, p. 527).

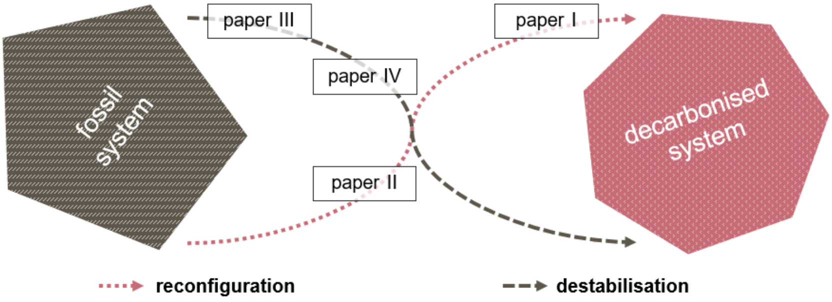

Figure 4

Schematic illustration of relations of papers to the theoretical framework.

The choice of research topics followed a sequential approach in which each paper was motivated by findings of earlier studies. *Paper II* investigates how the potentially viable technology assessed in *Paper I* could be scaled up, considering that previous innovations have frequently faltered in the commercialisation stage of the innovation process, also called the ‘valley of death’ (Nemet, Zipperer and Kraus, 2018). *Paper III* follows up on the conclusion of *Paper II* that found that subsidies would be more effective than demand-side approaches. An important lesson from power sector decarbonisation is that carrots are not enough but sticks in form of factual capacity reductions are what matters for actual emission reductions (York and Bell, 2019). *Paper III* thus investigates how blast furnace capacity reductions could be brought about. Finally, *Paper IV* continues on the track that its predecessor cleared, but takes a different angle by focussing on the fossil fuel itself, rather than the equipment it is used in. It was motivated to a good extent by my observation and involvement in the Cumbria coal mine case (see *section 4.1*), which revealed the vast and widespread lack of understanding of met coal – my own and others’ – to me.

The sequential approach taken in this thesis implies certain shifts in focus, scope, and audience. While the earlier two studies were more concerned with strict assessment to inform policy makers, the latter two addressed a wider and increasingly global audience of decarbonisation and climate change mitigation scholars and practitioners. Included in this progression is a shift in focus from a narrow understanding of policy as legislation towards an expanded vision of change brought about by a variety of actors in a polycentric manner (Jordan *et al.*, 2015). Overall, the selection of research topics was influenced by my background in engineering and my access to particular resources, for example through interactions with engineers and industry researchers within the HYBRIT RP1 research programme.

5.1 Paper summaries

I Assessment of hydrogen direct reduction

The first published study of this thesis (Vogl, Åhman and Nilsson, 2018) sought to contribute to a better understanding of hydrogen direct reduction technology, which at the time began to be picked up by iron and steel companies in their long-term plans. From 2016 onwards, a number of steelmakers in the EU announced their intentions to develop alternatives to the integrated steel mill model based on hydrogen use in direct reduction shaft furnaces. The writing process for the paper began in the summer of 2017 and was concluded in spring 2018. By that time, the few existing studies on hydrogen direct reduction (H-DR) had either based their analyses on the Circored process known from the Trinidad tests around the turn of the millennium (Fischedick *et al.*, 2014; Otto *et al.*, 2017) or investigated hydrogen use in the blast furnace with only limited emission reduction potentials (Yilmaz, Wendelstorf and Turek, 2017). However, shaft furnace ironmaking using hydrogen was not a new idea but builds on earlier technical studies, for example those performed under the ULCOS project (Ranzani da Costa, Wagner and Patisson, 2013).

Paper I analyses the steel production process with renewable hydrogen in shaft furnaces. It proposes a process design and develops material and energy balances to determine the raw material and energy needs of the process. Based on these results, the techno-economics of the process are assessed, and the resulting production costs are compared with those of the integrated steel production method. The overall finding of *Paper I* is that the hydrogen-based process follows a different *operational logic* compared to integrated steel production, which rests on several different sources of *flexibility*. The techno-economic assessment shows that although the hydrogen-based process has higher production costs than integrated steel production, the difference in production costs is not prohibitively large. The carbon price necessary to close the production cost gap ranges between 10 and 180 EUR per tonne of carbon dioxide for the electricity cost and scrap use range studied in the paper, with the lowest production costs for situations of high scrap use and low electricity costs.

The study shows how H-DR can be operated flexibly so as to make use of lower cost electricity that is the result of its variability. Several factors determine the flexibility of the proposed process design. The demand-responsiveness of electrolyser and electric arc furnace technology allows to schedule operation with respect to the temporal development of electricity costs. The aggregate phase of sponge iron made through direct reduction – solid in contrast to the blast furnace’s liquid iron – allows for stockpiling hot briquetted iron (HBI), which in turn facilitates the abovementioned scheduling. The ability of the electric arc furnace to operate on primary ferrous raw materials or on scrap, respectively, or flexibly on variable ratios between the two further allows to ramp up or down hydrogen production and ironmaking on an hourly-to-daily rhythm. Finally, the possibility to integrate the process with hydrogen storage further adds to the operational flexibility of the process design. The different operational logic could have further implications for supply chains and business models. The adaptability of the technology allows for a tailoring of business models to local circumstances, for example by using cheap peak-hour electricity or adjusting to the respective local availability of scrap (see also Toktarova *et al.*, 2022). The *de facto* de-linking or iron- and steelmaking that the paper demonstrates furthermore opens up the door to investigating the techno-economics of ironmaking in locations where electricity can be generated at low costs, as some studies have already embarked on (Gielen *et al.*, 2020; Trollip, McCall and Bataille, 2022).

II The making of green steel

The second paper of this thesis (Vogl, Åhman and Nilsson, 2020) is a policy evaluation of supply and demand-side approaches to commercialising low-carbon production methods for primary steel. Supply-side approach here refers to policy targeting the production of iron and steel, while demand-side means policy that aims to steer demand towards low-carbon iron and steel products. The study was inspired by previous successes of feed-in tariffs, renewable portfolio standards, and contracts for difference in commercialising renewable energy technologies (Mitchell *et al.*, 2011). Between 2009 and 2014, growth in renewables outpaced growth in fossil electricity generation 'driven mainly by falling technology costs and support policies' (IRENA, IEA and REN21, 2018, p. 14). The novelty of these instruments was their departure from the idea of carbon pricing as a single-instrument approach (see *section 6.2*). In the EU, a cap-and-trade scheme for carbon pricing (EU ETS) had been in place since 2005 and had been revised through several phases. However, energy and trade-intensive industries such as iron and steel had successfully lobbied for the free allocation of emission allowances by exaggerating their vulnerability to climate policy (Okereke and McDaniels, 2012). This reduced the effectiveness of the ETS and leading to partial windfall profits (Carbon Market Watch, 2016). Consequently, EU carbon pricing policy was caught between threats of carbon leakage and problems regarding its political feasibility. The successes of quotas and feed-in tariffs in the power sector and the revival of industrial policy (Aiginger and Rodrik, 2020) more generally, motivated us to investigate the possibility of a different policy approach to industrial emitters more closely related to an idea of shaping rather than fixing the market (Mazzucato, Kattel and Ryan-Collins, 2019)

Paper II thus follows this lead and compares supply-side approaches in the form of carbon contracts for difference (CCfD) with the demand-side instruments such as quota schemes and public procurement. The paper has an EU scope and evaluates these approaches based on their integration with the existing EU climate policy framework for the steel sector and in particular the EU emission trading system (ETS). The policy evaluation follows four criteria: effectiveness, efficiency, feasibility, and fairness. The criteria are deployed against the policy goal of commercialising low-emission steel production technology. The primary finding of the study is that supply-side policy in the form of subsidies is more effective in bringing about the designated policy goal. The investigated demand-side approaches face inherent limitations, in particular due to the global, fragmented, and opaque nature of steel supply chains, which lowers their effectiveness. The study further illustrates the challenges of designing decarbonisation policy for heavy industries within existing institutional and social contexts. It finds that the identified more effective subsidy-based approach risks to lead to an unequal distribution of benefits and burdens. It further identifies existing institutional barriers to decarbonisation in the EU ETS that hamper the efficiency of the proposed policy instruments. Besides existing policy, further integration is required between the type of commercialisation policy investigated in the paper and other areas of industrial decarbonisation policy such as material efficiency and demand reduction, as well as complementing the subsidy carrot with a stick to ensure emission-intensive production capacity is taken offline on equal terms.

III Phasing out the blast furnace

The third study included in this thesis (Vogl, Olsson and Nykvist, 2021) is an assessment of the committed emissions of the fleet of integrated steel mills. Committed emissions are, per definition, the cumulative emissions that are to be expected if current fossil infrastructures are to be operated until the end of their economic lives (Davis, Caldeira and Matthews, 2010; Davis and Socolow, 2014). Initial studies using the committed emissions concept had focussed on fossil energy infrastructures and shown how their continued operation threatened the goals of the Paris Agreement (Davis, Caldeira and Matthews, 2010; Pfeiffer *et al.*, 2016), or vice versa, how pursuing the Paris goals could result in stranded assets (Pfeiffer *et al.*, 2018). Later studies have then extended the method of committed emissions accounting to other assets such as industry and mobility by largely adopting the approach developed for the power sector (Smith *et al.*, 2019; Tong *et al.*, 2019).

This is where *Paper III* takes its starting point. Based on a large dataset of the global blast furnace fleet (VDEh, 2018), we estimate the emissions commitment of integrated steel production. We find that previous studies had overestimated the emissions to be expected from current integrated steel assets by a factor of two or more. This large discrepancy emanates from the borrowing of the committed emissions accounting methodology for analyses of the industry sector, not accounting for differences between the power sector and industry. In particular, previous studies had assumed economic lifetimes of 35-40 years for steel mills, whereas we found the median historical operating life of blast furnaces to be 17 years, with this result being subject to very large variability. Based on this finding, the paper describes the main differences between the sectors relevant to committed emissions analyses. More specifically, it makes the case to focus on the asset level rather than on the whole industrial asset in committed emissions accounting, and to take into account the possibility to rebuild existing integrated steel mills for low-carbon production. Accordingly, the paper argues that the relining of blast furnace is the most relevant target for a phase-out policy on integrated steel assets. Since the reconfiguration of existing integrated mills can follow different technological trajectories, committed emissions accounting in industry is a more demanding analytical task than in the power sector.

Paper III further discusses the inherent limitations of extrapolating historic operating patterns into the future as it is done in committed emissions accounting. The large variability in historic economic lifetimes of blast furnaces suggests that blast furnaces cannot be regarded to have a fixed lifetime (cf. Worrell and Biermans, 2005). This means that methods such as committed emissions accounting run the risk of underestimating the potential for rapid climate action by reifying the fundamentally political character of asset economic lifetimes. Finally, the paper further explores the dynamics of blast furnace phase-out and global overcapacity in steel production. In particular, it finds that phase-outs have no effect on emissions from the sector as long as overcapacity prevails. It finds that low-carbon capacity additions could exacerbate the overcapacity in conventional (i.e., fossil) steel markets if their production can be traded on exclusive markets for green steel.

IV The forgotten fossil fuel

The final paper included in this thesis explores the politics of phasing out metallurgical coal. It does so by analysing metallurgical coal, met coal in short, from three distinct theoretical perspectives of ‘deliberate decline’ (Rosenbloom and Rinscheid, 2020). Deliberate decline in the context of sustainability transitions research is concerned with processes of deliberate leaving behind unsustainable social practices, such as in this case the production and use of metallurgical coal. The study of processes of deliberate decline is a response to repeated criticism towards the innovation bias of sustainability transitions research (e.g. Shove and Walker, 2007; Shove, 2012). Despite representing a sixth of global coal consumption (see *Paper IV*), metallurgical coal has so far been entirely left out of the coal phase-out debate. However, lessons from studying thermal coal might not be fully transferable since, as *Paper III* already showed, phasing out power sector and industrial sector assets partly follows different logics. *Paper IV* thus takes a first step towards understanding the phasing out of metallurgical coal. It does so by analytically deploying three perspectives that it locates under the umbrella of the concept of phase-out: substitution, destabilisation, and unmaking. These perspectives are operationalised as phase-out strategies with distinct scopes, actors, problem formulations, and means. The phase-out of met coal is then analysed according to the three strategies and the findings are compared with each other.

On an aggregate level, *Paper IV* locates a large potential for the building of broad and heterogenous coalitions aiming to phase out met coal. It further outlines different ways how campaigns on phasing out met coal can be joined with the existing efforts to phase out thermal coal, for example by further exploring the connections between the two, or by challenging incumbent discourses framing met coal as a raw material rather than as a fossil fuel. Through analysing met coal according to three distinct perspectives, *Paper IV* sketches initial action points for a politics of phasing out met coal. These include increasing efforts to create knowledge, data and awareness around met coal, the nurturing and diffusion of anti-met coal norms, and the politicising and challenging of the Eurocentric heuristic that steel is essential for modern lives. The study concludes with a discussion on the relationship between the different perspectives of deliberate decline. It concludes that a politics around phasing out met coal as opposed to the phasing out of the blast furnace as investigated in *Paper III* is able to accommodate a wider set of actors and grievances and thus opens up towards a larger variety of pathways towards sustainability (Leach, 2010).

Paper IV was submitted to a peer-reviewed journal on 6 October 2022 and was under review at the time of submission of this thesis.

Reflections

Before moving into the discussion, I briefly want to reflect upon the relationship between the papers and the writing process. A thread weaving through all papers in this thesis is the relation between industrial and power sector decarbonisation. The process assessment in *Paper I* assumes the availability of plentiful renewable electricity and the industrial competitiveness of the technology hinges primarily on the costs of electricity generation. The choice of policy instruments in *Paper II* was strongly inspired by recent successes in government support for deploying renewables in Germany's *Energiewende* and beyond. *Paper III*, in turn, presents a methodological critique of the committed emissions accounting for industrial assets, which had been rather crudely adopted from studying power sector decarbonisation. Finally, *Paper IV* seeks to link the phasing out of met coal to existing and increasingly successful campaigns against thermal coal. Clearly,
the decarbonisation of the power sector is a crucial background process that heavily ties into industrial decarbonisation and that needs to be understood in order to grasp the dynamics of industrial transitions.

A variety of other developments during the writing years of this thesis have shaped the research process. Overall, steel decarbonisation has been a rapidly moving study object. The years after the Paris Agreement saw a rapid diffusion of net-zero target setting in many nation states, companies, and other organisations. At the same time, the steel decarbonisation increased in prominence as a concern for global environmental governance. A Scopus keyword search in October 2022 reveals 82 publications on 'steel decarboni*ation'[11] in 2021, up from 17 in 2016 and eight publications in 2015. Within just a few years, steel has evolved from 'hard-to-abate' to increasingly feasible to decarbonise. Initiatives such as the Leadership Group for Industry Transitions (LeadIT) launched at the 2019 UN Climate Action Summit and the First Movers Coalition launched at COP26 are a testimony to this increasing profile of steel decarbonisation. By 2022, the iron and steel industry has announced plans to deploy a total of over one hundred million tonnes of 'low carbon' steel production by 2030 (Agora Energiewende, 2022). Some more recent developments with potential to influence and shape the steel transition are the potential passing of coal-based steel production in China, which could mark the beginning of a shift towards steel recycling in China (Li *et al.*, 2022). Furthermore, Russia's invasion of Ukraine ongoing at the time of writing will have yet unknown implications for steel decarbonisation.

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[11] The asterisk allows to accommodate British and American English spelling

6 Decarbonising primary steel

In this chapter I answer the three research questions based on the findings of the papers and the theoretical framework. In line with these questions, the chapter is structured in three parts. The first part argues that the imperative of decarbonisation increasingly challenges the idea of fixing steel production through carbon capture and storage, while encouraging the uptake of alternative ways of producing steel and in particular the electrification of steel production. In the second part, I argue how a socio-technical transitions perspective is needed to effectively advance the project of decarbonising primary steel. Here I discuss different approaches to destabilise and reconfigure the primary steel socio-technical system based on the findings of the four papers included in this thesis. Finally, I discuss the role and limitations of my research in contributing to transformations towards sustainability.

6.1 Out of blast

The blast furnace route is the dominant mode of iron and steel production today. About 1,000 blast furnaces (see *Paper III*) and their downstream operations crank out 1.4 billion tonnes of steel each year (Worldsteel, 2022). Despite its popularity up to today, the blast furnace seems to be losing its appeal. Up to the Paris Agreement, blast furnace carbon capture and storage was the main technological contender in the steel industry's long-term plans. After the Paris Agreement, this began to change, with more and more companies swapping CCS for hydrogen in their roadmaps and climate communications (Vogl *et al.*, 2022). In the following, I show how the imperative to decarbonise in conjunction with the progress of renewable energy technology increasingly challenges the idea of fixing the existing steel socio-technical system that has evolved around the blast furnace and metallurgical coal. In its place, a qualitatively different socio-technical system based on the electrification of primary steel production is emerging.

The need to phase out the blast furnace

As long as partial emission reductions seemed a sufficient response to the evolving landscape of climate target, fixing the blast furnace by means of CCS appeared as a legitimate strategy. With the Paris Agreement, this began to change. Today, the need to fully decarbonise that follows from the Paris treaty increasingly clashes with the materiality of blast furnace ironmaking. In particular, the requirement to radically reduce and eventually eliminate greenhouse gas emissions strains the limits of coal use in the blast furnace. Although metallurgical coal used in blast furnace ironmaking can be substituted partially by other energy carriers, a minimum amount of metallurgical coke is required to guarantee the stability of the production process (see *Paper IV*). The shift from *emissions reductions* to *decarbonisation* is hitting this limit and hence casting doubt on the blast furnace itself.

Modern blast furnaces have evolved on the premise of coking coal. The switch from charcoal to coking coal with its high crushing strength removed the material constraint on maximum possible furnace heights, and consequently blast furnaces grew in size and capacity with the introduction of coking coal and associated innovations in furnace design (Smil, 2016, see also *section 2.2*). The modern blast furnace's dependency on coking coal is a consequence of this co-evolvement. Deep emission reductions in the blast furnace are circumscribed by a minimum coke rate that is required for the stable operation of the blast furnace process (Díez, Alvarez and Barriocanal, 2002; Suopajarvi *et al.*, 2017). In order to fully decarbonise the blast furnace, both carbon capture and storage technology potentials and bioenergy inputs into the process need to be maximised (Mandova *et al.*, 2019). While such deep emission reductions in the blast furnace are theoretically possible (Mandova *et al.*, 2019; Tanzer, Blok and Ramírez, 2020), the requirement to maximise bioenergy and CCS potentials leaves the industry little flexibility to adjust to local conditions or market situations. What is more, the maximising of bioenergy and CCS potentials strains the techno-economics of blast furnace ironmaking. Pushing the limits of emission reduction potentials in the blast furnace requires that CCS be mounted to several exhaust pipes (cf. emission sources in *figure 3*) and that large amounts of carbon-neutral charcoal need to be procured, which can be associated with high costs and logistical challenges in many parts of the world.

These factors leave little flexibility for blast furnace operators to react to market conditions since several factors need to fall into place to get close to emission reductions such as those required in line with decarbonisation. Iron and steel production is characterised by strategic investment decisions and periods of boom and bust that can stretch over years (D'Costa, 1999). Flexibility is crucial for steel companies to deal with uncertainties at the time of investment, for example uncertain future policy developments or changes in the market. Consequently, blast furnace CCS is becoming an increasingly risky investment choice for steel producers. It depends on a long-term predictable and dynamically stable carbon price (Richstein and Neuhoff, 2022) and is vulnerable to developments such as the proper reporting of coal mine methane emissions (see *Paper IV*) and climatic events or land use conflicts that could endanger the supply of carbon-neutral biomass. These risks threaten the blast furnace's ability to comply with climate target and thus its long-term viability. The number of factors that 'need to be right' for blast furnace ironmaking to become caron neutral suggests that the applicability of blast furnace CCS might be limited to a small number of suitable locations. Furthermore, the changed cost structure of carbon neutral ironmaking in blast furnaces needs to be competitive in face of adopters of alternative technology.

Advancing renewables and the recovery of an old idea

While decarbonisation increasingly challenges the idea of blast furnace CCS, it does not itself explain the recent industry shift from blast furnace to hydrogen-based steel production. Here I argue that it is the drastic cost reductions of renewable energy that encourages the shift to hydrogen in a situation where the blast furnace is being challenged by decarbonisation requirements.

Within two decades, the generation of renewable electricity, in particular wind and solar, has drastically reduced in cost. The cost of electricity from solar PV has decreased by 89% since 2000 (Clarke *et al.*, 2022, p. 23) and electricity from wind power generation was 38% cheaper in 2020 compared to 2010 (Clarke *et al.*, 2022, p. 29). This matters because, as *Paper I* shows, electricity costs are the main cost driver in steel production based on renewable hydrogen. The findings in *Paper I* indicate that the technology can be close to competitive with the blast furnace-based production route in locations with low costs for renewable electricity generation. As electricity costs are the main determinant of production cost, recent developments in renewable energy performance and the expectation of the continuing of this trend have allowed steel producers to resurrect the old idea of electrifying steel production.

Hydrogen direct reduction had been commercially tested over decades ago (see *section 2.4*). After the short-lived Trinidad trials, the technology was reconsidered under the ULCOS project, where it did not make the cut due concerns over energy efficiency and cost performance (Birat, Patisson and Mirgaux, 2021). However, past predictions of future renewable energy developments have notoriously underestimated the pace of progress (Myllyvirta, 2017). The negative ULCOS assessment of hydrogen direct reduction fits this pattern. Today, the rapid developments in renewable energy performance and generation costs are changing the odds for hydrogen steel production. While the Trinidad plant ran on hydrogen generated from fossil fuels, many of the recent industry announcements target the use of renewable hydrogen, at least if the industry’s long-term plans are to be believed (Vogl *et al.*, 2022). While some producers aim to move towards pure hydrogen operation via using natural gas as an intermediate technology, others have announced to move into renewable hydrogen directly. However, it is too soon to speak of a full-fletched shift to hydrogen yet since most of these plans are in their early stages. As the following sections will demonstrate it is up to policy and other advocates of steel decarbonisation to harvest this loosening of carbon lock-in in the steel sector.

6.2 Decarbonisation as systems change

I have so far argued that the intersection of the decarbonisation imperative with recent progress in renewable energy technology systematically challenges CCS and encourages the electrification of steel production based on renewable energy. The electrification of steel production, however, requires significant changes to the existing socio-technical system that has evolved around cheap fossil fuels. Here, I continue the argument by showing how the departure from the blast furnace-based production model requires a simultaneous abandonment of the approach of *fixing* the existing socio-technical system and towards an approach of steel decarbonisation as a *socio-technical transition.*

Fixing the existing socio-technical system describes the idea to reduce emissions while largely retaining the existing socio-technical system. This approach corresponds to what I have called 'substitution' in *Paper IV:* the fixing of a negative externality through fuel shifts within the existing production setup. The promise of blast furnace carbon capture is a paradigmatic attempt of fixing since it leaves the socio-technical elements at the heart of steel's climate problem – blast furnace, metallurgical coal, coke ovens etc. – largely untouched. Fixing primary steel instead involves the addition of CCS as an end-of-pipe technology to the blast furnace and potentially other parts of the steel mill, as well as the substitution of non-coking metallurgical coal with charcoal where possible. In contrast, the electrification of primary steel production requires substantive changes to core components of the socio-technical system. Hydrogen direct reduction technology, as studied in *Paper I*, for example does not need blast furnaces, metallurgical coal, basic oxygen converters, sinter plants or coke ovens. Instead and depending on the configuration of the process, it requires their replacement with different elements such as electrolysers and electric arc furnaces (see also *Paper III*). A change from blast furnace-based to electrified steel production thus represents a substantial qualitative shift in the composition of the steel socio-technical system, or in other words, a socio-technical transition. This shift in turn has implications for policy making and the (geo-)politics of climate change mitigation in primary steel production.

The choice of approaching the challenge as fix or transition, respectively, has large implications for the identification of strategies to climate change mitigation in primary steel production. In this chapter, I conceptualise the decarbonisation of primary steel as a socio-technical transition based on the theoretical framework presented earlier. First and based on findings of the four papers, I discuss different ways to destabilise the existing fossil socio-technical system and to reconfigure it around a different set of core components. Next, I argue that the transitions approach demands a mission-oriented policy approach, and that the revival of industrial policy represents a promising seed of an approach to advance steel decarbonisation. At the end of this chapter, I show how all of these strategies – destabilising, reconfiguring, and mission-oriented industrial policy – are part of an emergent politics of steel decarbonisation.

Destabilising met coal and the blast furnace

To comply with increasingly ambitious climate targets, many steelmakers have announced their intentions to move beyond coal in steel production. However, today large incentives exist for steelmakers to continue using metallurgical coal. In other words, steel is locked into metallurgical coal (see *Paper IV*). Destabilising the coal-based steel system and thus the phasing out of blast furnaces and metallurgical coal begins with an identification of the roots of carbon lock-in in primary steel production. Based on my conceptualisation in *section 3.2,* metallurgical coal and blast furnace technology gain their stability within the steel socio-technical system from their interrelations with other elements. An example for this stability through interrelations can be found in *Paper III,* which provides an identifies several components of integrated steel mills that are unique to the blast furnace production route, for example sinter and coking plants. Since these assets typically have long economic lives of two decades or more, a reinvestment into one of these assets creates an incentive to further reinvest in the others. However, actors seeking to destabilise the steel socio-technical system by aiming at some of these components must have at least a basic understanding of the alternative configuration for which they are aiming. This is because different alternative configurations might require the destabilisation of different components of the existing system (see below). Other examples besides the technological or infrastructural lock-in investigated in *Paper III* (Seto *et al.*, 2016) are the institutional enshrining of the metallurgical coal-blast furnace way of making steel. In *Paper IV,* I discuss institutional lock-in in the form of the EU Critical Raw Materials List (European Commission, 2020b) and in *Paper II* in the shape of perverse incentives in the design of the benchmarking system in the EU ETS.

Once identified, efforts of destabilisation should be directed at the core elements to be phased out and the relations that stabilise them. *Paper IV* discusses the potential of various strategies aimed at increasing the risk of doing business with metallurgical coal, for example the building and nurturing of anti-met coal norms through challenging incumbents on a discursive level, as well as protest, litigation, and divestment. Another type of target for destabilisation is the pipeline of planned projects that, if realised, would further entrench the use of fossil fuels in steel production. As part of the data collection process for *Paper IV,* I observed the political process around the Cumbria coal mine (see *section 4.1*). With regards to integrated steel mills, *Paper III* argues that it is most promising for actors their efforts on trying to prevent the relining of blast furnaces to avoid locking in future greenhouse gas emissions. This strategy is being taken up in practice, most recently in the debate over relining at the *BlueScope* mill in Port Kembla, Australia (Buckley, 2022).

Reconfiguring steel production

For a transition to occur, destabilisation must be accompanied by efforts to reconfigure the socio-technical system. The substance of reconfiguring, however, depends on an understanding of the new system configuration and the ways in which it differs from the current system. *Paper I* analyses one possible configuration based on the hydrogen direct reduction process and finds several characteristics of the process that can act as starting points for reconfiguration. These include different flexibility potentials inherent in the process, the key role of electricity, and the potential to split iron- and steelmaking process stages and locate them in different places. Reconfiguration furthermore takes its starting point in the existing socio-technical system. *Paper II* analyses how policy approaches to commercialising low-carbon steel production methods can be designed based on the existing institutional framework in the EU, which has evolved around cap-and-trade carbon pricing as its principal component.

Newly introduced elements do not typically fit into the existing socio-technical system neatly. Consequently, the task of reconfiguration includes the creative re-tying of those 'fossil relations' that are being disrupted by destabilisation around the integration of new elements into the system. Recent concerns around iron ore and steel product quality requirements that could become bottlenecks to the transition illustrate this well. Since current direct reduction technology requires high-grade iron ores, researchers and companies were concerned about bottlenecks in raw material quality that could decelerate the transition (IEA, 2020; Nicholas and Basirat, 2022). In response, different steelmakers and technology suppliers started investigating alternative configurations of the hydrogen direct reduction process that can accommodate lower quality ores (Nicholas and Basirat, 2022). A second major worry in the steel decarbonisation field is that certain steel qualities, which today are achieved in blast furnace-based production, can potentially not be realised in electric arc furnaces (Hoffmann, Van Hoey and Zeumer, 2020). This concern will similarly require reconfiguring work, either through technological innovation on the side of electric arc furnaces, or by trying to alter the demand for steel products of the respective quality characteristics.

Reconfiguration can furthermore make use of different properties that emerge through the new system configuration. Just as the blast furnace-based system creates incentives for integrating steel mills and locating them in specific locations, so new system configurations will have their own properties and tendencies. *Paper I* finds that the hydrogen direct production process is characterised by a number of degrees of flexibility such as the stockpiling of solid sponge iron, the flexible use of scrap and primary iron input, and different potentials to adjust the energy consumption of the process over time. Based on this analysis, a transition to hydrogen-based steel production can potentially be furthered by integrating the production process with the energy system as a means of balancing the grid (Toktarova *et al.*, 2022). Furthermore, the adoption and diffusion of novel technologies have historically been important forces behind processes of steel industry restructuring (D’Costa, 1999). The possibility of splitting ironmaking from steelmaking in the hydrogen direct reduction process allows actors to explore new business models and value chain setups. A promising variation is to locate ironmaking in places with access to low-cost renewable electricity and iron ore while retaining downstream operations where they are located today (Gielen *et al.*, 2020; Trollip, McCall and Bataille, 2022). In this way, the properties of an electrified steel socio-technical system condition the process of steel industry restructuring, as comparative advantages are reshuffled with a shift from coal to electricity in steel production.

Mission steel decarbonisation

A shift from the fixing to transitions requires a change in approach to climate policy for primary steel production. In this section, I argue that the idea of fixing the socio-technical system has co-evolved with the prevailing approach of carbon pricing. Steel decarbonisation understood as a socio-technical transition, however, is better aligned with a mission-oriented approach to climate policy for industry. The recent revival of interest in industrial policy is a promising though not straightforward development towards a ‘mission steel decarbonisation’.

European steel CCS efforts were premised on the idea of carbon pricing to level the playing field. The additionality of CCS as an end-of-pipe technology means that its economic competitiveness inherently hinges on continuous government support to level its production cost disadvantage over unmitigated steel production. In order to level out this disadvantage, a carbon price or some other form of continuous and reliable compensation for elevated production costs is needed to ensure the competitiveness of CCS on the existing market. Mazzucato et al. (2019) call this the market fixing policy framework. Market fixing attempts to internalise negative externalities such as greenhouse gas emissions through market-based approaches. It is grounded in ‘the simple theory of externalities [that] indicates that only one instrument is needed to internalize one externality’ (Hepburn, 2006, p. 231). Accordingly, the market fixing framework stipulates effective carbon markets as the main (van den Bergh and Botzen, 2020), or in some cases only instrument to address the issue of greenhouse gas emissions. Any additional policy instruments would, in theory, distort the cost-efficiency of carbon pricing (Lilliestam, Patt and Bersalli, 2020).

In the EU, carbon pricing for heavy industry has proven to be politically difficult, especially due to the industry’s repeated threats of carbon leakage (see *Paper II*). Although no evidence of carbon leakage up to the date of writing exists (Grubb *et al.*, 2022), the steel industry has been very effective in avoiding paying for its emissions through the carbon leakage threat (Okereke and McDaniels, 2012; Carbon Market Watch, 2016; Simon, 2022). Other factors limiting the effectiveness of carbon pricing in heavy industry are the strategic nature of iron and steel investments (see *Paper III*) and the related uncertain expectations over future climate policy that prevent industries to take strategic investments (Chiappinelli and Neuhoff, 2017; Richstein and Neuhoff, 2022, see also *Paper II*).

The imperative of decarbonisation and the respective shift from fixing socio-technical systems to transitions challenges the market fixing approach fundamentally. This is because electrified steel production has an entirely different investment and scaling logic than CCS. *Paper I* shows that hydrogen-based steel production could be close to competitive with blast furnace-based production in places with preferable conditions such as the ample availability of low renewable energy, but also a demand for 'green steel' (Vogl and Åhman, 2019). Although production costs will likely be higher for a first-of-a-kind plant, once technology learning and economies of scope have set in, electrified steel production has the potential to take off without or with only little subsidies and scale from there. This stands in contrast to CCS, which by definition results in a permanent and relatively constant increase in operating costs compared to unmitigated blast furnace-based steel production, with few learning potentials to be realised.

Mazzucato et al. (2019) contrast market fixing with a mission-oriented approach to policy, which is based on the idea that all markets are co-created by public, private and third sectors. Accordingly, it is the role of governments to shape markets in a way so as to support public purposes such as decarbonisation of heavy industries. This can be done with a variety of instruments coordinated as policy mixes around a particular goal (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016). In this light, the recent revival of green industrial policy[12] (Aiginger and Rodrik, 2020) is a promising development that chimes with a socio-technical transitions approach to steel decarbonisation. Green industrial policy describes the pursuing of environmental policy objectives through policies affecting industrial development (Nilsson *et al.*, 2021), for example through state-led development of clean technologies or whole industries (Rodrik, 2014; Meckling, 2021). The return of industrial policy in a green shape manifests itself in policy strategy packages such as the European Green Deal and the EU Industrial Strategy, as well as in the 2022 US' Inflation Reduction Act. These policy strategies were pre-dated by the successes of policy instruments such as feed-in tariffs, which have been credited for successfully accelerating the development of renewable energy technologies (Mitchell *et al.*, 2011).

Inspired by the revival of industrial policy, a 'mission steel decarbonisation' would have to take the necessary risks to overcome the challenges of first-of-a-kind technology demonstrations in order to then benefit from and scale via technology learning effects (Mazzucato, Kattel and Ryan-Collins, 2019). This does not mean that carbon pricing cannot play a role in such a scheme, just that it is one of the elements of a decarbonisation policy mix (Rosenbloom *et al.*, 2020). Policy options

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[12] My focus here is on the implications of the return of industrial policy in the EU and to some extent the US, both due to my position at a Swedish university and since EU actors are at the forefront of decarbonising primary steel production.

under a mission-oriented approach include subsidies (see *Paper II*), blast furnace bans (see *Paper III*), as well as government-industry negotiations and respective government assertions of transition support as most recently visible in steel decarbonisation projects in Spain (ArcelorMittal, 2021) and the Netherlands (Tata Steel Netherlands and The State of the Netherlands, 2022). However, policy mixes need to go beyond decarbonising primary steel and integrate the need for decarbonising primary production (supply-side) with material efficiency and demand reduction (demand-side) as central strategies of steel decarbonisation. The closing section of this discussion will discuss the respective contributions and not always complementary relationship between supply and demand-side approaches to decarbonisation.

The emergent politics of steel decarbonisation

It is clear from the examples introduced so far that the destabilising and reconfiguring of socio-technical systems is inherently political (Meadowcroft, 2009; Lockwood *et al.*, 2017; Newell, 2019). Destabilising and reconfiguring intersect with a wide range of debates and activities that are inevitably contested. The overcoming of incumbent interests (Johnstone, Stirling and Sovacool, 2017; Newell, 2019; Muttitt and Kartha, 2020), debates over the role of carbon pricing (Patt and Lilliestam, 2018; Rosenbloom *et al.*, 2020; van den Bergh and Botzen, 2020; e.g. Green, 2021), and issues of green colonialism and problem shifting (Dunlap, 2018; Kröger, 2020; Feola, Koretskaya and Moore, 2021; de Leeuw and Vogl, 2022) are just some examples of political processes that tie into the decarbonisation of primary steel (see also the unmaking of met coal in *Paper IV*). As such, activities directed at the destabilisation and reconfiguring of the steel socio-technical system begin the basis of an *emergent politics of industrial decarbonisation.*

These activities play out across different scales, actors, and objects of political contestation. Local instances of steel decarbonisation politics include campaigns against steel mill pollution or relining, coal mines, renewable energy development, or labour organising in response to local and regional job losses in relation to the decarbonisation process. Globally, states and subnational actors have begun to form coalitions such as the Leadership Group for Industry Transition, the First Movers Coalition, or the Global Steel Climate Council. The contents of steel decarbonisation politics range across the spectrum of politics to include issues of resource allocation, institutional design, framing (Leach, 2010), and the recognition of certain social groups and their grievances (Boswell, 2020). In all these examples, steel decarbonisation is but one of many intersecting issues at play. In the last section of this chapter, I discuss the central challenge of aligning the decarbonisation of primary steel with progress on other pressing social and ecological issues in order to avoid problem shifting and facilitate transformations towards sustainability.

6.3 Primary steel in a transforming world

In this closing section I reflect upon the synergies and trade-offs between transitions in the steel sector and wider societal transformations towards sustainability. In the first two sections I discuss the relationship between decarbonising primary steel and other approaches to decarbonisation around recycling, material efficiency, and demand reduction. In the final two sections of this chapter, I further reflect on the trade-offs between decarbonising primary steel making and broader pursuits of sustainability and how these two can be aligned.

The need to engage with primary steel production

The aim of this thesis has been to understand how the decarbonisation of primary steel production can be brought about. In this section I discuss the need for a critical engagement with this topic that accepts the need to decarbonise primary steel while taking seriously its entanglements in social and ecological problems. Primary steel is eight times more energy-intensive than secondary production (Hasanbeigi, 2022) and its cumulative environmental impacts outstrip other basic materials in many environmental impact categories (OECD, 2019). Primary production's high historical responsibility for greenhouse gas emissions (Wang *et al.*, 2021) and its other environmental and social stresses (see below) have justly been called into question by advocates of demand-side steel decarbonisation, who promote increased circularity, material efficiency, and demand reduction. A burgeoning literature has demonstrated the significant potential of demand-side approaches to reduce greenhouse gas emissions from iron and steel (Allwood *et al.*, 2011; Allwood and Cullen, 2012; Cooper-Searle, Livesey and Allwood, 2018). Demand-side strategies are advocated by the International Energy Agency (IEA, 2020), the IPCC (Bashmakov *et al.*, 2022), and the International Resource Panel of the United Nations Environment Programme (IRP, 2020). The large potentials for demand-side solutions in face of the high socio-ecological impacts of primary production raises two main questions. First, which role, if any, can socio-technical change in primary steel production play for steel decarbonisation; and second, how do advances in supply-side decarbonisation influence demand-side approaches, and vice versa?

Watari et al. (2020) find that reaching the 2°C climate target would require drastic reductions in steel demand in high income countries. Even under such a (rather optimistic) scenario of substantially curtailed steel demand in the Global North, primary production is yet to peak on a global level and might decline only slowly thereafter. This suggests that, even in more transformative scenarios with reduced material throughput in society, some primary steel production will be required for the foreseeable future. I take this to imply that devising low-carbon production methods can generally improve the chances to meet the Paris targets.

Based on these insights, the contribution of novel, low-carbon technologies such as hydrogen direct reduction is likely to play a bigger role in countries which have little steel scrap available to cover their domestic steel demand. Such countries must rely on primary steelmaking to produce steel since they cannot benefit from scrap becoming available due to past steel consumption. Countries with longer histories of industrialisation, on the other hand, enjoy a 'scrap privilege' that is at odds with the CBDR-RC principle of the Paris Agreement and the UNFCCC. The scrap privilege means that countries primarily responsible for the problem and the largest capacities to address it are privileged by the availability of steel scrap, which reduces their need to deploy low-carbon primary steel production technologies. In other words, high-income countries could largely decarbonise their domestic steel industries through switching to steel recycling (if they decided so), whereas middle and low-income countries need to rely on likely more expensive primary steel production, since little end-of-life scrap exists that can be recycled (Pauliuk *et al.*, 2013). Global and regional trade in steel and its raw materials might complicate this picture slightly, but the overall trend certainly holds. The scrap privilege adds to the challenge of steel decarbonisation and emphasises the responsibility of high-income countries to support and finance steel decarbonisation in low and middle-income countries based on the CBDR-RC principle.

The crowding out of non-technological approaches

The academic literatures on supply- and demand-side decarbonisation of steel have to large extent evolved separately. While the prior focusses on technological innovations and energy efficiency in iron and steel production, the latter is concerned with material efficiency and demand reduction, as well as more holistic approaches to circularity. Research on demand-side decarbonisation has demonstrated the large mitigation potential of measures that reduce the demand for steel or get more services out of the same amount of steel. However, material efficiency and other demand-side options have not succeeded in taking their due spot on the climate policy agenda (Cooper-Searle, Livesey and Allwood, 2018). Critics have justly emphasised the large mitigation potentials of deploying demand-side solutions alongside existing technology and cautioned against over-reliance on yet undeveloped technologies (Allwood *et al.*, 2019; Allwood, 2022). These critiques raise the question whether supply and demand-side decarbonisation are as compatible as often presented, or if one side does not in fact systematically undermine the other. In other words, it is worth investigating in which ways promises of technical fixes (Markusson, 2017) in primary production potentially distract from and crowd out demand-side solutions.

It is underappreciated in the main contributions to industrial decarbonisation today that technological approaches to decarbonisation are at a systemic advantage over demand-side approaches. Instead, it is common that supply and demand side approaches to steel decarbonisation are presented as complementary (IEA, 2020;

e.g. Bashmakov *et al.*, 2022). In this argumentative line, demand-side efficiency improvements can ease the job for supply-side technological solutions by reducing the overall demand for steel to be produced in cleaner ways. Politically, however, supply-side and demand side approaches to decarbonisation are not only compatible but compete and contradict each other in important ways. It is a common feature throughout environmental policy that industries tend to decarbonise only once they can shift into alternative opportunities for capital accumulation. David Harvey calls this the 'spatio-temporal fix', which describes how capital tends to solve its internal contradictions such as the increasingly untenable generation of greenhouse gas emissions through geographical expansion and temporal deferment (Harvey, 2005). The steel sector's current hydrogen hype is a case in point, insofar as it seeks to build up a new industry and market around green steel.

In doing so, one of its main strategies is the signalling of control over the problem via promises of technical fixes (Markusson, 2017) to garner the support needed to create a green steel market. A main function of technical fixes is the 'performance of control' that discursively reduces uncertainty to manageable risk (Scoones and Stirling, 2020). This performing of risk management through technological promises via advertisements, flashy policy reports, and the mass media, among others, in turn comforts policy and civil society actors by signalling that solutions to the problem are already underway (de Leeuw and Vogl, 2022). It is through these performances of control that non-technological approaches to decarbonisation get crowded out by technological promise and hype around new commodities (ibid.).

This crowding out effect of demand-side decarbonisation is likely even more pronounced in incumbent-led transitions (Hess, 2020) such as the case of iron and steel. In the case of primary steel, policy makers are dependent on the steel industry to develop the technology that is needed to decarbonise it. This means that industry is in a powerful position over the progress, direction, and timing of supply-side decarbonisation. In the past, the EU steel industry has been successful to lobby against carbon price stringency while at the same time stalling and stopping technological developments on blast furnace CCS. By floating CCS as the main technological option while simultaneously lobbying against the policy enabling the technology, the net effect of blast furnace CCS in the past two decades has in effect been a deterring of climate change mitigation (McLaren, 2016; Markusson, 2022). In this context, states are bound in the ways they can counteract industry since they have mixed interests in the transition themselves (Newell, 2019). Spatio-temporal fixes, insofar as industries do not relocate outside national limits, can act as drivers for employment and domestic economic development. Steel industries are often connected to downstream manufacturing sectors and support many more jobs in manufacturing than those located directly at the mills. On the other side, states should have interests in material efficiency, which also supports domestic economic performance, as well as environmental and social objectives. These mixed interests as well as the fact that in some cases steel firms are state-owned (OECD, 2018), curtails the ability of states to prioritise demand-side decarbonisation.

Decarbonising primary steel as problem shifting

Steel decarbonisation is but one process of change in one domain of society and approaching it without regards to other ongoing processes of change risks to exacerbate existing problems and creating new ones. Primary steel production ties into other issues such as biodiversity, air pollution, soil degradation, poverty, inequality, decoloniality, and feminism, among others. In each of these issues transition-like processes of change might be ongoing and intersect with the decarbonisation of primary steel. Efforts such as the UN agenda to Leave No One Behind in the pursuit of the Sustainable Development Goals aim to capture and coordinate the manifold transitions and transition-like processes towards a common goal. I have earlier defined transformations as the product of this interweaving of transitions in different domains that can give rise to unruly trajectories and surprising outcomes (see *section 3.3*). In light of the SDGs and the academic debate on transitions and transformations, the question becomes to which extent, if any, transformations towards sustainability can be purposefully created and governed. In the process of creating this thesis, I have aimed the idea to ‘identify the next best transition steps with the greatest transformative potential’ (Eckersley, 2021, p. 256). In order to align transitions and transformations then one needs to understand how transition steps such as single policies or the deployment of a new technology relate to transitions in other domains of society, and how these steps can be shaped in order to harmonise the transition with developments in intersecting issues. Since this is a vast task and cannot possibly be achieved by one person alone, I want to limit myself to offering some discussion points here.

At its best, decarbonising iron and steel can contribute to ‘human well-being, social equity and environmental integrity’ (Leach, 2010, p. 5). Phasing out the blast furnace and the metallurgical coal industry with it could lead to significant emission reductions and further improvements in the reduction of coal-related impacts such as air pollution and local extractive harms. In addition, however, these developments posit demanding situations for workers, communities and whole economies invested in metallurgical coal. As shown in *Paper IV* and other contributions (Vogl, 2021; de Leeuw and Vogl, 2022), iron and steel transitions are necessarily political and contested and involve actors with diverse goals.

In order to align primary steel decarbonisation with other pressing social and ecological issues, the problem-shifting potential of alternatives to the blast furnace needs to be scrutinised. Issues pertaining to the realisation of hydrogen steel production, for example, include land and freshwater usage, as well as potential emissions to air. These issues are socio-ecological insofar as they build on existing structural inequalities and tend to affect those in vulnerable or marginalised positions more. The papers included in this thesis address some examples of such intersections of steel decarbonisation and existing structural inequalities. *Paper II* discusses how market-shaping policy based on tenders for government support risks to exacerbate the EU-internal East-West divide. *Paper IV* analyses how coal phase-outs affect different societal groups such as workers and their communities and how transition assistance (Green and Gambhir, 2019) might be a necessary component of a steel decarbonisation policy mix. *Paper IV* further shows that steel transitions play out in an industry already riddled with socio-ecological conflict, in particular due to land issues around iron ore, coal, and alloying ore extraction (Temper, Bene and Martinez-Alier, 2015). In another text, Georgia de Leeuw and I show how state interests in supply-side decarbonisation can stand in conflict with indigenous interests and livelihoods, and we make recommendations for how these conflicts could be developed constructively (de Leeuw and Vogl, 2022). In sum, the realisation of hydrogen steel production might lead to a spatial and temporal shifting of socio-ecological problem if it mitigates one of them (greenhouse gas emissions) but exacerbates others or creates new ones.

Decarbonisation in the service of transformation

Navigating the process of destabilisation and reconfiguration in line with the need to act on other pressing social and ecological issues is a central challenge for civil society and policy. It was furthermore an aspirational goal for the research presented here. Based on my own experience, I have found reflexivity and collaboration to be helpful strategies to deal with the tension that is inherent in trying to bridge problem solving and critical research (Eckersley, 2021). In hindsight, it seems to me that this tension is irreducible in efforts to pursue the idea of critical problem solving, and that it is the constructive engagement with this tension that is the vital component of ‘problem solving in the service of transformation’ (ibid., p. 256).

Civil society plays a crucial role in incumbent-led transitions (Hess, 2020) with mixed state interests (Newell, 2019) as in the case of primary steel here. In such cases, civil society is a central actor to keep technological promises in check and avoid problem-shifting to other ecological or social domains. In doing so, civil society as well as policy actors have to themselves navigate the tension inherent in critical problem solving. Between destabilisation and reconfiguring, engaging in the prior seems to be the less contradictory task, however. Anti-fossil fuel norms (Green, 2018; Blondeel, Colgan and Van de Graaf, 2019) are increasingly widespread and destabilisation avoids some of the potential normative trade-offs that are inherent in reconfiguration (see previous section). Along these lines, *Paper IV* identifies the phasing out of metallurgical coal as a promising political objective that can gather a large and diverse group of supporters.

For most of the duration of this PhD project, the technicity and the low profile of the steel decarbonisation issue seems to have deterred civil society from focussing on the steel sector (Vogl, 2021). However, recent developments are encouraging, and the steel transitions becomes increasingly scrutinised by various civil society actors. It is my hope that the findings of this thesis can inform these efforts and empower actors seeking to decarbonise steel in the service of transformation.

7 Conclusion

Within the five years of this PhD project, decarbonising primary steel production has grown from pipe dream and future worry of the climate community to increasingly contested political issue. Today, steel is attracting growing attention as other sectors have begun to decarbonise and as awareness of steel's climate impact spreads. Confrontations around coal mining projects and blast furnace relinings, hydrogen trade deals and the revival of industrial policy are just some facets of the emerging political process that is beginning to shape the future of iron and steel.

This thesis lays out the core elements of a socio-technical perspective on decarbonising primary steel. It shows that decarbonising steel in line with the Paris Agreement increasingly compels a global phase-out of blast furnaces and metallurgical coal. The necessity of this phase-out is rooted in the materiality of blast furnace ironmaking itself, as well as in the increasing riskiness of carbon capture and storage as a viable strategy to comply with climate targets. Furthermore, rapid technological progress in renewable energy technologies encourages the steel industry to electrify its processes. In contrast to earlier attempts aimed at fixing the steel socio-technical system through CCS, this thesis has argued that a transitions approach is better suited to grasp the implications of – and the ways to bring about – steel decarbonisation.

Informed by such a perspective, the four papers of this thesis together with this thesis summary outline a number of strategies to advance the decarbonisation of primary steel production. *Papers I* and *II* contribute to a better understanding of reconfiguring the steel socio-technical system by analysing the functioning and scale-up of alternative production methods based on renewable hydrogen. *Papers III* and *IV* analyse aspects of the destabilisation of coal-based steel production such as the temporality of blast furnace relinings as well as phase-out strategies such as targeted policies, divestment, litigation, anti-fossil fuel norm building, and protest.

This thesis is part of a larger conversation on societal transformations towards more sustainable and equitable ways of life. As such, it discusses several potential trade-offs between decarbonisation and larger transformations towards sustainability. Among these are the capability of blast furnace CCS to meet climate targets, claims over the indispensability of steel, the over-reliance on technical fixes, and the social and ecological problem-shifting potential of electrifying steel production. These issues deserve careful attention and will demand creative strategies to avoid choking off early efforts of decarbonising primary steel.

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Steel Beyond Coal

Often invisible yet with relations reaching in almost every nook and cranny of my surroundings, steel was everywhere once I started looking. When I looked even more, steel soon ceased being just steel and became a lens for whatever is at the end of its many octopus-like relations. Steel, that is infrastructures and cutlery, cars and bikes, hegemonic masculinity and development model. It is mining conflict as it is barricade, wind turbine as oil rig, Putilov, Kiruna, Linz, and Azovstal. This thesis is about some things that steel needs to stop being, and about what it could become instead.

Valentin has a background in chemical and process engineering from Graz University of Technology and Aalto University. The enthusiasm for steel runs in the family – Valentin's parents run a metalware business.

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