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Transforming the Steel Industry with Green Hydrogen: Challenges and Opportunities in Duisburg

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Abstract

The focus of the thesis is the precise study of the transformation process in the steel sector in the region of Duisburg in the context of the sectors conversion to hydrogen-based direct reduction and its prospects for deep decarbonization. Using the Challenge-Oriented Regional Innovation Systems (CORIS) framework, it analyzes how technological constraints, cost dynamics, governance structures, and social impacts shape the transition. Based on a systematically conducted literature review and interviews with experts, the study reveals critical barriers: the interdependence of infrastructure and industrial investment ("chicken-and-egg"), high operating costs, and regulatory uncertainty. On the other hand, it points out regional opportunities concerning the capabilities of the industries and social partnerships. The results show that the current process in Duisburg represents ambitious reorientation based upon multilevel governance coordination, a business case created politically, and a commitment to a low-carbon future.

Im Mittelpunkt der Arbeit steht die detaillierte Untersuchung des Transformationsprozesses im Stahlsektor der Region Duisburg im Kontext der Umstellung auf wasserstoffbasierte Direktreduktion und deren Perspektiven für eine tiefgreifende Dekarbonisierung. Mithilfe des theoretischen Rahmens „Challenge-Oriented Regional Innovation Systems" (CORIS) wird analysiert, wie technologische Beschränkungen, Kostenschwankungen, Governance-Strukturen und soziale Auswirkungen die Transformation prägen. Basierend auf einer systematischen Literaturrecherche und Experteninterviews deckt die Studie kritische Hindernisse auf: die Wechselwirkung von Infrastruktur und Industrieinvestitionen (Henne-Ei-Problem), hohe Betriebskosten und regulatorische Unsicherheit. Gleichzeitig werden regionale Chancen im Hinblick auf die Kapazitäten der Industrie und Partnerschaften aufgezeigt. Die Ergebnisse belegen, dass der aktuelle Prozess in Duisburg eine ambitionierte Neuorientierung darstellt, die auf einer Mehrebenen-Governance-Koordination, einem politisch erzeugten Business Case und dem Bekenntnis zu einer kohlenstoffarmen Zukunft beruht.

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List of Abbreviations

BF-BOF : Blast Furnace – Basic Oxygen Furnace (Conventional steelmaking route)

BMWK : Bundesministerium für Wirtschaft und Klimaschutz (Federal Ministry for Economic Affairs and Climate Action)

CAPEX : Capital Expenditure

CBAM : Carbon Border Adjustment Mechanism

CCfD : Carbon Contracts for Difference (Plural: CCfDs)

CORIS : Challenge-Oriented Regional Innovation Systems

DBI : Duisburg Business & Innovation

EAF : Electric Arc Furnace

EEG : Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)

ETS : Emissions Trading System (see EU ETS)

EU ETS : European Union Emissions Trading System

FNB : Fernleitungsnetzbetreiber (Transmission System Operators – Gas)

GHG : Greenhouse Gas

GW : Gigawatt

H2 : Hydrogen (Molecular)

H2-DRI : Hydrogen-based Direct Reduction of Iron

H2-DR : Hydrogen-based Direct Reduction

HKM : Hüttenwerke Krupp Mannesmann

IPCEI : Important Project of Common European Interest

MWh : Megawatt-hour

NG-DRI : Natural Gas-based Direct Reduction

NGO : Non-Governmental Organization

NRW : North Rhine-Westphalia (Nordrhein-Westfalen)

OPEX : Operational Expenditure

PEM : Proton Exchange Membrane (Electrolysis technology)

RIS : Regional Innovation Systems

SAF : Submerged Arc Furnace (Electric melting unit)

TKSE : Thyssenkrupp Steel Europe

TWh : Terawatt-hour

ZBT : Zentrum für BrennstoffzellenTechnik (The Center for Fuel Cell Technology)

1 Introduction

The climate change is one of the big topics of the 21st century, therefore decarbonization of energy intensive industries are an enormous part of tackling these problems. Around 9% of the global and 4% of EU CO2 emissions are produced by the steel sector, which makes it one of the most CO2 emitting industries (Kurrer, 2020). The method of steel production with hydrogen direct reduction is in this context considered as a key pathway in the direction to the decarbonization of the steel industry. This technology could replace coal as main resource for the industrial steel production (Gajdzik et al., 2023). Germany is as one of Europe's largest steel producers. The country is under pressure to meet climate targets and therefore managing high energy prices and big needs for industrial transformation (Guevara Opinska et al., 2021). Many energy-intensive industries are located in the state North-Rhine-Westphalia what makes it to an important cluster for this transformation due his high hydrogen demand potential (Bräuninger et al., 2022). Duisburg plays a central role in this situation. The city is reasonable for around 35% of Germany's crude steel output and has Europe's largest integrated steelmaking site. The city is not only a critical spot for the national transition (Schlemme et al., 2019) it is also a region with a long history of structural change (Lim & Limbach, 2023).

With that central role of Duisburg as Germany's largest steel production site, the transition toward climate-neutral steelmaking appears as a complex challenge for the region. Hydrogen-based direct reduction is seen as a key technological pathway, but the transformation encompasses technological, economic, political, and social uncertainties that influence the feasibility and direction of change. This thesis, therefore, adopts the Challenge-Oriented Regional Innovation Systems (CORIS) framework, which identifies the analytical lens used in this thesis to evaluate how regional capabilities, actor constellations, and governance activities shape the transition. In this context, this thesis explores the factors that influence the transition of Duisburg's steel industry toward hydrogen-based production. This leads to the central research question:

"Which technological, economic, and political factors at the regional, national, and EU level influence the transformation of the Duisburg steel industry towards sustainable production with green hydrogen, and what challenges and opportunities arise from this?

This thesis addresses the question by analyzing technological, economic, political, and social factors that shape the transformation process of Duisburgs steel industry. The challenges and opportunities are investigated on a regional, national, and EU level, and the influence of existing structures, spatial embeddedness, and governance activities for the transition to hydrogen-based steel production are considered. The analysis integrates a systematic review of academic and policy literature with semi-structured expert interviews. Target is to capture both, structural conditions as well as actor perspectives relevant for the ongoing transformation.

The thesis is organized as follows. Chapter 2 sets out the theoretical and conceptual framework, focusing on the CORIS approach. Chapter 3 describes the methodological design, data collection and also the analysis. Chapter 4 analyzes the technological, economic, political, and social challenges and opportunities driving the transformation of Duisburgs steel industry. Chapter 5 synthesizes the empirical findings, while Chapter 6 discusses the results in the light of the theoretical framework and assesses Duisburgs trajectory of transformation. Chapter 7 is devoted to the conclusion, recommendations to ensure the transformation, limitations, and ways of future research.

2 Theoretical-conceptual framework

The concept of Regional Innovation Systems (RIS) acts as an approach that has been adopted within the context of studies related to analysis on innovation dynamics. The main reason for developing this concept was to enhance competitiveness within regions depending on innovative collaboration among firms, research organizations, and public sector entities. Conventional RIS has largely been concentrated on technological innovation and economic growth (Tödtling et al., 2022).

Recently, however, the traditional RIS strategy has been increasingly criticized for concentrating too much on economic growth and neglecting challenges like climate change, inequality, and environmental problems (Trippl, 2023). Taking into account these concerns, the Challenge Oriented Regional Innovation System (CORIS) has been introduced. It not only considers these challenges but helps with an easy transition towards more sustainable forms of innovative processes (Tödtling et al., 2022; Isaksen et al., 2022).

2.1 Principles of CORIS

The CORIS model, enhances the traditional RIS paradigm with stronger emphasis on societal challenges and sustainable growth (Trippl, 2023). While RIS concentrates on economic growth and technological advancement, CORIS shifts focus to real-life challenges such as climate protection and sustainable energy or social inclusion. It explicitly asserts that innovation is not only for corporations or technocrats but incorporates new actors like NGOs and civil societies into rigorous development activities related to innovation. It’s clear that instead of relying only on internal factors for regional performances, trends or global factors significantly affect these topics (Tödtling et al., 2022; Trippl, 2023). A major characteristic of CORIS is that it enhances an increase in innovative thinking. Innovation systems traditionally showed considerable preference when it comes to technological innovation. CORIS attaches considerable importance to societal or organizational innovations rather than just focusing on technological ones. It can thus be stated that those innovative systems not only focus on innovation but on processes or societal structures that could potentially benefit regional problems related to or arising because of that (Trippl, 2023).

In addition, CORIS looks at innovation not only with regard to its place of origin but also with regard to application and dissemination. It can therefore be concluded that an innovative system for sustainable development must not only focus on innovative developments but should also emphasize their implementation to achieve an overall societal effect. On the other hand, CORIS believes that not only can innovative activities bring positive outcomes , but there could also be negative consequences (Tödtling et al., 2022; Trippl, 2023). It can therefore be said that CORIS holistic approach to innovation becomes important when regions face major structural transformations, such as in the case of Duisburg's steel industry transformation.

2.2 Reorientation and Transformation

According to Isaksen et al. (2022), the transformation of a regional innovation system can occur either through a reorientation or a transformation. The first strategy focuses on improving existing actors and networks and modifying established innovation system structures to induce this process of transition. According to this strategy, basic innovation system structure continues with only selected amendments introduced into these systems. While the first only requires an evolutionary adaptation, in the second strategy, there is an extensive reorganization of new actor networks with deconstruction of established structures and incorporation of disruptive factors with emphasis on technological and market factors.. In general, while an evolutionary adaptation looks highly possible, far-reaching redesigns are needed for areas where existing structures cannot sustain long-term potential innovative capabilities. The transformation of a regional innovation system does not have to follow one of the two ideal-typical paths exclusively. In practice, a combination of gradual adaptation of existing structures and radical transformation can occur.

2.3 Identifying CORIS

The determination of challenges and resources for regions can then be viewed as an important aspect of CORIS because it incorporates not only an evaluation of societally important factors but also those factors of infrastructure, technical knowledge, and governance which can help transformation efforts. The other important element would therefore relate to innovations and their development which would involve an analysis of how innovations could benefit at the regional level. This involves looking into how new technologies or social innovations could be tested, implemented, and scaled to realize their full regional impact. Important building blocks of the transformation process are unlocking and exnovation, this involves the demolishing of unsustainable structures, and the way in which such transition can be managed for the affected businesses and workers. Orchestration and governance is coordinating actors from industry and research, politics, and civil society, and the political measures and financial incentives which can promote or hinder the transformation process (Trippl, 2023; Trippl et al., 2024). These processes are particularly relevant for the transformation of the steel industry in Duisburg, as they highlight the structural adjustments necessary to enable sustainable production with green hydrogen.

2.4 Application of the CORIS framework to the transformation of the steel industry in Duisburg

The current transformation of the Duisburg steel industry into hydrogen-based production is a good opportunity to apply the CORIS approach. Some of the key factors in this transformation are the understanding of specific technological, economic, and social challenges in Duisburg for the shift toward hydrogen-based steel production and to find out regional resources and location factors that could make the process easier. The central questions concern how the major actors in the innovation process collaborate: business, research institutions, politics, and civil society.

Equally important are the political and institutional contexts: Which government programs and subsidies relate to the transformation and how can these barriers be overcome politically? Furthermore, there is the issue of technological development and application: Which technologies for producing hydrogen existent in Duisburg and how far has the transformation of steel production through hydrogen direct reduction (H2-DRI) been realized? Important infrastructure: Are there already pipelines for transporting hydrogen gas or solutions for storing it? Are there enough capacities for renewable energies for large-scale transformation? Further, it should not only focus on those areas where new infrastructure and installations need to be built but should emphasize which old infrastructure or buildings need to be torn down or upgraded to ensure space for new technological and economic developments without leading to major disruptions in the economy. Furthermore, how can these various parties involved in transformation be managed? Second, not only should positive aspects of transformation but also adverse consequences with regard to employment or urban development not be ignored. It is vital to discuss how Duisburgs steel industry fits into this global transformation: What interregional or global competitive situations exist, and how can Duisburg strengthen its position in this context? Which funding measures and regulations influence the transformation?

Within the CORIS framework, the question ultimately arises whether the transformation will occur through a gradual adaptation of existing structures (Reorientation) or require a radical realignment with new actors and value chains (Transformation). Analyzing these factors enables a comprehensive assessment of the transformation processes in Duisburg and their long-term perspectives.

2.5 Relevance of CORIS

CORIS delivers a new, innovative theoretical framework to understand transformations of the steel industry in the region of Duisburg. Focusing on major societal challenges, CORIS might integrate the role of new actors and different forms of innovation for developing feasible solutions for steel sector decarbonization. For Duisburg, the central question is whether the transformation will be a reorientation, through development of existing structures, or as a fundamental transformation.

3 Methodology

For this study, a qualitative multi-method research design with a systematic literature analysis and expert interviews has been chosen. By using this research design, it will be possible to explore thoroughly the technological, economic, and political factors influencing the shift towards producing steel using hydrogen in Duisburg. A systematic literature review was performed to carve out the theoretical basis for carrying out this study. The search was done using academic databases like Scopus, Web of Science, Google Scholar, and Science Direct. Apart from scholarly work, this study incorporates policy papers, strategy reports, trade journals, and studies produced by related think tanks because these offer empirical insights into trends related to transformation processes and therefore cannot be ignored for purposes of carrying out this study. Semi-structured expert interviews complement literature analysis with more qualitative insights into actor perceptions and processes. Further details on research design and method for gathering and analyzing interview data can be found in the succeeding subchapter. To improve linguistic clarity and readability, a digital writing assistant (ChatGPT) was used for text refinement and translating citations from the Interviews. For literature management and reference organization, Zoter, a literature management software, was used.

3.1 Expert interviews

The thesis incorporates a comprehensive analysis of literature studies with semi-structured expert interviews with the objective of adding a regional context with expert opinions on transitioning steel production using hydrogen. The expert interviews will add value to the paper-based analysis with regionally contextual insights related to perceptions on challenges and opportunities identified by important regional players related to the research question posed. The research question will gain insights related to technological, economic, political, and socio-cultural nuances with emphasis on the regional context of Duisburg.

3.1.1 Case and expert selection

The reason for choosing Duisburg was that it represents an industry region with strong path dependencies which now attempts to shift their steel production to hydrogen-based production systems. It therefore offers an insightful case study for how different agents within the region experience and cope with the transformation related to the transition to hydrogen steel production systems. Expert sampling was applied to achieve a diverse set of positions related to transformation processes within the region. The primary criteria used for inclusion were expertise related to decarbonization processes of steel production in Duisburg with either expert or practice knowledge. Experts took part from different sectors to ensure that diverse elements of the innovation system were described: industry and logistics organizations, city government and economic development bodies, research institutions/think tanks, employee representation bodies. A total of eight expert interviews were carried out. Experts were approached via email invitations. Efforts were taken to secure expert contributions among state/governmental/ EU governmental bodies. However, these actors generally declined to participate in interviews, which slightly limits the direct representation of higher-level policy perspectives in the empirical material.

3.1.2 Data collection

The interviews followed a semi-structured, guideline-based format. A master interview guide was developed on the basis of the literature review and the conceptual framework and was, if needed, then adapted to the specific background of each interviewee. The guide was structured around seven thematic blocks, each comprising three to four open questions that emerged from the literature review, including aspects that remained underexplored in existing work: Introduction and contextualisation, Location Duisburg, Technological challenges, Economic risks, Social impacts, Governance, Outlook and open points These thematic blocks were designed to cover the four core dimensions of the study (technological, economic, political/governance and social) as well as the regional dimension, while also encouraging respondents to reflect on interlinkages and network relations. All interviews were conducted online, in German. The interviews took place between April and September 2025. The average duration was around 50 minutes. With the consent of the participants, all interviews were audio-recorded. The recordings were fully transcribed using the software Turboscribe and subsequently checked and manually corrected to ensure accuracy.

3.1.3 Data analysis

The interview data were analyzed using a thematic analysis with a structured codebook, drawing on the approach outlined by Braun and Clarke (2006). The analysis combined deductive and inductive elements. Deductively, initial themes were derived from the core dimensions of the research design (technological, economic, political/governance, social). Additional attention was paid to the spatial dimension of Duisburg as an industrial region, as well as to introductory and closing sections of the interviews that often contained broader reflections. Based on these starting points, a codebook was developed in which themes were structured according to the seven blocks of the interview guide and individual codes were defined on the basis of the specific questions within each block. Each code also represents a meaning unit. During the coding process, relevant statements were identified in the transcripts and assigned to one or more codes. These coded segments formed the basis for the subsequent thematic interpretation. Coding was carried out using Microsoft Excel. The final thematic structure used in the empirical chapters was built by distilling the core statements of each meaning unit and clustering them into overarching themes. For each theme, a synthesised core statement was developed, which then served as the basis for the results presented in the chapters. The detailed codebook and an overview of the coded material are provided in the annex.

3.1.4 Ethical considerations, reflexivity and limitations

All interviewees were made aware of the purpose of research, that taking part was optional, and how planned data would be used. Consent to participate and record interviews was granted before every discussion took place. For purposes of ensuring respondent anonymity and protecting their private interests, anonymization was done while analyzing these interviews for this study. Additionally, individual contributions to research can only be referenced using Actor-ID selections instead of other more specific details of individual identity. Onesided biases could occur given that some interviewees work directly for firms like the steel firm that participate directly or drive this transformation process strongly. Biased perspectives can therefore relate to particular interests or shortcomings associated with this transformation process when viewed differently or negatively or otherwise favorably or more favorably instead. These can be mitigated to some extent by considering multiple actor categories and systematically comparing interview outcomes with insights derived from literature analysis. The qualitative research design and ambition of a master’s thesis set specific boundaries. The number of expert interviews could not exceed eight. However, sampling primarily concentrates on those actors closely related to the Duisburg case study. Although these interviews cover major actor categories related to the case study at hand, they cannot yield a representative overview of available insights potentially derived from different perspectives. In addition, the strong focus on Thyssenkrupp Steel reflects the company's dominant role in the regional steel industry but also narrows the empirical lens.

4 Literature Review

This chapter establishes the theoretical foundation of the thesis by systematically synthesizing the current state of research on industrial decarbonization, as well as the technological, economic, political and social dimensions of the transition within the context of Duisburg

4.1 Regional Pathways for the Sustainable Transformation of Industry

The challenge of carbon-intensive industry transformation comes with numerous factors for which their success depends. According to Sovacool et al. (2024), the success of low-carbon transitions rests largely on achieving alignment at three different levels: organizational, where established corporations can find opportunities and reduce risks. Individual, where management builds expertise and seizes opportunity. And supply chain, where suppliers can adapt and enhance their power. Industry transformation and decarbonization can therefore be viewed as processes that relate to multiple scales because these processes develop with complexity over time. There comes a need for strategic agility because firms need to simultaneously identify threats while taking advantages of new opportunities that arise with time while finding ways to adapt their processes either with incremental or with transformative paths leading to an increase in competitiveness and sustainability.

Yet, industry transformation does not occur in isolation. It unfolds within swithin broader Regional Innovation Systems, which consist of three interrelated sub-systems: knowledge infrastructure systems, industrial systems, and governance systems. Regarding green restructuring, knowledge infrastructure systems function as drivers. However, these systems commonly impede themselves because they refuse to change their established knowledge base. Overcoming this rigid institutional thinking marks an important step towards green restructuring efforts within RIS (Fløysand et al., 2022). On this basis, using Njøs et al. (2020) analysis of research carried out within Evolutionary Economic

Geography studies shows how path creation conceptually depends on multiple related factors at once. According to their description, factors like regional capabilities, multiscalar dynamics, actors and agency as well as policy interventions set path creation into action.

Extending these findings, Sovacool et al. (2024) examine that the transformation towards a net-zero industry not only faces challenges related to sociotechnical transformation but also incorporates spatial elements. These findings resonate with Path Creation Theory under Evolutionary Economic Geography because spatial factors significantly impact RISs while influencing not only places where important actors need to concentrate but also enabling areas for cooperation and networks creation. Spatial factors define how industries can spatially cluster together, how innovations spatially diffuse from different regions, or how firms can tap into localized capabilities when pushing for sustainable transformation.

Since innovation unfolds on path-dependent trajectories, there is a need for comprehending sociotechnical systems and innovation systems if mission-oriented policy intervention is to occur effectively. On this basis, institutional evolution occurs on account of interactions and collectivities. More importantly, industry bodies within RISs can induce transformative outlooks pertaining to sustainability transitions despite being associated with inert responses to transformative thinking (cf. Bugge et al., 2022). The degree to which these structural changes and actor interactions amount to substantial transformation depends on the level of green restructuring. There can be different degrees of restructuring ranging from incremental to transformative change. An incremental restructuring policy entails isolated actions with existing markets and using existing policy tools. On the other hand, profound restructuring entails multi-level policy planning with new resource allocation and new market creation. The level of restructuring denotes the extent to which industries and economies can transform themselves into sustainable low-carbon economies (Sovacool et al., 2024). On the basis of the significance of industrial and public policy tools for influencing green transformation, there need to be different policy tools to ensure successful transformation. Industry policies spur research and development and restructuring of the economy, while public policies provide incentives and tools for sustainable transformation. For successful transformation, there need to be balance between both (Nilsson et al., 2021). Apart from restructuring depth, policy frameworks provide important impacts to new industrial paths with overall directional influences on development orientations. While some emphasize incremental innovative processes with extensive, decentralized activities, others focus on major projects with large transformational influences (Njøs et al., 2020). Expanding on the role of policy frameworks in shaping industrial pathways, green restructuring must not only drive path creation but also enable long-term systemic change. To elaborate on the importance of policy frameworks for influencing industrial trajectories, green restructuring should not only focus on path creation but should also focus on supporting system transformation over time. These system transformations need restructuring of systems rather than modifying existing systems. Therefore, it requires long-term policy formulation because it implies transformation of vital societal systems rather than modifying existing ones (Voß et al., 2009). Effective directionality in green restructuring cannot only be achieved with top-down government action. Instead, it calls for the promotion of bottom-up collaboration among private and public bodies. Although overarching top-down structures such as climate laws contain vital policy guidance, industry-wide road-maps and installations can significantly steer the process (Nilsson et al., 2021). In establishing low-carbon innovations, it is important for the state to create incentives and lead markets with regard to low-carbon technologies to overcome risks associated with project financing and encourage low-carbon innovations. Although incentives for firms can assist with decarbonization related to industry, market mechanisms alone cannot assist with scaling and speed related to the particular challenge of transitioning to low-carbon technologies industry-wide. There is determination among industries to adopt low-carbon technologies. However, these efforts can relate to continued competitiveness at the international level. Therefore, effective decarbonization requires policies that balance technological feasibility with economic viability (Hildingsson et al., 2019). Despite increasing regulatory reforms, climate policies have become quite popular, but businesses continue to value being competitive. They refrain from being a part of or investing in low-carbon transition unless prompted to act. The sectors regimes continue to depend almost entirely on fossil fuels, with low-carbon transitioning failing largely on long-term perspectives and exploring the relevant technological know-how (cf. Geels, 2022) Among energy-producing sectors, areas such as the manufacture of steel, being energy-intensive, experience technical difficulties to produce basic materials without CO2 emissions. Despite the varying specifics of each technological process, each emission-free technology is essentially of a systemic type that makes producing them much costlier without offering immediate advantages or added value (Åhman et al., 2017). The emphasis on local value creation is vital for justifying transition measures because it ensures stakeholder engagement and economic resilience. The knowledge and experience derived from local green initiatives can offer a starting point for industry-wide sustainability transitions because it demonstrates possibilities for systemic transformation (Bugge et al., 2022). Market nurturing is an important element necessary for green restructuring because it promotes green product development that struggles to compete with existing alternatives. Market failures related to demand uncertainty, lack of standards, or cost uncertainty require government intervention measures such as safeguarding areas and taxation incentives. Demand-side measures offer important momentum for green technology promotion. Demand articulation efforts, especially public sector demand expression via public procurement efforts, offer important momentum for green technologies promotion. More extensive demand-side policy measures can offer vital momentum for green restructuring promotion too. On top of that, resource reallocation offers important momentum because industrial development infrastructure within specialized areas demonstrates path-dependent evolution. Since corporations technological abilities and workers expertise offer path-dependent evolution because of historical development patterns and trends, hence necessary measures relate to adapting resources to fit green restructuring criteria (Jakobsen et al., 2022). To overcome these competitive disadvantages faced by green technologies, there need to be strategic policy measures taken to overcome fossil fuel subsidies, regulations, and production costs. To create markets on an equal level, there need to be positive incentives (e.g., subsidies or quota mandates) and negative incentives (e.g. taxes or regulations) introduced into public policy for these technologies to succeed. Policies targeting areas of demand like carbon footprints and government purchasing power can prove vital for market creation for green materials. Lead markets for products in the green sector can prove helpful for speeding up low-carbon production at an internationally accelerated scale (Nilsson et al., 2021). Lock-ins caused by existing specializations mean that it is difficult to mobilize support among actors for measures that undervalue previous investment and challenge existing interests. The challenge can be addressed by finding ways to green established industries using new technologies like hydrogen technologies that reduce adverse effects on the environment. For RIS to achieve success when it comes to greening industrial transformation successfully, they need to address weaknesses related to capability problems, failure in networks, and shortcomings within institutions that can limit innovation. Policies can significantly help to develop and assist regional actors while ensuring that appropriate regulatory structures exist. These measures face even more challenges when implementing green transitions and need measures that target integrating new technologies to make established industries more sustainable and innovating into new green industries using the knowledge of regions with different capacities (Grillitsch & Hansen, 2019). It is necessary for a just transition to take into consideration the sensitivity of those areas that depend heavily on CO_2-producing sectors. These sector changes, along with the imposition of carbon taxes, creating a dilemma for such areas to adapt to these changes. Even without considering the effects such as loss of employment and depletion of assets, the loss of human capital to other areas threatens the economy of these areas. If this happens, the public's acceptance for climate policies can be undermined. It is thus necessary for these areas to be encouraged to be a part of this transition, as stated by Rodríguez-Pose & Bartalucci (2024).

4.2 Technical Challenges

Hydrogen-based direct reduction, or H2-DRI, is generally regarded as a prominent technology for the transformation of the primary steel-processing industry. Despite this, implementing H2-DRI is associated with a range of challenges, from, for example, technological necessities to system-related dependencies. This chapter identifies the key technical challenges for H2-DRI, especially for the case of Duisburg.

4.2.1 Technological Foundation

Iron ore reduction through hydrogen is a significant technological method for a climate-friendly transformation of the energy-intense steelmaking industry. Compared to the conventional blast furnace procedure, hydrogen-based direct reduction is, from both ecologically and process technical points of view, a far better method. CO2 emissions can be avoided by using hydrogen as a reducing gas, and this makes easier controlling of processes connected to chemical reactions. Moreover, because of the optimized balance of diffusion processes and reaction kinetics, new properties of materials appear in reduced masses, and this can influence positively the quality of produced steel, especially because of its positive effect on purity of produced materials (Binti Che Ibrahim et al., 2015). Technologically, this method is mainly realized through the introduction of shaft furnaces. These furnaces can work continuously, being of vertical type. Iron ore is dropped through gravity from top to bottom of the furnace, and simultaneously, a rising gas, such as natural gas or hydrogen, passes through a reactor. This type of counter current process makes possible heat and mass transfer. Moreover, because of its modular structure, these furnaces can be made flexible, adapted to different regional conditions, such as local energy availability, space, or necessities of logistics (Jiang et al., 2013) Therefore, this method is highly applicable from a technical and space-integrated aspect, of immense importance for already developed areas for industrial activities, such as Ruhr or, for this case, a specific place of Duisburg.

Presently, this potential is being realized at a massive industrial development effort at Duisburg. The tkH2SteelR Project is the name of this innovative technology being adopted by Thyssenkrupp Steel Europe as a transformation effort for its facility. It can be noted from the company's strategy that this innovative technology replaces conventional blast furnaces fueled by coal for the production of Steel. This is a plant that uses a shaft furnace fueled by natural gas or hydrogen. It makes the entire process coal-free. It operates at a temperature of about 1,000 degrees Celsius, where the removal of oxygen from the iron ore reduces it to direct reduced iron or DRI. Although hot, this product is moved to the adjoining units called electric melters for processing to produce liquid pig iron. This close coupling significantly increases process efficiency by ensuring optimal energy use within the existing infrastructure (thyssenkrupp Steel Europe AG, n.d.).

4.2.2 Hydrogen Demand

Although hydrogen-based operation of shaft furnaces provides much potential for emission reduction, hydrogen operation of these furnaces is much more challenging. The reduction reactions of iron ores and hydrogen are highly endothermic. That is, these reactions require much heat. Thus, a considerable cooling effect is experienced in the furnace, and the reaction rate is low. However, much high hydrogen quantity at a high temperature is required to make up for such shortcomings. This is much demanding for energy provision and system operation (Jiang et al., 2013). Despite this, hydrogen possesses a number of advantages over other reduction agents, such as high diffusion ability, high reactivity at high temperatures, and better penetration ability for porous materials. The effect of hydrogen is also accompanied by reduced CO2 emissions, since the by-product of the reaction is merely water vapor (Liu et al., 2021).

Despite these advantages, a hydrogen-based DR process consumes a considerable amount of hydrogen for every ton of direct reduced iron produced. Although this demand can be estimated differently depending on various process configurations, a considerable hydrogen demand is estimated through models. These differences can be mainly attributed to the system boundaries and distinctions according to gas losses. The hydrogen for a H2-DR process is applied for two primary purposes. It is mainly utilized as a reducing agent for the formation of metallic iron from iron oxides, and hydrogen is also applied to provide sufficient thermal energy for the process (Rechberger et al., 2020). In order to provide a better estimation of this demand, it is helpful to have a look at a known process model. This task was accomplished by Vogl et al. (2018). The authors provided a mechanistic process model of a fully electrified primary steel production plant, combining hydrogen-based direct reduction with hydrogen-based direct reduced iron through hydrogen-based direct reduction and a hydrogen-based electric arc furnace (EAF). It calculates the energy and mass demand through numerous process parameters, such as metallization, scrap rate for the EAF, or electrolyzer efficiency. For the "Base Case", the calculation assumes a unique power demand of 3.48 MWh/ton of liquid steel, along with a hydrogen demand of 51 kg of hydrogen per ton of liquid steel. These assumptions include a scrap rate of 0% for the EAF and 72% relative to the lower heating value for electrolyzer efficiency. Here, two-thirds of the power demand is allocated to hydrogen electrolysis. It is apparent that this process model demonstrates the adaption difficulties of a complete transition of existing steel production processes to hydrogen-based processes (Vogl et al., 2018).

These model assumptions give a rough estimate of the hydrogen and energy demand corresponding to a full transition. The detail improvement of this model by Radloff et al. (2023) shows that such difficulties can be realized for the concrete case of the Duisburg location. Vogl et al. (2018) had published a generic process model for H2-DR. Radloff et al. (2023) strengthen this effort to a considerable extent, addressing the regional setting of the region of North Rhine-Westphalia. They embed the roadmap of Thyssenkrupp for the Duisburg site, into a detailed, location-specific process model. The authors combine technological information with a regional material flow analysis, enabling the assessment of regional and cross-sectoral effects of a decarbonization of the steel industry for different scenario variants. Technological differences, among others, include a development of gas cycles combined with large-scale melting units (EAF). These can be directly connected to a DR furnace to directly process the hot DRI. This way, a hot charge is provided to this furnace without the existing cooling and reheating, as arranged for EAF processes. This approach results in a highly efficient process, saving considerable energy. The result of this concrete research shows that, for example, a complete transition to H2-DR until 2045 requires a maximum of 52.5 TWh demand of renewables, roughly a quarter of Germany's total actual renewable power capacity in 2023, unless supplemented by natural gas, as published by Radloff et al. (2023).

4.2.3 Storage and Transport Infrastructure

Besides the high energy demand and process intensification of hydrogen-based steelmaking, hydrogen storage is a persistent technical and infrastructural stumbling block. According to Tang et al. in 2020, hydrogen storage, together with hydrogen production, is among the most prominent technical challenges that need to be resolved for existing hydrogen-based direct reduction processes. Although high-pressure gas storage or cryogenic liquefaction is among the most frequently considered methods, this is particularly challenged by a range of scalability, safety, and energy efficiency issues.

These issues have also recently been critically reflected by Rampai et al. (2024), who stress that existing hydrogen storage methods, regardless of the tank system or underground storage, lack the technology maturity required for practical applications. In particular, the combination of hydrogen's low volumetric energy density and the necessity for high-pressure conditions leads to additional energy consumption and cost-intensive infrastructure investments. When analyzed from a system perspective, a key message from Cloete et al. (2021) is that hydrogen storage, or for that matter, any energy chain component, cannot be considered independently. The inability of hydrogen storage to cope with a high rate of variability of energy demand and supply is especially a factor that can cause operational bottlenecking if the supply of renewables, such as solar or wind power, varies from time to time. Given this fact about hydrogen storage, the steady supply necessary for a steel plant is clearly difficult to provide through local storage for a gigawatt-sized demand. In this case, local storage's task is essentially transferred to the grid.

Accordingly, a factor that is frequently underestimated, but nevertheless of immense technical importance for the transition to a hydrogen-based route, is the development of a corresponding hydrogen transport infrastructure. Ganter et al. (2024) illustrate, using a scenario-based optimization, that for a successful transformation, a geographically extended and flexible hydrogen pipeline network is a vital precondition. In this respect, a European hydrogen pipeline network that connects locations of high hydrogen demand to areas where high quality wind energy is available may be a key factor for regional long-term security of supply. Another aspect of the technical transition is the spatial decoupling of hydrogen production and demand.

Figure 1 - Hydrogen core network (Source: FNB Gas, n.d.)

The technical potential for the production of green hydrogen, especially via electrolysis driven by excess renewable power, is mainly found in northern Germany, as was confirmed by a countrywide study of Germany performed by Emonts et al. (2019). This creates a bad spatial distribution, especially relative to long transport and hydrogen storage. Additionally, geological sites favoring underground hydrogen storage, such as salt caverns, are hardly regionally balanced, making regional hydrogen storage capacity unlikely in most areas around centers of industry. Another transport-related aspect is that hydrogen transport is coming with technological as well as institutional hurdles, since, although hydrogen transport is regarded as economically favored, especially when linked to underground storage, high initial investments, long-term perspectives, and institutional frameworks (Emonts et al. 2019). An important factor for a transformation of the Duisburg region is its integration into the national hydrogen backbone network, which was approved in October 2024. This pipeline network, stretching 9,040 kilometers, is designed to connect the centers of industries, import, and hydrogen production. Mainly using existing gas pipelines, the hydrogen network is to be largely operational by 2032, thus providing basic supply to key consumers such as the metal industry. As illustrated in Figure 1, Duisburg is an integral component of this planned core network (FNB Gas, n.d.). The fact that Duisburg is placed along supra-regional transport corridors linking import terminals to industries in the north is a definite advantage. Also, being close to the new pipeline route is a basic requirement for H2-DRI. Besides, the city creates a networking environment through anchor projects such as tkH2Steel and institutions such as ZBT (Center for Fuel Cell Technology). The high concentration of demand ensures that the node is preferred over other locations, even if far from the sources of energy, as stated by (Stadt Duisburg, n.d.). Demand conditions give rise to spatial disconnects that require supra-regional networking. For a hydrogen economy to be successful, there must be infrastructure planning relying on multistakeholder collaboration to cross boundaries of sectors, infrastructures, and governance.

4.2.4 Electricity Demand

Without a doubt, among the most basic challenges linked to hydrogen-based steel production is its dependency on green electricity. Even if the most popular hydrogen-based direct reduction route is viewed as the most advisable for a high CO2 mitigation potential, as identified by Fischedick et al. (2014), this requires a certain transformation of the broader energy system. This is confirmed by Conte et al. (2022), who emphasize that this requires a shift of the energy demand of this sector from coal to the power system. As a result, the steel industry becomes substantially more dependent on the electricity grid, introducing potential systemic risks.

The quantitative aspect of this dependency is enormous. For DR steel-plant operation on a manufacturing scale, gigawatt-sized electrolyzers must be developed. According to a study by Rechberger et al. (2020), to produce one ton of direct reduced iron, a high number of megawatt-hours of power is required. Based on this, a significant proportion of the EU's total power consumption can be estimated. Its magnitude is evident through a concrete example, that being the case of Duisburg. According to the previous section, a projection of up to 52.5 TWh of renewable energy is required for the complete transition of the Duisburg steel ensemble, as estimated by Radloff et al. (2023), a substantial proportion of this capacity corresponding to the national total for Germany.

It is, however, important to note that mere energy supply is not enough. Instead, the system's ability to stabilize the availability of energy from renewables is called for. Notably, a case study by Pimm et al. (2021) among the UK's steel industries makes a compelling case for the fact that the feasibility of this transition route is contingent on balance capacity. Variability of power costs according to peak periods dictates flexibility for processes. Additionally, a hydrogen-producing unit is required to be largely oversized to store hydrogen produced during periods of low power costs to be utilized at peak periods, according to Toktarova et al. (2021). However, the integration of these systems also requires technical challenges to be overcome. SWOT, according to Simoes & Santos, 2024, identifies the shortcomings of existing electrolyzers. For instance, the rate of response for alkaline electrolyzers is quite low, whereas PEM-based systems require enhancements related to materials costs and longevity. These technical maturity issues make the integration of these systems quite difficult, especially since energy systems dominated by intermittent renewables require a smooth system integration (Simoes & Santos, 2024,). The feasibility of hydrogen-based steel manufacturing is dependent on spatial considerations, type of grid carbon emissions, and collaborative development of the required infrastructure (Digiesi et al., 2022).

4.2.5 Path Dependencies

Furthermore, a complete makeover of the industrial plant is required for the transition from the conventional BF-BOF route to hydrogen-based processes. Here, existing plant equipment such as blast furnaces, coking, and sintering plants give way to electrolyzers, shaft furnaces, as well as electric melting furnaces. It is to be noted that, along with a different plant topology, different technical parameters such as different energy balances, including process gases, or greater energy imports through the power grid, require attention. The conventional route had provided a surplus of process gases, a characteristic that is lost for the DR-based route. This loss brings is a higher dependency on the power grid because of this, stressing the importance of novel energy management techniques for maintaining plant stability (Suer et al., 2022). Yet another factor that slows the pace of transition in the steel industry is the long-term operation of existing blast furnace capacity. Conventional blast furnaces, for example, have a technological lifetime of 40 to 50 years, according to a scenario analysis of a technology-specific case done by Arens et al. (2017) for Germany. This implies that even if hydrogen-based methods such as H2-DRI become economically and technically feasible, their adoption, especially on a massive scale, can be contingent on when the existing capacity needs to be replaced, a process that might take place decades after a climate-friendly alternative is developed.

This is reflected in the transition plan of the company Thyssenkrupp in Duisburg, where the company aims to introduce gradually hydrogen-based direct reduction lines side by side with the operation of most of its existing blast furnaces until these reach the end of their lifetime. Economic imperatives, as well as the need to ensure a steady quality of steel production even during the transition period, affect the way this transition is done, as noted by Radloff et al. (2023,). In this regard, the lifetime of existing infrastructures can play a crucial delaying role in the transition towards the retirement of carbon-based technologies. Finally, the shift to a hydrogen-based steelmaking process exceeds the scope of a specific facility. Notably, a growing dependence on externally sourced energy supplies makes the environmental sustainability of the direct reduction process essentially linked to the carbon footprint of the energy system. In other words, to be fully sustainable, a systemical shift that integrates technological modifications of the process, combined with a massive development of green energy and hydrogen networks, is required (Rechberger et al., 2020).

4.3 Economic Challenges

This chapter analyzes the economic viability of the transition, focusing on the green cost gap and risks related to energy prices and global competition.

4.3.1 High Costs

One of the main drawbacks of H2-DR is that its cost is substantially higher than conventional blast furnace processes. This includes high CAPEX investments for new plant construction, as well as high OPEX costs because of high prices of electricity, hydrogen, and high-quality ores. These factors generate high risk for the economy, and thus, assessments stress that without targeted policy support, such as climate contracts can make such processes economically viable (Agora Industrie et al., 2023). The above-mentioned detailed study of Radloff et al. (2023) for the location of Duisburg shows that the cost of steel production for a complete H2-DR system will be about €565 for each ton of crude steel produced. This is 45–52% above the average price of conventionally produced steel sold within the EU, as of 2019. The main reasons for such a high cost of steel production through hydrogen route include raw material costs, contributing a share of around 40%, and energy costs, contributing a share of around 35%, mainly because of the enormous hydrogen electrolysis-related power demand. Even if hydrogen-based steel is produced considering optimal hypotheses of a low price of only €20/MWh for electricity, its economic competitiveness is lacking, according to Radloff et al. (2023). Literature verifies that although H2-DR is a promising method for decarbonization, economically, H2-DR is challenged significantly during the initial stages. According to Fischedick et al. (2014), for H2-DR to be economically feasible, its main dependency is on low-cost renewables. Moreover, high CAPEX investments for infrastructure development result in high risks, especially due to uncertainties about the price of electricity and CO2. It is predicted that H2-DR can be economically successful only by 2030-2040. In addition to the costs of production, the transition faces numerous challenges from the infrastructural and resource side. Substituting blast furnaces with H2-DRI technology requires additional inputs, especially power and water. Adding electrolysis requires that the energy production side, dominated by power, becomes a serious backward linkage of the industry and shifting dependencies toward the national power grid. Although this transition provides long-run security, the short-run cost of this security is still a serious challenge (Conte et al., 2022). Additionally, the site-specific design that is planned for Duisburg, a hydrogen-based direct reduction plant integrated with electric melters, is filled with investment uncertainties. Since this design is not replicated elsewhere, there is a lack of reliable costs for its installation and operation, making long-term investment decisions even more difficult (Radloff et al., 2023). Based on site-specific uncertainties, other systemic challenges affect hydrogen transition feasibility. According to Simões and Santos (2024), the risks of costs and investments stand as key hurdles for hydrogen transition. Even though green hydrogen is much costlier than existing energy sources, its costs range from 3 to 9 USD/kg. These costs depend on the price of electricity and the availability of renewables. Furthermore, the relative immaturity of the technology pertaining to electrolyzers is such that it adds to this uncertainty. Both proton exchange membrane and alkaline water electrolysis, for example, have challenges such as low current density, short lifetime, and high capital costs because of the high cost of materials. Moreover, the lack of development of the transport network and a lack of standardization of policies, combined, form a high-risk environment (Simões & Santos, 2024). Adding to these system-related problems, Cloete et al. (2021) emphasize economic hurdles related to the production of renewable hydrogen. The key problem here is that the capacity factor of electrolyzers is low in areas where variable renewable energy is available, thus increasing the variable costs of hydrogen due to inefficient utilization of capital-intensive equipment. Moreover, hydrogen can be produced where renewables are available, and hydrogen can be consumed where the availability of hydrogen is required, thus creating system-related tradeoffs. Furthermore, hydrogen's low energy density increases the costs of its storage and transport. Although underground salt caverns provide a cheap form of hydrogen storage, their availability is geographically limited. It is, therefore, difficult for green hydrogen to be cost-effective relative to fossil fuels, a fact that makes its mass adoption difficult without coordinated effort across the system (Cloete et al., 2021). Tied to both production and transport, a key expense-related aspect highlighted by Emonts et al. (2019) is that of storage. Huge storage facilities, especially underground salt caverns, play a vital role in offsetting renewables but come at a high CAPEX. Despite economies of scale, this initial expense is a serious bottleneck. Notably, different gases have different costs and efficiencies for storage techniques. Although portable solutions are appropriate for decentralized, remote areas, salt caverns prove to be cheaper and efficient for larger, centralized sites, as stated by Emonts et al. (2019). Furthermore, referring to the above, Toktarova et al. (2021) elaborate on system integration tradeoffs. Even if electrolyzers can be managed flexibly according to the price of electricity, this reduces the costs of operation but leads to a high degree of over-dimensioning. Notably, system optimization is conditioned by the local renewables dominance, such that regions dominated by winds call for long-duration storage, whereas solar-dominance is driven by cycles.

One such detailed cost consideration for hydrogen-based direct reduction processes is the quality of iron ore, namely that of pellets. Directly reduced iron, requires DRI-quality pellets, the quality of which is far more stringent than that of blast furnace quality ores. Based on Agora Industrie’s analysis, this quality consideration significantly raises the cost of raw materials for the case of hydrogen-based direct reduction processes, thus making a direct impact on the cost of climate-friendly steel processes (Agora Industrie et al., 2023). Doucet et al. (2024) emphasize a key paradox, that is, although the industry is a high-priority case for hydrogen because of its efficiency, this is also the most difficult case to achieve economically. Also, unlike the transport sector, for example, the industry, although currently being facilitated through mechanisms such as emission quota trading, is expected to be the last to achieve market competitiveness relative to fossil baselines such as natural gas.

At the company entity of Thyssenkrupp Steel Europe, a massive transformation to H2-DR is being undertaken, entailing considerable investments. At the regional authority, various actors take part, such as companies, public funding bodies, energy, and infrastructure actors (Radloff et al. 2023).

4.3.1.1 Hydrogen Costs

Hydrogen produced through electrolysis using green power, is the main energy carrier for this novel method of producing steel, although its price is extremely high at this stage. The highest expense is related to the cost of power. It is estimated that power costs make up to 75-80% of the electrolytic production cost of hydrogen (Aslam et al., 2023). Bhandari & Shah (2021) stress that obtaining required cost reductions is contingent on the development of electrolyzers manufacturing capacity to achieve economies of scale and, most importantly, advances in storage solutions for enabling a complementary role of intermittent renewables. Emonts et al. (2019) claim that hydrogen storage costs cannot be see independently, Any attempt to make such costs viable calls for integrated system models that embrace these system relationships.

However, the economic competitiveness of hydrogen is still constrained by high investment costs for electrolysis infrastructure and the challenges of efficiently storing surplus renewable energy (Bhandari & Shah, 2021). Although todays costs of green hydrogen of €4-6/kg make a non-competitive price profile compared to fossil fuels. Although projections forecast a decrease to about €2/kg for 2030/2040 because of lower costs for renewables, this can become a reality with a massive expansion of renewables or import-dependent basis for Germany. Transportation costs become less relevant, the key price, however, is the price of electricity, which should be below low to make green steel economically viable (Aslam et al. 2023). 100% renewable hydrogen energy system, although possible, is still economically limited. Market conditions actually favor less expensive fossil-based processes such as coal gasification. Much greater reductions in the costs of electrolyzers and renewables, as well as investments in storage and transport, are necessary to make this economically viable. Bolz et al. (2024) necessarily emphasize this by making a case for total cost of ownership. They claim that such costs serve as a hindrance to the introduction of the market. Even if the technical feasibility is possible and even if there is government backing. Without comprehensive financing mechanisms, the combined weight of capital and operational expenses severely limits private actors willingness to invest.

The spatial decoupling of renewables-based power generation in northern Germany from local industries makes a high transport and storage capacity necessary, as explained by Emonts et al. (2019). These costs affect the Duisburg case negatively. The H2-DR transformation of Thyssenkrupp Steel Europe is largely dependent on cheap green hydrogen.

4.3.2 Market and Policy Dependencies

One of the key areas of uncertainty is the price dynamics of power and hydrogen. H_2-DRI high dependency on renewable power for electrolysis and metal melting makes price dynamics a challenge. Agora Industrie brings to attention that price volatility affects the costs of operation and thus makes investments even more difficult, and this requires price stabilization through policies (Agora Industrie et al., 2023). Pimm et al. (2021) describe high uncertainties in the market, illustrating that H2-DRI economic feasibility is heavily dependent on CO2 pricing and electricity market conditions. Even without high CO2 prices, H2-DR is less desirable than existing methods. Although cost parity can be realized about 2030, this is subject to upcoming events related to emissions trading and carbon border adjustments.

Although costs of CO2 abatement have improved, they remain above the current carbon market price, even assuming benign electricity price forecasts. It is for this reason that the importance of economic feasibility, making use of specialized tools such as Carbon Contracts for Difference (CCfDs) is stated high (Radloff et al. 2023). The efficacy of the economy is largely dependent on the efficiency and costs of electrolyzers, as these components consume most of the power. Additionally, besides the costs, the flexibility offered by incorporating hydrogen production into the energy system. Even though this creates opportunities for generating income, there is a high barrier to entry for such infrastructure (Bhaskar et al., 2020). According to Muslemani et al. (2021), the lack of a mature market is a key barrier. Market competitiveness is undermined because of the absence of a standard "green" definition, uncertainties of carbon accounting, as well as greater costs of production compared to regular steel. The initial adoption rate is predicted to be for niche applications. In order to avert the "greening" of steel from being priced out of the world market, the authors strongly recommend active policies, such as green public procurement or "Carbon Border Adjustments". An important aspect is that of the growing global market for green iron itself. According to a study by Bilici et al. (2024), a unique cost advantage exists for areas where lower-cost renewables can be found. Importing green iron from these areas could be cheaper than a fully integrated process.

The case of Duisburg is a good example of the discussed relationships. Being a central location for the production of steel, the ability to sustain itself is contingent on EU and national policies such as ETS, CBAM, and subsidies.

4.3.3 Long-Term Perspective

Johansson & Kriström (2020) emphasize, that the transformation must be independent of voluntary price premiums. Given that the public willingness to pay is limited to a niche, voluntary price premiums merely aren’t enough for a transformation. They, therefore, conclude that a transformation is possible, not because of market-related premiums, but because of regulatory frameworks that include costs for the environment. Pimm et al. (2021) emphasize that H2-DR infrastructure must be supported through long-term investments of 10 to 20 years. Nevertheless, this contradicts the existing regulatory uncertainties linked to the regulatory frameworks for the electricity market and the price of carbon. They thus that the whole transition is fundamentally subject to policies. Mostafa et al. (2024) illustrate that green hydrogen is currently much more expensive than natural gas procured through the grid. Without policies such as a carbon price or subsidy, there is little likelihood of being economically competitive. On this basis, they argue that for massive decarbonization to be economically viable, a system of support is required. Rootzén and Johnsson (2016), illustrate a key inefficiency: although a decarbonization of the energy system significantly increases costs for the production of steel, its effect on consumer products is minimal. Although this verifies that green steel can be integrated into the value chain, the challenge of cost pass-through, without uniform pricing mechanisms or leakage protections, green steel remains non-competitive against fossil alternatives. Khanra et al. (2024) illustrate that although H2-DRI raises the demand for electricity, the adoption of demand-side flexibility can effectively decrease costs. By decoupling the hydrogen production process from the prevailing power price through the adoption of hydrogen storage, power generators can take advantage of the resultanting opportunities, especially when faced with a low demand situation. Birat et al. (2021) stress that a lack of a business model is a critical barrier. It is a fact that to this day, questions about who is to pay for the costs of demonstration, the consumer, the government, or the industries, remain unanswered. They mainly depend for now on public funding. According to Jacobasch et al. (2021), H2-DR production costs are higher than conventional methods even by 2050, making CCfDs or CO2 price floors necessary. In this regard, they suggested that a transition to a system that integrates hydrogen on a partial basis is beneficial to optimize investments. It is noted by Moritz et al. (2023) that the transportation of hydrogen that is of high purity through the maritime route for example can be expensive, especially because of its low energy density. It is submitted that because of the dependency of hydrogen costs on local renewable energy, a region-specific plan is required for making them cost-competitive.

In the case of Duisburg, a long-term politico-institutional stability is required for this transition. The regional heritage of this area imposes a sequential transition, for which regional actors harmonization with the national and EU frameworks is crucial to determine the conditions for successful implementation.

4.4 Political challenges and opportunities

This chapter investigates the political dimension as both a barrier and an enabler.

4.4.1 Political framework and control instruments

One of the main governance tools is the European Emissions Trading System (EU ETS), where CO2 costs will be factored into the system to promote a low-carbon economy. According to the “Fit for 55” package, a reduction of emissions to 61% lower than the 2005 levels by 2030 is likely to increase CO2 price. It aims to make low-cost green technologies economically optimal by making non-green methods increasingly non-economic (Agora Industrie et al., 2022). The "Fit for 55" package is analyzed by Vilela et al. (2024) who emphasize that complementary policies such as CBAM and renewables targets have disparate regional effects. This leads the authors to recommend a Just Transition approach to address social justice. Additionally, the authors pick up on the importance of implementing policies at the EU, Member State, and regional levels, as a key issue defining climate policy effectiveness.

Alongside these governance tools, the EU Taxonomy is a crucial instrument for steering investments towards sustainable economic activities, created through the Regulation (EU) 2020/852. The aim of this is to increase transparency in the financial system and combat greenwash by creating a common classification system of environmentally friendly activities (Regulation (EU) 2020/852, 2020). Tettamanzi et al. (2023) note that the EU Taxonomy imposes high compliance costs to companies, thus posing a risk of transferring these costs to consumers and this is contributing to greater socio-economic inequalities. If this is the case, this may cause a delay in the transition process. It is for this reason that Tettamanzi et al. submit that the EU Taxonomy requires a complementary socio-economic agenda.

However, the existing price system for CO2 is still inadequate for fostering investment dynamics. According to Agora Industrie et al. (2022), price volatility and the allocation of free CO2 emission allowances to CO2-intensive industries had contributed to this situation, making green innovations less favored. To this end, a proposal exists to gradually remove these free CO2 emission allowances for industries such as the manufacture of steel from 2026 to achieve a total abolishment by 2035. After Blöcker (2022), actual drivers of carbon leakage include worldwide dynamics such as price dumping and overcapacities that undermine the competitiveness of European steel. In this regard, to mitigate this challenge, the authors urges that adequate industrial policies be adopted to safeguard this objective. These policies include the Carbon Border Adjustment Mechanism, Temporary Free Allowances, and Carbon Contracts for Difference, among others, that can be supplemented by the lead green markets (Blöcker, 2022). To prevent carbon leakage, a CO2 price will be charged on imported products via the Carbon Border Adjustment Mechanism, starting from 2026, to bring them into line with EU prices. The objective is to protect European green steel from so-called grey imports. Nevertheless, because of uncertainties, this system makes the planning of investments difficult (Agora Industrie et al., 2022).

4.4.2 Funding instruments and investment incentives

Special programs have also been initiated by Germany to aid the transformation of its industries. Of these is the real-world lab H2Stahl that was funded by BMWK, enabling the installation of a hydrogen pipeline of 4 km from Air Liquide to the plant at Duisburg. This was accomplished in 2022, representing a pilot plant that linked the facility to the H2 network, thus proving the viability of hydrogen transport to industries (thyssenkrupp Steel, 2022). Vogl et al. (2021) examine the policies for the commercialization of green steel, noting that contracts for difference, particularly CCfDs, play a crucial role. By addressing the difference between CCfDs strike price and the actual European Union Emissions Trading System, or EU ETS, price for a term of 20-30 years, risks and costs of investments can be mitigated. For added efficiency, Vogl et al. recommend to enhance efficiency and viability to combining them with competitive bidding and long-term electricity price guarantees. Also, a two-celled strategy is offered by Sutherland (2020) to encourage green steel. Supply side: CCfDs are regarded as crucial to mitigate the price difference relative to market price, offering a funding guarantee that is independent of dynamic assessments of leakage, such as CBAM or free allocation. Demand side: The proposal is to establish a controlled market through CO2 footprint or product warranties, seeking to increase willingness to pay and decrease reliance on publicly funded subsidies. Notably, high administrative burdens are involved, according to Sutherland. Most significantly, such policies efficacy is contingent on regional equity, failing which, CCfD can create a skewed playing ground, favoring areas that already enjoy lower electricity costs, to name a case.

Both trade associations, as well as trade unions, call for such contracts to avert the transfer of steel-producing capacity to places where climate policies aren't as restrictive. By providing a guarantor for a climate-friendly budget, these contracts can thus ensure the security of local capacity, along with the promotion of the decarb. of industry (Blöcker, 2022). CCfDs provide a form of insurance that pays for the additional cost involved when clean is a costly form of production, thus making the transition towards H2-DRI a bankable option, even though the rules as well as prices are fluxing (Agora Industrie et al., 2023). The H2-DRI requires investments of billion euros, the returns of which are unsure. In this regard, Germany, along with the EU, initiated a number of funding programs such as the Hydrogen IPCEI (Important Project of Common European Interest) a sum of €8 billion, along with the Climate Protection Immediate Program to trigger investments of over €33 billion. Furthermore, there is the national hydrogen backbone and a target of 10 GW of electrolysis capacity for the year 2030 (Blöcker, 2022).

4.4.3 Demand policy and market formation for green steel

Vogl et al. (2021) discuss "market-creation policies," aiming to attract investments via guaranteed demand. Here, the main policies comprise green public procurement, product norms, and emission labels. Although these policies increase transparency, Vogl et al. outline risks of complicated CO2 calculations and uncertain voluntary demand. They, therefore, advise that these policies must be integrated with binding norms to be efficient. In a case study, Ringsgwandl et al. (2022) assess the German regulatory system to pinpoint the most important hurdles for the development of green hydrogen-infrastructure. The main challenge to this development is high electricity costs, mainly because of state charges, contributing about 50% to power costs in 2021. Although policies such as EEG (Renewable Energy Sources Act) provide exemptions for electrolyzes, this is done through a set of constricting terms, such as necessarily limited hourly capacity and sources. Moreover, the regulatory unbundling of this system makes grid companies ownership of electrolyzes impermissible, hindering those that can develop this kind of infrastructure. Jesse et al. (2024) examine the role of government intervention in the hydrogen industries of Germany and the Netherlands, where the levers of binding targets, fiscal aid (IPCEI), and EU directives can be applied. They, however, observe that although policies such as Renewable Energy Directive (RED) II have a positive stimulating effect, the lack of timely implementation causes planning uncertainties. Moreover, there is a concern about being overregulated, as suggested by the advocacy of flexible certification methods.

4.5 Social Challenges

Decarbonizing Duisburg is fundamentally a social transition. The analysis focuses on how firms, unions, and public actors orchestrate social and institutional innovations to manage these shifts.

4.5.1 Transformation of Jobs

The decarbonization of the steel industry by hydrogen-based direct reduction (H2-DRI) is anticipated to affect employment negatively in the medium term. Direct reduction is not less labor-intensive than the blast furnace process, but highly digitized modern direct reduction plants make such processes much more efficient. This is a risk that continues even if the levels of steel produced remain constant. The main cause of this risk is that technological advances result in improved productivity, whereby fewer workers can be required to produce a certain quantity of steel (Schoppengerd, 2024). Researchers, therefore, forecast a substantial overall decrease in employment once the new processes have had time to be fully established. In the baseline scenario of a German model calculation, a reduction of about 25 percent is forecast for the number of employment opportunities directly affected by the changes in the mid-2030s. Massive redundancies can hardly be anticipated in the short term. Also, because of the coexistence of old blast furnaces and modern systems until the early 2030s, even a temporary personnel surplus can be generated. Massive redundancies can be anticipated only after the new technology is operational (Simic, 2022). According to a report by Käckenhoff and Heine (2024), Thyssenkrupp Steel had a drastic restructuring plan to remove about 11.000 workers, or 40% of the company's workforce, by the year 2030. At the same time, the company's production capacity is to be reduced from 11.5 to 9 million tons in the Duisburg plant. Union and works councils have strongly opposed such a plan, threatening bitter resistance. Simic (2022) identifies a demographic advantage, where 25% of the workforce was above 55 years of age as of 2021, and reductions can be socially responsibly managed through attrition and early retirement. Although this is a considerable transition, this affects 89.000 direct and up to 4 million indirect employment opportunities in Germany. The green transformation is also a generator of new employment opportunities, albeit mainly within different industries. It is even stressed by Thyssenkrupp that the realization of a hydrogen economy promises immense job opportunities. In this respect, already for the region of North Rhine-Westphalia, approximately 130.000 new jobs in hydrogen technology could be generated in the long term, according to a report by Thyssenkrupp Steel (thyssenkrupp Steel, 2021). Public acceptance of green hydrogen projects, especially in Germany, is largely driven by areas such as perceived safety, local value added, as well as transparent communication. Issues of trust in developers, local value added, and participation opportunities have emerged as key drivers here (Buchner et al., 2025). According to Simic (2022), a revolution in skills is being generated by hydrogen and digitalization. H2-DRI parks, being analogous to a chemical plant, require a shift in skills towards process, gas, and security technology. Moreover, the high demand for digitalization requires better IT skills, making retraining necessary for classical steel workers. In line with upskilling, the “Qualification Opportunities Act” was extended to provide funding for company-based training of workers who risk being made redundant by technological change. Additionally, to address this, the modernized "Upgrading Training Assistance Act" now encourages high-quality vocational training qualifications for areas that experience structural change. Finally, through the "Skilled Immigration Act", shortages of human capital can be dealt with, and foreign experts can be allowed entry to work in this country (European Commission, 2022). Trade unions also form a crucial aspect of socially responsible rearrangement of the steel industry. The IG Metall and works councils, working within the industry, enjoy strong co-determination rights, mainly because of the Montan Co-Determination Acts, which require balanced representation of power in decision-making at companies that deal in steel products (Simic, 2022). It is essential to note that the social implications of the transition for the steel industry will differ geographically and that this, among other matters, will depend on workers demands and visions, and their representation within trade unions (Vogl et al., 2019). The prominent role of trade unions, especially IG Metall, in mediating a socially balanced transformation is specially highlighted by Blöcker (2022). Based on the Montan co-determination model, employee representatives enjoy equality in decision-making power on the supervisory board, ruling out strategic decisions such as plant closure without the approval of workers. This emphasizes that Blöcker favors a transformation process dominated by collective negotiations and state intervention as opposed to market forces. Note the significance of the steel industry, according to Oliver Wyman & IW Consult, (2024), who cite its massive employment footprint. The directly employed 80.000, along with a value chain of more than5.5 million workers, or 12 percent of the workforce. Additionally, 2 million Small and medium-sized enterprise workers rely on the steel industry, and its failure can mean a breakdown of a whole value chain, as opposed to mere unemployment.

5 Findings

This chapter presents the empirical findings of the study. It draws on the thematic analysis of eight semi-structured expert interviews and links the resulting themes back to the conceptual framework developed in the previous chapters.

5.1 Scope of the analysis and excluded themes

The method of content analysis applied to the interview data is based on the thematic coding of the obtained information into meaning units and themes, as explained in the methodology chapter (see Table 1 for an overview of the meaning units per theme and interview). However, for this final displaying of the findings, not all parts of the original codebook were kept for representation. Firstly, the theme of "*1 Introduction and contextualization*" was left out of the findings. This section of the interviews was essentially a way of putting the talk into context, as well as contextualizing the background of the interviewed individuals. It did not provide any concrete findings that directly contributed to the topic of this research or to the identified four main dimensions. The meaning units assigned to this theme did, therefore, not receive any attention for their interpretation. Secondly, a number of meaning units have had to be left out because of a lack of empirical significance. Specifically, the meaning units identified by codes "*3.3 Technical Risks at Scale*", "*7.2 What must happen by 2030/2050*", and "*7.3 Additional Remarks*" had only a limited number of statements that can be considered relevant to the matter, or even had absolutely none (see table 3). They, therefore, did not provide a basis for a comprehensive identification of themes. Their lack is, nevertheless, a key finding about areas that, at this stage, lack importance to regional discourse, but they also lack a separate findings section for this chapter.

Themes	Interviews								
	I01	I02	I03	I04	I05	I06	I07	I08	Total
1 Introduction & Contextualization	2	1	2	1	1	3	2	2	14
2 Location Duisburg	3	3	7	3	4	3	2	2	27
3 Technological Challenges	5	5	6	2	4	1	6	1	30
4 Economic Risks	8	8	5	4	5	8	5	7	50
5 Social Impact		2	1	3	1	2	1	4	14
6 Governance	3	4	7	6	8	8	5	7	48
7 Outlook & Open Points	2	1	3	3	1	1	5	2	18
Total:	**23**	**24**	**31**	**22**	**24**	**26**	**26**	**25**	**201**

Table 1 - Section by Interview (Source: own graphic)

5.2 Location

The thematic block "Location" comprises 27 out of 201 analyzed Meaning Units (13.4%). Within the overall corpus, the three associated meaning units are clearly weighted: "Location Advantages" 19, "Model Region Potential" 13, and "Actor Constellations" 10. Location advantages take the lead, thanks to a model region and networking (see Table 2). The findings clearly demonstrate that location advantages, duisport/the Rhine, and connections to the hydrogen core network constitute a unique system advantage for import, transport, and utilization of hydrogen. Clusters of offtakers logistics, and pipelines certainly expedite market development and provide security of supply through integration into the North-West European network. This is enabled by a dense networking landscape of actors from the city, the port, TKSE, research, and networks.

5.2.1 Model Region Potential

The model region structure is apparent in the case of Duisburg, where a strong European inland port, high density of industry/research and a hydrogen core network form a unique location factor for hydrogen import, distribution, and handling. The concentration of demand actors forms a first-mover situation creating a positive market dynamic enabling ramp-up.

The system-oriented perception of this case, whereby there is a synergetic unit of industry, logistics, and infrastructure, is adequately articulated by respondent I08.

#Q1: *"Everyone will say: 'Yes!'—a model region for green industries, for hydrogen, for what we already are today: the largest steel site in Europe, including the other plants, HKM and ArcelorMittal, and, so to speak, the infrastructure with the inland port—the* *largest in Europe—Duisburg is basically predestined for this." (I08, Union/Works Council (TKSE), p. 4 l. 35 – p. 5 l. 4, author's translation)*

The importance of technical infrastructure and actor density as key drivers of this profile is reinforced by I04 (Industry, TKSE). This quotation complements I08's strategic vision with the concrete technical implementation:

#Q2: *"First, we will have a connection to the hydrogen core network. We will have a hydrogen pipeline that leads directly onto our plant site. We are in a region with an enormous amount of industry, with the chemical industry not far away, which will also depend on hydrogen. And in this constellation of industry and research institutes located here, I do think this can become a model region." (I04, Industry (TKSE), p. 2 l. 14–19, author's translation)*

5.2.2 Location Advantages

The reasons for Duisburg's strength lie in its large group of off-takers, its port importance for import origination through duisport/Rhine, and connections to the hydrogen basic network, including crossborder pipelines to the Netherlands and Belgium. The coupling of demand, logistics, and basic infrastructure supports faster market development, and crossborder integration is the key to price and security of supply on the Rhine-Ruhr market. Research activities, such as at ZBT, and existing basic infrastructure, Europe's largest steel works, can be seen as an advantage.

The interlocking of demand, logistics, and basic infrastructure is decisive for the region's development, according to industry actors, as Interviewee I06A (DBI) stated:

#Q3: *"We have the offtakers, for example in the steel industry. We also have duisport, the port, which can play that crucial role in providing, or importing, hydrogen. The regions here will be connected to the hydrogen core network, the German hydrogen core network. That means the links here are, of course, very, very good. Yes, absolutely—I am convinced that the Rhine-Ruhr region, and Duisburg in particular, will play a decisive role." (I06A, City Economic Development (DBI), p. 2 l. 4–7, author's translation)*

This primary finding of internal coupling is complemented by spatial proximity to international partners. Interviewee I02 highlights the external logistical embedding within the North-West European port system:

#Q4: *"We have proximity, after all, the Ruhr area is close to the seaports; we are very well connected to Rotterdam or Wilhelmshaven, and also to Antwerp." (I02, City, p. 7 l. 31–33, author's translation).*

5.2.3 Actor Constellations

The institutional setting is such that there is a dense network of actors who coordinate. These actors include the city, TKSE, Duisport, and research institutions. It is this institutional setting that makes the hydrogen and transformation agenda possible.

The cooperation model is effective both vertically, among local actors, and horizontally across borders. Collaboration on logistics is also efficient. Actors can access the rewards of a combined cross-border strategy. I03 (Regional Development) emphasizes the effectiveness of this international cooperation:

#Q5: *"In fact, all the actors work well together. For example, the international seaports cooperate closely, such as Rotterdam and Antwerp-Bruges. Both also work with the Port of Duisburg. The cooperation functions well because they all face very similar challenges and know that the market is large enough for everyone to benefit. (I03, Regional Development, Business Metropole Ruhr, p. 8 l. 28–32, author's translation)*

Collaborative behavior at the local level is apparent through local activities and a shared strategic focus on the hydrogen hub. I04 (Industry) verifies that key actors at the local level coordinate their activities functionally:

#Q6: *"From my perspective it works well because Duisburg itself now aims to develop into a hydrogen hub. There are various joint activities, starting with the redevelopment of former industrial sites toward use within this hydrogen hub. The port in Duisburg has also committed itself to the hydrogen agenda. Collaboration works on different levels. For example, we are active here in the High Region Rhine-Ruhr. I think that works very well. We are also in constant exchange with actors not only in Duisburg but also in the Ruhr Regional Association." (I04, Industry (TKSE), p. 3 l. 7–14, author's translation)*

5.3 Technical Challenges

The thematic block "Technological Challenges" comprises 30 out of 201 analyzed statements (14.9%). In the overall corpus, the associated meaning units are clearly weighted: "H2 Supply, Networks & Storage" 27, "Scale-up & Process Integration" 17, and "Transitional NG-DRI (Bridge or Lock-in)" 5. Substantively, a pragmatic, risk-minimizing path is to optimize existing assets with DRI, adding smelter, step-by-step growing hydrogen from natural gas to H2. By this, initial, controlled hydrogen can be produced without necessarily relying fully on 100% H2. Supply chain matters, especially import through sea or land transport to determine hydrogen volume, price, and availability timing.

Meaning Units	Interviews								
	I01	I02	I03	I04	I05	I06	I07	I08	Total
Actor Constellations			3	2	1	2	2		10
Competitiveness & Demand for Green Steel	2	3	5	4	2	5	5	3	29
Cost & Market Risks	3	5	2	4	1	6	2	5	28
Dependence on Political Will	4	2	2	1	2	2	2	2	17
Evolution vs. Paradigm Shift	1		1	2	1	1	2	1	9
Expert Role & Relevance	2	1	2	1	1	2	2	2	13
Funding Landscape	3	2	1		1	3	1	2	13
H2 Supply, Networks & Storage	3	5	7	1	5		5	1	27
Institutional Hurdles	2	5	2	1	3	2	1		16
Instrument & Network Effectiveness	2	1	5	4	4	4	2	2	24
Location Advantages	1	3	6	1	4	2	1	1	19
Model Region Potential	3	1	1	1	2	2	1	2	13
Multilevel Steering Quality	2	3	2	2	7	5	5	7	33
Org Touchpoints with H2 & Steel	2	1	1	1	1	2	2	1	11
Role of Social Actors		1	1	3	2	3	1	6	17
Scale-up & Process Integration	2	3	5	1		1	4	1	17
Skills, Reskilling & Social Risks		2	1	5	1	2		2	13
Transitional NG-DRI (Bridge or Lock-in)	1	1		1		1		1	5
Underestimated Aspects	2	2	2	2	1	1	3	3	16
What must happen by 2030/2050			2	2	2	1	5	2	14
Total	**35**	**41**	**51**	**39**	**41**	**47**	**46**	**44**	**344**

Table 2 - Top Meaning Units (Source: own graphic)

5.3.1 Scale-up & Process Integration

The technology route for Duisburg is based on the DRI route with smelter and, thus, existing assets such as converters can also be utilized. This way, risks of transformation can be avoided, and integration of processes can be accelerated. The share of hydrogen can be gradually enhanced. Initially, this can be done through natural gas or a hybrid mode, and finally through increased hydrogen content. In this way, a progressive transition can be managed without relying on 100% hydrogen from the initial start.

Minimizing risks of transition through maintaining existing phases of the value chain is considered to be a sound strategic decision. Searching for synergies with existing assets is identified as a key success factor of the selected DRI route by I07 (Research):

#Q7: *"thyssenkrupp says we can continue using a great many of our assets, this steel production and so on, while still trying to integrate these hydrogen DRI plants and look for those synergies." (I07, Research/Think Tank, p. 5 l. 6–8, author's translation)*

This approach is not seen as a disruptive break with tradition but as a technologically feasible and manageable innovation. Interviewee I08 confirms that the challenge lies primarily in scaling rather than in an untested technology.

#Q8: *"Operating direct reduction plants with hydrogen was indeed something innovative, but not something that had never been tested technologically on a small scale." (I08, Union/Works Council (TKSE), p. 3 l. 12–14, author's translation)*

5.3.2 Transitional NG-DRI (Bridge or Lock-in)

The first expansion step of the Duisburg plant integrates the DRI process with the smelters and continues to employ existing converters. This makes the substitution of blast furnaces possible without overloading the development of scaling and integration. The main activities include the integration of the areas between the DRI process, the smelter, and the converter, the step-by-step increase of hydrogen consumption, and the electrical interconnection and load management. The need and benefit of a staged entry through natural gas can be verified directly from the respondents. By this, the industry can quickly enter and transition fully only when the hydrogen infrastructure offers enough certainty and volume. Respondent I02 (City) identifies the step-by-step substitution of natural gas as follows:

#Q9*"For commissioning we will still use natural gas; that is possible with the process being applied. In a second step we will then gradually switch to hydrogen in that area as hydrogen becomes available. That is the current plan for the steel sector." (I02, City, p. 3 l. 2–6, author's translation)*

5.3.3 H2 Supply, Networks & Storage

The supply of hydrogen to the Duisburg plant will be ensured through the delivery from somewhere else. The Hydrogen comes per import through the ship or the main network to the plant. Cross-country pipelines (NL/BE, Delta-Rhine route) act as the trendsetter for volumes, price, and timing of deliveries. Storage and buffer systems, as well as so-called bridging paths such as ammonia, can ensure that supplies to the plant can be maintained until the supply of hydrogen is increased.

Whereas the strategic locational advantages are undeniable, experts emphasize that the required implementation of the necessary infrastructure is difficult. Moreover, the pace of the market's startup was considered to be much too optimistic. This is reflected by interviewee I03 (Regional Development):

#Q10: *"Of course, we were all far too optimistic about how quickly the hydrogen market ramp-up would progress. Yes, it will come, but not in quantities that would make us say 'great!'. The timeline is shifting more towards 2030 or 2032. There are also infrastructure gaps, particularly regarding the connection of industrial and commercial areas. And it is no consolation for us in Germany that the Dutch are facing similar difficulties in developing the Delta Rhine Corridor. (I03, Regional Development, Business Metropole Ruhr, p. 9 l. 25–28, author's translation)*

The difficulties of infrastructure construction are further exacerbated by high population density and the need to cross urban areas. I03 specifies the practical and temporal hurdles of network build-out and concludes with a central call for patience:

#**Q11**: *"I think we have to consider that when you build a new hydrogen network, for example in rural areas, you can of course work much faster than when you need to construct a hydrogen pipeline through cities like Bochum or Essen. That is where it becomes more difficult. I believe we were too optimistic with our timeline. Above all, we need patience. Patience and perseverance." (I03, Regional Development, Business Metropole Ruhr, p. 10 l. 10–17, author's translation))*

5.4 Economic Risks

The thematic block "Economic Risks" comprises 50 out of 201 statements (24.9%). In the overall corpus, the meaning units are clearly weighted: "Competitiveness & Demand for Green Steel" 29 (14.4%), "Cost & Market Risks" 28 (13.9%), "Dependence on Political Will" 17 (8.5%), and "Funding Landscape" 13 (6.5%) (see Table 2). In any case, it is evident that in the absence of sufficient politico-economic support, it is impossible to create any viable business case. Then, the cost gap and risks of CO2, power and hydrogen availability are of vital importance in this early phase. ETS and CBAM together with lead markets create conditions for competitiveness and demand, and it is only clear and plannable funding conditions that can create conditions for firms to formalize binding investment decisions.

Meaning Unit		Counts
3.2	Transitional NG-DRI (Bridge or Lock-in)	5
6.4	Evolution vs. Paradigm Shift	9
2.3	Actor Constellations	10
1.2	Org Touchpoints with H2 & Steel	11
2.1	Model Region Potential	13
4.2	Funding Landscape	13
1.1	Expert Role & Relevance	13
5.2	Skills, Reskilling & Social Risks	13
7.2	What must happen by 2030/2050	14
6.2	Institutional Hurdles	16
7.1	Underestimated Aspects	16
3.1	Scale-up & Process Integration	17
5.3	Role of Social Actors	17
4.3	Dependence on Political Will	17
2.2	Location Advantages	19
6.3	Instrument & Network Effectiveness	24
3.3	H2 Supply, Networks & Storage	27
4.1	Cost & Market Risks	28
4.4	Competitiveness & Demand for Green Steel	29
6.1	Multilevel Steering Quality	33
Total:		**344**

Table 3 - Top Meaning Units Count (Source: own graphic)

5.4.1 Cost & Market Risks

There is no strong business case for green steel at present in the absence of political backing. ETS and CBAM are very important tools to help overcome cost competitiveness in the next years. Funding for start can kick-start several projects, yet it is still less than adequate for large-scale development. Even taking into considerations funding factors, it is difficult to say that it concerns considerable risks within the area of the cost of hydrogen and its supply. The relative cost factors, uncertainty about hydrogen supply and cost, and the availability of effective tools, for example, funding and lead markets, bring risks for businesses with them. The need for state assistance in the sector is viewed as necessary for filling the current cost gap. It is generally agreed that the emerging methods of steel production are still economically suboptimal and can only be maintained in this manner due to incentive programs for assistance. Interviewee I04 (Industrie) asserts the role of funding sources in motivating the turn to this sector:

#Q12: *"I do think it is important to support projects that no single company can shoulder on its own. We are moving away from a proven and, let us say, economically optimized* *production route toward something that still has to prove itself in the future. It will evolve. There will also be a point where green steel becomes cheaper than grey steel simply due to ETS pricing. But we have to get there first. That is why start financing is important at this stage." (I04, Industry, TKSE, p. 6 l. 4–10, author's translation)*

In addition to this, irrespective of the cost of production, the whole process is overshadowed by the risk of supply in the marketplace for hydrogen. Implications of this risk are felt in the current economy, and this risk can be explained in the given scenario of the I06A (DBI) explanation of the risk of hydrogen availability:

#Q13: *"ArcelorMittal has just announced that it is stopping its project and returning funding, though not in Duisburg. One reason given for pausing or not pursuing the transformation is concern about whether there will be sufficient hydrogen." (I06A, City Economic Development, DBI, p. 5 l. 21–24, author's translation)*

5.4.2 Funding Landscape

Funding conditions are considered as the push that must be given, but it suffers from delays and uncertainties in approval and notification. However, the rule of thumb is support for upfront investment costs creates incentives to invest, while permanent support for ongoing operating costs is looked at as something that needs to be viewed in a different manner. In this case, some hard and fast rules are required instead of indefinite reliance.

A central critique of the instruments concerns how subsidies are designed. It is asserted that the subsidy needs to be focused on investment expenditures for supporting the change in technology, and any operating expenditure needs to be market-driven. I01 (Research) argues for investment-linked subsidy schemes.

#Q14: *"Because I think that if German and European policymakers used these funds only for investment and kept out of companies operating costs, that would already help a great deal to make the leap to a technology shift." (I01, Research, p. 8 l. 31–34, author's translation)*

Regardless of the type of support, planning certainty is cited as the decisive factor. The funding landscape must provide reliability to enable investment decisions, since a business case cannot rest on the mere promise of subsidies. I05 (Port Authority) underscores the need for stable framework conditions:

#Q15: *"In the end politics must ensure, and we have indeed seen this in recent years, that there is, let us say, a stable and reliable hand extended so that companies can actually plan, and of course combined with targeted support. At the same time it cannot be that a business case depends on whether one receives a subsidy or not. In my view that falls short." (I05, Port Authority, duisport, p. 11 l. 1–7, author's translation)*

5.4.3 Dependence on Political Will

In the case of the Duisburg transformation, the political factors are very influential. In addition, in the absence of secure and on-time decisions in relation to funding and guidance, final investment decisions and investments will fail to emerge. Subsidy can be seen as a catalyst and at the same time poses a risk of dependence in the short and long terms.

According to researchers, the prevailing business case is considered externally driven. Being economically unviable in the short run makes it fully reliant on the political agenda. Here, reliance is seen as basic or vital in the formulation of I07 (Research):

#Q16: *"From my personal perspective it depends almost entirely on that. The business case is a politically created business case. Under current conditions it is not an intrinsic business case. If there were no climate policy targets and regulation, but also funding, you can argue it from both sides. But if there is no political drive to do it, then there is basically no reason to do it, and no chance to do it." (I07, Research/Think Tank, p. 13 l. 9–15, author's translation*

That political action is required is evident from the point that without some original stimulus from funding projects, a strategic change of course would never have been put on the table. Investment in hydrogen infrastructure and production is confirmed by I01 (Research) as political incentive-driven:

#Q17: *"If such funding had not existed, or if there had been no hydrogen infrastructure project from the EU, could Duisburg even have imagined switching to hydrogen-based production? No." (I01, Research, p. 7 l. 23–26, author's translation)*

5.4.4 Competitiveness & Demand for Green Steel

Green steel competitiveness in this scenario appears possible in the medium to long-term horizon once the politico-economic conditions are in place. CO2 pricing and CBAM narrow the cost difference when compared to imported steel. And at the same time, demand pull assistance in lead markets and procurement is required on account of offtake agreements to develop the learning curve for green steel restarts. International location competitiveness becomes relevant at this point. That is exactly why CBAM in the EU can be classified as protection until cost or stable green steel prices are achieved. Industry expects this "push" regulation to trigger the turning point:

#Q18: *"Beyond that, CO2 emissions will, due to rising CO2 certificates, reach a level from, let us say, the mid-2030s at which grey steel will no longer be a business model. That is, grey steel as opposed to the green steel we aim to produce." (I04, Industry, TKSE, p. 2 l. 4–7, author's translation)*

In addition to CO_2 pricing, demand pull on the buyer side is required in order to introduce the first, yet more costly, volumes of green steel onto the market and thus achieve the necessary scalability. In this area, researchers believe that the public sector and the regulation system play an important role in:

#Q19: *"And of course steel flows massively into infrastructure, so if you link this in some way to green-steel quotas or certain procurement criteria, you have a huge lever. There is also leverage through regulation currently being developed in the EU to bring green steel into the automotive sector." (I07, Research/Think Tank, p. 12 l. 34 – p. 13 l. 4, author's translation)*

5.5 Social Impact

The thematic block "Social Impact" comprises 14 out of 201 statements (7.0%). In the overall corpus the most visible meaning units are "Role of Social Actors" 17 (2.5%) and "Skills, Reskilling & Social Risks" 13 (1.9%) (see Table 2). From a substantive perspective, the prevailing policy paradigm is employment neutral, shifts in roles rather than layoffs, mitigated through re-education and upskilling as well as through retirements based on demographics. Social risks appear manageable if investment in early education takes place. Institutional design gives push-and-pull effects. Social actors hold the trigger for program implementation. Co-determination, chambers, as well as social networks, underpin transition routes, coordinate education, as well as secure acceptance.

5.5.1 Employment Effects

Looking ahead, the transition towards hydrogen-based processes will result in changes in job requirements, as well as reduced employment requirements within defined process steps. However, new job opportunities will also arise within complementary areas of the value chain, along with employee requirements for furthering their skills. What will happen will depend largely on whether the industry the region, take retirements within the workforce as a buffer approach instead of layoffs. From the industry point of view, the objective is that, despite technological change, the number of employees must not reduce. This strategy lies on internal redeployment and retraining. Consequently, the net outcome remains neutral:

#Q20: *"And the transformation itself will basically proceed employment-neutral, so you really cannot say that jobs will be lost because of the transformation." (I04, Industry, TKSE, p. 2 l. 4–7, author's translation)*

This strategic objective is supported in terms of feasibility within the firm. Interviewee I08, as one representing employee co-determination, explains the ways in which the necessary reskilling/up-skilling is being organized within the existing operating processes so that the employees impacted can be integrated into the new processes as early as possible:

#Q21: *"For those whom we know, for example, are working at the blast furnace today and will be at a DRI plant tomorrow, we offered qualifications and essentially hired people so they can look at blast-furnace technology now but be trained on the job, so that they are in place when the DRI plant is running. That worked quite well." (I08, Union/Works Council, TKSE, p. 10 l. 16–21, author's translation)*

5.5.2 Skills, Reskilling & Social Risks

Such a transition carries defined social risks, but with concerted efforts on the side of companies as well as the region, they can be manageable. Social changes will come along with changes in job descriptions, with fewer traditional blast furnace operators and more hydrogen related process paired with continuous education as a centerpiece. Social tensions or polarization will come if there's a breakdown in trustworthy communications. One essential method of remedying skill risks is to retain retraining offers close to the affected employees, in terms of both geographical proximity and topic. Also, establishing so-called specialized centers is meant to ensure that retraining will not provide a barrier. I02 (City) verifies the industry effort that focuses on anchoring new skill paths directly on site:

#Q22: *"For example, there are plans to set up an H2 training center here. The idea is to give employees from the areas affected by the transformation an opportunity to take up further training and retraining offers, and to do so directly on site. This is, of course, being done at the initiative of the industrial companies." (I02, City, p. 11 l. 2–7, author's translation)*

Along with targeted measures of qualification, the regional culture represents a key social strength. Due to its traditional experience with deep structural changes, the Ruhr region's attitude is solution-oriented, not problem-centered, which represents a crucial social buffer for the acceptance of the transformation:

#Q23: *"Fundamentally, I think we have a region here in the Ruhr that is used to making transformations. The region does that. It can do it. People here focus on solutions rather than on problematising. That is, of course, a very decisive advantage." (I05, Port Authority, duisport, p. 16 l. 11–14, author's translation)*

5.5.3 Role of Social Actors

Social partners, chambers, and networks play a pivotal role in this transition:

Co-determination, as well as trade unions, helps enhance workforce trust in the transition routes. They serve as the link between management, politics, and the workforce. Chambers of industry or commerce, as well as education/training partners, coordinate the matching process of qualifications with profiles, which is essential, particularly with regard to skill shortages. Innovation networks/clusters (e.g. “High Region”) provide actor alignment, infrastructure, as well as offtake issues, which facilitate public support. Often, this group of measures together promotes acceptance, speed, and actor coordination.

An essential aspect required for acceptance in the workforce is the involvement of social partners. Co-determination provides assurance that decisions are not only supported by management but also supported by the workforce. Evidence from interviewee I08 illustrates the legitimising aspect:

#Q24: *“And because we are, I would say, involved there as co-determination, the works council and so on, it was immediately accepted.” (I08, Union/Works Council, TKSE, p. 11 l. 40 – p. 12 l. 2, author’s translation)*

5.6 Governance

The thematic block “Governance” comprises 48 out of 201 statements (23.9%). In the overall corpus, the meaning units are weighted as follows: “Multilevel Steering Quality” 33 (16.4%), “Instrument & Network Effectiveness” 24 (11.9%), “Institutional Hurdles” 16 (8.0%), and “Evolution vs. Paradigm Shift” 9 (4.5%) (see Table 2).. There is consistency in the image. Regulatory certainty and well-defined responsibilities create investment opportunities, whereas problems with coordination and sequencing, as well as bureaucratic and unclear criteria, slowing implementation. Financial tools and networks are only a kick-off mechanism and achieve their potential only in well-defined markets and together with consolidated demand. It is better to adopt an evolutionary approach that may include some elements of paradigm change, in which case the speed of decision and inter-level alignment may restrain ramping up.

5.6.1 Multilevel Steering Quality

The quality of steering regarding investment in the EU, at the federal level, and in the member states remains mixed. Frameworks and financing opportunities in the EU create investment opportunities, sequencing problems such as the chicken-and-egg issue between pipelines and DRI investment, bureaucratic delays, and shifting policies create drag. In investment security in the industrial sector, commitments and rapid “smart” inter-level coordinating on investment decisions are required in terms of adjustable “green” conditions. The most prominent problem undermining investment security is the chicken-and-egg dilemma in the timing of infrastructure and industrial investments. Without a clear and binding political framework, actors block each other, as I08 describes from the perspective of employee co-determination:

#Q25: *"Hydrogen suppliers say, 'We cannot start yet because the plant is not there, and the company says, 'We cannot invest yet because the hydrogen is not there. That is the chicken-and-egg problem, sometimes pushed back and forth. Politics has to create the framework to provide this investment security. For everyone. And when politics creates this framework, companies will invest, and then a hydrogen pipeline will come here, and then the whole thing can work." (I08, Union/Works Council, TKSE, p. 13 l. 35 – p. 14 l. 5, author's translation)*

In this problem, it requires higher-order political action for resolution on the issue of coordination, and it needs to strike a balance between speed and bureaucratic conservativeness. According to I01 (Research), investments complexity and amount excuse some slowness in decision-making due to possible errors:

#Q26: *"However, if one wants to accelerate things and do them much faster while keeping the same legislative policy, you end up with framework conditions that are not well thought through, that do not do justice to everything, and with such rapid implementation you get errors in many places. That is why this slower bureaucracy also has advantages, especially when it comes to funding in the billions of euros. I can understand that the process then also proceeds slowly." (I01, Research, p. 9 l. 33–36, author's translation)*

5.6.2 Institutional Hurdles

The hurdles are: slow and non-transparent permitting and administrative proceedings, undermanned authorities, unclear "yes/no" decisions, and sequencing on grid connectivity and infrastructure (hydrogen and power grids). Standards and criteria (what is "green" and when), and state aid notifications are additional delays. In order to secure investments, companies require timely processing, clear criteria, and synchronized grids and expansions. Time is viewed as critical. The length of permitting processes threatens compliance with political targets and prevents the early realisation of key projects, as I05 explains from the perspective of the port authority:

#Q27: *"Actually we are dealing with two things. Construction will certainly take about three years, roughly estimated, with everything that goes with it. It is not just stacking stones, but also the engineering and so on. And indeed, permitting, that is where we are in the administrative processes, which simply have to go much, much, much faster. So let me put it this way: if we want green hydrogen by 2030, then we have to build now. That means we need approvals now, decisions on the approval side, so that whoever wants to build such a terminal can go to their bank." (I05, Port Authority, duisport, p. 16 l. 11–14, author's translation)*

This observation is shared by actors in economic development, who point out that approval procedures in Germany fail to be internationally competitive. The problem is systemic, and it goes beyond individual projects. I06A emphasizes the necessity of a radical speeding up of processes:

#Q28: *"The whole topic of permitting procedures, including how long permitting takes in Germany compared to other countries." (I06A, City Economic Development, DBI, p. 10 l. 1–3, author's translation)*

5.6.3 Instrument & Network Effectiveness

Funding instruments are only scalable to some extent in absence of any definition concerning markets and products (so-called "green steel"). By securing lead markets and government contracting, offtake commitments enhance the efficiency of investments and render them "bankable". Innovation networks and clusters provide networking and agenda-setting for speeding up applications, partner searches, and political networking. Interview partners agree on the leverage effect of public funding, emphasizing that it makes funding schemes affordable within the current cost structure and that it increases planning reliability as actors from the DBI say.

#Q29: *"It is true, of course, the money is coming. It is not the case that the federal government says, I will not give you this now. I would rather say it makes projects bankable, that is, it makes projects financeable that would not be financeable without these funds. And of course it provides a certain degree of planning certainty." (I06A, City Economic Development, DBI, p. 6 l.26–29, author's translation)*

Because of initial momentum, size hits a roadblock in terms of unclear political regulation. Market efficiency is obscured inasmuch as "green" standards are unclear. I01 (Research) illustrates the problem of the missing product definition in that:

#Q30: *"Europe funds companies to produce green steel, but it cannot itself define precisely what green steel is, and that of course leads to confusion. Other steel companies then come and say, I also want to receive this funding because someone else received funding to produce green steel, and then they go to the EU and say, OK, what are the criteria so that I can apply for this funding as well?" (I01, Research, p. 10 l. 8–13, author's translation)*

5.6.4 Evolution vs. Paradigm Shift

Specialists view this evolutionary reorientation process as advisable, risk-free, and possible within existing frameworks. However, this is only half the recipe for change, and genuine change means fast-tracked, binding, and synchronized decisions at different levels in core sectors. From an industry perspective there is a clear preference for evolutionary stability. A radical paradigm shift in regulation is seen as harmful because it would undermine the planning and investment certainty that is urgently needed. I04 (Industry) articulates the need for prudence and reliability in policy:

#Q31: *"Of course I cannot, on the one hand, demand that the framework conditions be stable and reliable and then, on the other hand, call for a paradigm shift. I think you have to adapt things to the situation and regulate with prudence. A paradigm shift is difficult to accompany appropriately." (I04, Industry, TKSE, p. 9 l. 8–12, author's translation)*

5.7 Outlook & Open Points

The thematic block "Outlook & Open Points" comprises 18 out of 201 statements (8.9%). At its core is the single meaning unit "Underestimated Aspects" with 16 (7.9%). The interviews stress that there is one aspect that rarely gets attention: that projects within the industrial sector and the hydrogen infrastructure can't do without each other.

5.7.1 Underestimated Aspects

What is often overlooked in this debate is that there is a mutual dependency between industrial investments such as DRI and hydrogen infrastructure. A hydrogen-based steel industry is required to facilitate the scaling up of hydrogen, and the steel industry requires hydrogen so that it always remains future proof. Experts argue that steel projects do not only appear as buyers in this new market but as pace setters, as well as the main demand source, responsible for the entire infrastructure development. Without such big offtakers, there would be no economic rationale for hydrogen infrastructure network construction. I07 (Research) explains the basic relevance of industrial projects as:

#Q32: *"how important these projects are for the hydrogen ramp-up; if these steel projects no longer exist, then you can basically forget about hydrogen altogether." (I07, Research/Think Tank, p. 15 l. 32–34, author's translation)*

This critical assessment is cast in existential terms by actors in economic development: the use of hydrogen in the steel industry is not merely an option but the only alternative to deindustrialisation. I06A formulates hydrogen as indispensable for the location:

#Q33: *"I think there is still too little discussion of the fact that there is no alternative to hydrogen. Well, there is one, and that is that the steel industry will be shut down. So there will have to be hydrogen; there is no other way." (I06A, City Economic Development, DBI, p. 11 l. 26–29, author's translation)*

6 Discussion

The following discussion synthesizes the technological, economic, political and social dimensions to analyze how multi-scalar dependencies and local agency shape Duisburgs pathway towards a green hydrogen economy.

6.1 Restating the research question and analytical approach

This thesis focused on the change in the Duisburg steel industry regarding the production of sustainable green hydrogen. Following the research question "Which technological, economic and political factors influence this transformation, and what challenges and opportunities arise?" the research questions were answered through analysis based upon the Challenge-oriented Regional Innovation System (CORIS) approach (Tödtling et al., 2022; Trippl, 2023). Based upon various technological, economic, political, and social factors, the main results can be summarized:

- Technological Dimension: The change involves the introduction of Hydrogen-based Direct Reduction and its gradual implementation in the existing route. The most important result obtained here revolves around the dependency transition from being solely plant-paced in terms of the rate of conversion towards being based upon external energy and hydrogen infrastructure systems. While this creates high risks regarding infrastructure timing, it offers Duisburg the opportunity to leverage its port and logistics assets to become a central European hydrogen hub.
- Economic Dimension: The existence of such a "green cost gap" and price risks makes the business case currently more driven by policy than markets. This leaves the region in particular highly reliant on complicated funding schemes and market-creation tools. But successful here would open up access to securing overall competitiveness over the long term and entering new markets through green steel.
- Political & Governance Dimension: The process is embedded in a complex multi-level system that exhibits clear directionality but lacks coordination. The key issue rests in closing the gap between political ambition and administrative feasibility (permissions being delayed or undefined, for instance). Where governance succeeds in aligning these levels, it opens crucial investment windows and de-risks first-mover projects.
- Social Dimension: The changeover is characterized by a strong culture of transformation in the context of unions and co-determination. Although the sector changeover from conventional fuels to hydrogen fuel impacts skill structure in terms of reduced employment in particular areas, there are indications of a managed changeover process that avoids compulsory redundancies through the use of buffers and reskill approaches.

This analysis demonstrates that the Duisburg transformation should be seen not only in terms of technical change but in the context of the complex restructuring of a regional innovation system in which technological primacy and viability are necessarily linked with political orchestration across multiple geographical levels. The following sections of this analysis will elaborate further upon each of these factors.

Dimension	Key Driver	Main Challenge	Main Opportunity
Technological	H2-DRI adoption, Grid integration	Dependency on external infrastructure (H2/Power)	Duisburg as H2-Hub & Logistics Node
Economic	Policy-induced business case	Green Cost Gap & Market failure	First-mover advantage & long-term competitiveness
Political	Multi-level governance (EU/Bund/NRW)	Permitting speed & Complexity of coordination	Model region for green industrial policy
Social	Demographic change & Reskilling	Vulnerability of mono-structure	Socially managed transition (no layoffs)

Table 4 - Compact Analyzes (Source: own graphic)

6.2 Technological Dynamics of the Duisburg Steel Transition

There is agreement between the literature on primary steel decarbonization and the Duisburg scenario that hydrogen-based direct reduction technology is the central technological solution for near-zero primary steel production (Fischedick et al., 2014; Gajdzik et al., 2023), although they give different priorities to the challenges and risks entailed.

In both views, the scenario with complementary DRI-based smelters, together with the preservation of converters, is considered a realistic solution for primary steel producers aiming for substantial GHG cuts within existing, relatively large integrated steel production clusters (Radloff et al., 2023; Vogl et al., 2018; cf. Section 5.3.1). According to this literature, this scenario would consist of a gradual reconfiguration of the production system, as new DRI-based modules will be phased in consecutively, with blast furnaces being phased out (Suer et al., 2022; Arens et al., 2017; Radloff et al., 2023). Experts in Duisburg report exactly this mode of transformation through the tkH2Steel scenario, attributing essential importance to the fact that the new DRI-based units will be integrated into the existing system, running alongside old facilities throughout the transition phase (Section 5.3.1). It seems that this works comparison brings forward that the focus of debate is not so much on technological choice but rather on addressing issues of sequence, pace, and risk involved in this transformation within a path-dependent region.

This comparison shows that the importance of challenges change. Indeed, in contrast with the literatures dual challenge of technology integration and the necessary availability of huge amounts of green electricity and hydrogen, the prevalent concern is infrastructure.

Actually, two different aspects of the literature highlight the challenges: availability of mature H2-DRI technology and the provision of massive amounts of green electricity and hydrogen (Binti Che Ibrahim et al., 2015; Jiang et al., 2013; Liu et al., 2021). There is also a strong stress on the need for a hydrogen infrastructure that connects import terminals with industry centers. Cross-border corridors serve as pacesetters (FNB Gas, 2024; cf. Section 5.3.3).

However, this literature stresses that technological innovation is not a concern in terms of its novelty (Binti Che Ibrahim et al., 2015). Thus, experts rate hydrogen technologies as largely known or controllable. The problem is rather, growing the pace of conversion of existing facilities synchronized with hydrogen infrastructure development is the overarching concern. Indeed, former views of the speed of transition scale-up have been to optimistic (cf. Section 5.3.1 & 5.3.3).

There is a marked point of departure with regard to strategic transition technology value. Namely in terms of the application of natural gas within the Direct Reduction. Strategies in transition that feature natural gas as a technology path appear to be regarded with a bit caution (Doucet et al., 2024; Mostafa et al., 2024). Much attention seems to be centered on being locked into either path dependence or carbon emissions, particularly within the perspective that any upgrading choice may serve as a temporary delay within the transition towards hydrogen operation (Grillitsch & Hansen, 2019). For Duisburg, the NG-DRI remains seen as being one of its most positive transition strategies (cf. Section 5.3.2). Rather than being implicitly positioned as any form of an all or nothing transition. This strategy is consciously framed as being essentially that of a transition entry, particularly starting with natural gas or hybrid solution models, with hydrogen introduction being scaled with increasing supplies. While the literature treats the bridge technology with caution due to lock-in risks, the empirical reality in Duisburg reframes it as an essential enabler.

For practitioners, the operational stability and early entry provided by the NG-bridge outweigh theoretical lock-in concerns, provided the long-term goal remains full hydrogen operation (cf. Section 5.3.2)

Path dependence and lock-in in primary steel production emerge due to the nature of asset longevity, investment cycles, and path dependence through institutions. Options related to upgrading or premature closure of blast furnaces locks-in or opens windows for, hydrogen-based technologies (Arens et al., 2017; Grillitsch & Hansen, 2019). This Duisburg example sets itself apart through the objective of maintaining a large part of the existing value chain in operation, such that the necessity of doing so leaves them with no other choice than engaging in complex sequencing of shutting down the old routes and new investments (see section 5.3.1.& 5.3.2). At the same time, new hydrogen hubs and corridors projects provide further windows of external opportunities that accentuate that technological strategies at the cluster level must be well synchronized with higher-order energy policies that define the risk and reward space associated with different investment alternatives.

Finally, both the literature and the Duisburg example treat the steel transition as a spatially embedded, multi-scalar process, albeit with different degrees of abstraction.

Scholarly literature speaks of generic hydrogen frameworks, corridors, and hubs, focusing on their task of connecting seaports, logistics nodes, and industry hubs (Emonts et al., 2019; Digiesi et al., 2022). The interviews translate these notions into tangible projects and constraints: specific pipeline routes through the Rhine-Ruhr metropolitan area, the positioning of Duisburg as a hydrogen hub, and the concrete difficulties of integrating large new energy flows into an already dense infrastructure landscape (cf. Section 5.2.1 & 5.3.3). In the Duisburg case, this spatial embeddedness is relevant in two respects: First, the transition time scale is more than a model parameter that can be improved through optimization calculations. Rather, transition is driven, in terms of scale, by infrastructure projects with project lifetimes that stretch years into the future. Second, its transformation will call for a synchronized effort that requires different spatial scales: ideally, local actors can optimize plant-level strategies, but the decisive levers for hydrogen availability, electricity system expansion and corridor development lie at regional, national and EU levels.

6.2.1 CORIS-based interpretation of technological change

From the perspective of CORIS, the transformation of Duisburg towards hydrogen DRI is definitely "challenge-oriented" (decarbonization), but highly path-dependent. The action strategy tends towards minimizing risks and being incremental (for example, via NG-DRI transitional technologies) prioritizing the continuity of existing industrial structures over radical disruption. Technological innovation is strongly developed, but organizational or institutional innovation is no match. The process of transition has been defined mostly in terms of internal engineering in the context of the existing companies and not in terms of possibilities of experimental renewal. The evidence supports the idea that regional innovation systems are open. There are many external multiscalar developments that shape and determine Duisburg's progress in this respect. That is, national and European hydrogen and electricity infrastructures. The approach puts more emphasis on "controlled unlocking" than exnovation. The innovation of new units with lower carbon emissions will live together with the old system infrastructure in this context. Consequently, exnovation is treated as a by-product of technological rollout rather than a deliberate innovation task. Today, there is a logic of reorientation in the region, but not one of transformation. The new technologies are layered upon the existing system. Despite the potential inherent in the shift owing to the scale involved, the realization of this will rest upon the rate of infrastructure development and exnovation.

6.3 Economic Dynamics of the Duisburg Steel Transition

On both the academia side and the expert side, economic terms appear as the primary obstacle for hydrogen-based primary steel production. On both, a large so-called green cost gap between hydrogen-based direct reduction and the blast furnace process is emphasized, caused by higher investment costs in new reduction, melting, and electrolysis capacities, as well as additional operating costs related to electricity, hydrogen, and high-quality DRI pellets (Agora Industrie et al., 2023; Radloff et al., 2023; cf. Section 5.4.1). Models from Duisburg predict that totally hydrogen-based production would be about 50% higher than the current EU steel costs and will not be economically viable until the 2030s with sufficient policy support (Radloff et al., 2023; Fischedick et al., 2014). Experts views from interviews confirm this, referring to this production path as being not yet economically optimized and thus largely unfeasible (see Section 5.4.1). Taken this together without policy incentives green steel in Duisburg lacks a self-sustaining business case.

A specific divergence occurs with regard to the implications of hydrogen economics. Literature sources trace back the green cost gap to high electricity costs, as well as electrolyser technologies that feature high capital costs and low durability (Aslam et al., 2023; Simões & Santos, 2024). Apart from production economics, the literature establishes system-level risks, perceiving hydrogen storage as a decisive economic tool necessary for decoupling production from real-time electricity price variations (Emonts et al., 2019; Khanra et al., 2024. In Duisburg, such system-level risks induce project-level hesitation. Experts pinpoint volatile electricity prices, as well as uncertain quantities, as decisive determinants within a fragile economic rationale, such that some firms halted their projects or returned funding due to reservations over the availability of supplies (cf. Section 5.4.1). By comparison, the literatures generic input cost problem translates in practice into a reluctance to commit capital. At the systems level, infrastructure and storage requirements thus provide effective verification not only as a technological necessity, but more particularly as a primary economic tool necessary for securing bankability.

A marked point of divergence emerges with regard to the application of support tools. Whereas the literature specifies required tools, the views of practitioners highlight the procedural risks involved with them. Closing the cost gap, researchers stress the importance of a well-designed policy mix that incorporates carbon pricing, CBAM, as well as capital subsidies (Agora Industrie et al.,2022; Blöcker, 2022). According to the literature, investment cycles with a lengthy duration interact with regulatory uncertainty, inducing a tentative investment climate (Pimm et al., 2021; Jesse et al., 2024). Interviews confirm the importance of tools such as IPCEI and CCfD but depict extreme dissatisfaction with their application. They assume that regulatory slowness and regulatory obscurity concerning approval directly affects planning reliability for projects worth multiple billion euros (cf. Section 5.4.2). Characteristically, the difference between literature and practice illustrates that the theoretical availability of support measures remains insufficient

The results show a complex difference of opinion on the form of financial support. The literature typically requires cost-sharing schemes to address additional production costs for green production, without specifying whether this would be shared through consumers, the public sector, or industry (Birat et al., 2021) However, there is a focus on reducing the cost gap through a range of tools, such as ongoing support (Vogl et al., 2021; Agora Industrie et al., 2023). There is a more specific design choice being provided by practitioners. They specify that public sector support would focus on investment costs as a trigger for technology change. By contrast, addressing OPEX costs as a fixed, permanent solution is considered problematic, as this would embed perpetual dependence, with interviewees expressing a preference for OPEX being driven through market forces once the regulatory environment is in force. Such a design consideration represents a focus on the difference within more generic requirements for support as found through literature. There is evidence through this empirical evidence that the "kick-start" solution is preferred over permanent "life support" measures (cf. Section 5.4.2). This represents strategic thinking, with public investment increasing production until the "politically created" market delivers through carbon pricing.

Both literature and interviews focus on competition in space, with literature predicting that low-cost regions with cheap renewables might specialize in the export-oriented production of green iron, thus moving value-added activity away from high-cost regions such as Duisburg (cf. Bilici et al., 2024), while interviews regard tools like CBAM as mere transition protections against this shift, thus recognizing that structural cost differentials must be addressed through European policies in order for Duisburgs competitiveness to be guaranteed (see Section 5.4.4).

There is contrast in the analysis between the likely evolution of demand for green steel. On one side, some literature refers to a green premium identified in niche markets and within the first movers, which would remain limited to specialized sectors (Muslemani et al., 2021; Johansson & Kriström, 2020). Duisburg experts would be more skeptical with respect to voluntary demand. A lead market would provide some initial volumes but only hard regulation will ensure competitiveness (cf. 5.4.4). Demand-side public procurement obligations, mandated through quotas, would be necessary as a bridging measure until the shift towards the broader transition facilitated by the EU ETS/CBAM. Based on interviews, the literatures skepticism would be supported with regard to voluntary green premiums. In practice, experts do not count on the willingness-to-pay driven transformation but on the enforcement capabilities of the state. With regard to the threat of a shift due to competition from low renewables costs, Duisburg experts would point out the positive effect of CBAM as a safeguard mechanism providing a transition time for higher cost regions that will move down the cost curve (cf. Section 5.4.4).

The insights indicate that the Duisburg transformation in the steel cluster is not dependent on technological viability but rather on establishing a firm political/economic system that shares risks, accelerates infrastructure and market evolution and effectively utilizes adverse regional factors within a prolonged transition process.

6.3.1 CORIS and regional economic capabilities

By considering the CORIS approach, the economics underlying the transition are defined by system failure. A "green cost gap" persistently exists that cannot be overcome through market reasoning alone. This renders green steel politically created business case. It does not operate independently but exclusively relies upon the mission-oriented climate policies and laws that inform traditional companies. The region is not an economic island but rather an operation point in a multilevel system. The use of Duisburgs industrial strengths is strongly connected to external circumstances like national electricity prices or federal infrastructure as well as German and European market frameworks (ETS/CBAM). The actors require sophisticated risk-sharing mechanisms (including CAPEX risks but keeping OPEX risks in the markets) rather than subsidies. But there are problems of complexity in procedures in instruments like IPCEI indicative of weaknesses in governance hindering the Regional Innovation System today. The economic strategy embodies a rather cautious reorientation. The objective here is to protect the existing companies and value chains from the rest of the world. Although this turns out to be quite stabilizing in current terms, the negative consequence of differentials in world energy prices may in the future trigger more profound transformation.

6.4 Political and Governance Dynamics of the Duisburg Steel Transition

There is a correspondence between the literature and empirical evidence that the transformation is essentially policy-dependent. Politics is seen in the literature as the key lever as well as potential bottleneck of the transformation.

The literature highlights that the transformation takes place within the rich, multilayered architecture, whereby the EU ETS, Fit-for-55, and national hydrogen strategies interact. This establishes the investment windows necessary for first movers (Agora Industrie et al.,2022; Tettamanzi et al., 2023). Duisburg empirically illustrates that the business case for green steel, therefore, was politically established. However, they formulate concrete "chicken-and-egg" problems: Suppliers of hydrogen remain reluctant to invest in infrastructure as long as offtakes remain unclear, whereas steel producers currently refrain from investing in DRI technology as long as hydrogen infrastructure investment is lacking (cf. Section 5.4.3 & 5.6.1). Both views concur that neither one nor the other will be remedied through spontaneous correction of the market. Rather, Duisburg specifies that the disalignment takes place in grid planning, pipeliness projects, as well as in the sequencing of infrastructure investments and DRI technology investments. Apparently, improving this infrastructure landscape represents a necessary antecedent enabling the 'unlocking of the policy framework.

There is a marked contrast between strategic intent and operational realities of regulation. Studies mentioned the importance of tools such as the EU taxonomy as key devices that can steer investments as well as prevent greenwashing. But they also pointed out that, if viability considerations were ignored, effective regulatory tools may pose unwanted difficulties. In fact, such challenges appear as strong organizational barriers. Obstacles such as slow permit processing were identified as risks associated with the realization of climate commitments in 2030 (Tettamanzi et al., 2023; European Parliament & Council, 2020). An important finding is that the absence of "green steel" definitions hampers the efficiency of its funding. The governance risks that were anticipated in the theoretical frameworks now appear in Duisburg as concrete frictions of administration (cf. Section 5.6.3 & 5.6.2). It is the tension between regulatory aspiration and administrative capacity that clearly appears as a key governance obstacle.

Schemes like Hydrogen IPCEI, national hydrogen, climate protection, CCfDs, as well as infrastructure funds, are regarded as essential tools for risk-sharing investment in capital-intensive, long-lived assets with a focus on channeling private finance, as they provide investment grants, operational costs, as well as infrastructure investments, with the goal of establishing essential infrastructure such as a hydrogen backbone, as well as massive electrolysis capacities (Pimm et al., 2021; Vogl et al., 2021). Experts in Duisburg concur that such instruments make projects bankable, which otherwise would not happen, particularly underlining time delays, procedure complexity, as well as difficulties with State Aid notifications, further advising that funding priorities must focus on investment costs, while operational costs must remain as much as possible within the responsibility of the market, in order not to develop a structural reliance on public aid (see Section 5.6.1 & 5.42). Both views thus confirm the primary importance of public risk-sharing as such, but with Duisburgs experience, there emerges a design-sensitive twist: that the key importance of such investment programming is its timeliness, simplicity, as well as its CAPEX structuring.

Finally, there is a notable tension with regard to the intended extent of governance reforms. Also, the scholarly literature asserts that merely upgrading the existing governance system might not be enough, requiring more fundamental transformations in industrial governance, as well as climate governance (Tödtling et al., 2022; Trippl, 2023), as in the case of Duisburg.

Duisburg participants recognize that faster, more binding and better coordinated decisions are required, though they clearly do not subscribe to a radical regulatory paradigm shift. Rather, they favor an evolutionary reorientation of existing regulatory structures, with modified carefully and selectively, if existing processes clearly impede launch (cf. Section 5.6.4). By implication, effective governance within a path-dependent cluster must walk a tight rope. It must be sufficiently transformative as to overcome obstacles but sufficiently evolutionary as to guarantee investment security for established corporations.

6.4.1 CORIS: orchestration, governance and policy mix

The example of Duisburg illustrates challenge-oriented governance and the clear mission: the deep decarbonization. The dense system of instruments provides a politically constructed business case. The policy not only aims to address market failures but also shapes innovation and pushes sector leaders towards adjusting. The system of governance is in parts fragmented. The process of transition is not dominated by any particular actor. Although there are intermediaries like networks and funding bundles. Also there are mismatches between different levels of governance in the EU, federal, and local levels. This causes failures in orchestration which is shown in the chicken-egg problem in the deployment of hydrogen. Orchestration remains highly influenced by state-industry coalitions. Although the level of orchestration regarding administration is broad, there lacks inclusiveness. Also it can be seen that civil society and NGOs are barely represented in governance platforms. The social partners contribute in traditional roles rather than co-designing policy. The portfolio of instruments involves complex supply-demand integration through supply and should be coupled with the creation of demand through green lead markets. The participants concern with planning certainty and clear definition (what is green steel?) over operating subsidies indicates institutional innovation in market structure. The current governance pattern focuses more on stabilizing the incumbents than paradigm-changing shifts. This fits the logic of reorientation: current institutional setups are modified in the context of new challenges. There are areas in the system that require paradigm-shifting solutions (points of friction like delays in permitting approvals), yet this system can be conceptualized only as an ambitious but incomprehensive orchestration attempt.

6.5 Social Dynamics of the Duisburg Steel Transition

The literature presents this change in employment terms as a significant transformation in employment patterns, whereby the use of hydrogen technologies and automation tends to diminish employment in the sector of primary production in the future. However, population aging emerges here as the most significant moderating factor in this process (Schoppengerd, 2024; Simic, 2022; Käckenhoff & Heine, 2024). The interviewees consider employment essential but point out that there should be an "employment-neutral" transformation. The idea is to have reduced employment requirements in some sectors but new jobs in other areas and implement this by relying mostly on demographic change and early retirement schemes combined with early preparation of blast furnace workers in DRI production (cf. Section 5.5.1 & 5.5.2). Both approaches require significant restructuring in the world of employment, but the literature underlines the scale of possible losses, in contrast to the capacity seen in local circumstances. The consequence of the Duisburg employment indicator would be more closely tied to the scale of successful use of buffers in adapting internal mobility than to technological achievement in employment itself.

The literature emphasizes the change in skill requirements towards process engineering, hydrogen operation, safety, automation and the reduced need for classic furnace operation. However, the literature asserts that continuous training and formal up-skilling through national qualification and immigration policies are necessary in responding to this challenge (Simic, 2022; European Commission, 2022). The interview respondents seem to agree with this adjustment and highlight approaches being implemented towards up-skilling workers in the industry, including preparing current workers in hydrogen and electricity through module-based education plans and preparing to open up the hydrogen training facility in the region with the objective of ensuring that the employees are relevant to the industry (cf. Section 5.5.2). This comparison not only confirms the literature's judgment regarding a skill gap issue but indicates that this situation is being remedied by local institutional mechanisms. This Duisburg example illustrates that national qualification policies are being implemented in the industry through concrete firm-level skill curricula and regional skill infrastructure.

The function of trade unions turns out to be another key factor in this context. According to the literature, unions and works councils are not only veto-players but also change agents in this process. They are believed to negotiate collective agreements regarding location security. This proves essential in ensuring that the process is guided by collective bargaining and not market forces (Vogl et al., 2019; Blöcker, 2022; Simic, 2022). This point receives strong support from the interviews conducted. The social partners are referred to there as key enablers and translators. Another key insight across various observations turns out to be in the context of co-determination. The interviews reveal that the strategic decisions regarding hydrogen projects were immediately accepted by the workers because of the formal role of co-determination institutions (cf. Section 5.5.3). Both approaches validate the point that just transition is not only a result but also a process. The existence of a strong level of co-determination in the steel industry in Germany functions as a legitimizing factor in this respect. It ensures that this period of strategic changeovers receives support from the workers. This reduces possibilities of frictions or actor failures in this context. The future of Duisburg's process will largely depend upon how this function gets combined.

The literature emphatically underscores the political delicacy of the process of decarbonising industry in carbon-dense regions: if benefit, security, and justice are not guaranteed, they may contribute instead to resentments of injustice and opposition towards climate-policy measures (Rodríguez-Pose & Bartalucci, 2024). The most effective communication and social safety nets are seen as key factors in securing this social acceptance (Buchner et al., 2025). The role of social acceptance in the region's transformation process incorporates the expert perspective in an interesting further aspect: they speak specifically of the Ruhr regions cultural background from the perspective of intangible asset value and highlight that this provides the benefit of being accustomed to changing themselves through transformation over many years. This favors a mind-set not necessarily more optimistic but more ready-to-work towards solutions. At the same time, however, they strongly argue that this social acceptance should be anticipated but fragile in the absence of trustworthy communication and social safety nets (cf. Section 5.5.2 & 5.5.3). Both views agree in assessing social acceptance in region-wise transformation processes crucial but weigh benefit and risk in social transformation differently. Within the context of Duisburgs transformation process, the existence of both transformation experiences and social participatory mechanisms may secure social support in this process if social promises are kept throughout this process.

6.5.1 CORIS, social and institutional innovation

From the perspective of CORIS, Duisburg views the change process as a highly social process. However, the strategy involves adjusting current institutions rather than introducing new ones altogether. The employment impacts are dealt with in terms of mechanisms like demographic off-ramps (early retirement schemes) coupled with reskilling through national qualification acts. Although the institutional setting shares many familiarities, a more incremental type of innovation emerges in terms of the provision of

H2 training centers in each locality. The regions co-determination system strengthens the position of unions substantially. The unions function not only as veto groups but also take proactive actions in securing employment contracts and organizational membership agreements. This fits well with the idea of new actor constellations proposed by CORIS but retain a classic structure in that civil society or NGOs are barely represented. The social trajectory that is currently in progress in this context is one of reorientation. The social structure in place works well in order to cope with this transition. A transformation towards social change would involve extending this social structure in the regional employment market.

6.6 Duisburg's Transformation Trajectory

Duisburg possesses the potential for a successful green transformation in the steel industry. This assessment rests on the following four dimensions, derived from a synthesis of the literature review (Chapter 4) and the empirical evidence (Chapter 5):

1. Regional Capabilities: The pattern in Duisburg corresponds with a reorientation of the resources. Duisburg has high capability and high lock-in. The resources in Duisburg include the steel sector and the logistics infrastructure, which both support path creation through hydrogen logistics but are strongly locked in with the high carbon path. The path dependency in this case works both ways. It provides critical mass for large-scale change but creates problems that requires careful management of legacy assets.

2. Multi-scale Alignment and Actor Agency: The region in question showcases the relationship between local activism and the level of dependence on the outside world that comes close to being absolute. The regions future in the context of the energy transition depends exclusively upon European Union policy and federal political choices. The politically constructed business case draws attention here to the fact that the region operates in a multi-scale system rather than being the core of action.

3. Depth of Restructuring and Policy Mix: The Duisburg site faces a high-ambition, but a medium-capability. The system formally has strong directionality and capability incentives but faces capacity constraints in terms of infrastructure and plant investment through permitting sequences The level of deep restructuring required only partially matches this capacity. The architecture for market nurturing exists, but orchestrative implementation lags behind.

4. Social Vulnerability and Transition: This region embodies both high exposure and high social buffers. Although sensitive to delays in the process of transformation in the region of Duisburg, Duisburg benefits from a robust labor market regime, demographic buffers, and proactive reskilling strategies. The culture of transformation provides buffers and

indicates that there are strong social foundations in place for the process a transition if the industry core remains intact.

In sum, Duisburg emerges as a region characterized by high capability levels and high levels of dependence. But on the other side with medium levels of preparation. The region has the infrastructure and the strategic context necessary for the change process. However, there are challenges in terms of infrastructure timing and market orchestration. This positive basis needs to be transformed into a continuous process.

6.6.1 Reorientation or transformation of the Duisburg steel industry?

With the conceptual framework of CORIS (Trippl, 2023) in mind, the current Duisburg trajectory is seen to be of the hybrid type with definite bias towards reorientation with emerging transformative elements as as evidenced by the literature review (Chapter 4) and empirical findings (Chapter 5).

- Technological: The technological trajectory here is incremental and integration oriented. The step-by-step addition of technologies allowed the foundational production logic of the sector to be maintained in the system. However, there is underlying transformational potential in the sudden infrastructural shift in favor of hydrogen.
- Economic: The situation marks a from challenges driven paradigm shift. The policy-created business case focuses more upon saving and de-carbonizing the current regional integrated steel sector than upon diversifying regional value production. Radical change is seen more as a risk in the future rather than current strategy.
- Governance: The institutional framework has remained quite traditional (negotiation in corporatist style, traditional financial mechanisms). The participants are now demanding the optimization of this system rather than a paradigm shift towards new governance patterns.
- Social: The approach involves a managed reorientation. The aim is employment stability via demographic off-ramps and reskill-ing. The system involves co-governance of the process by known system participants (unions and companies) and innovation in the existing corporatist framework instead of expanding system participants to include society.

Synthesizing all of these dimensions, Duisburg embarks upon an ambitious course of reorientation. The region with such high capabilities turns the current trajectory in the direction of green hydrogen and postpones the point of irreversible transformation. Whether this would finally result in transformation or not would be based upon open variables like the rate of infrastructure development, the evolution of strong markets in green technologies, or the propensity towards exnovation beyond the limits of compliance. For now, the evidence suggests that Duisburg is moving along an ambitious reorientation path, one that keeps transformative options alive, but has not yet crossed the threshold into a fundamentally new industrial regime.

7 Conclusion

This final chapter synthesizes the main research findings to answer the central research question and derives key implications for policy and practice

7.1 Answer to the research question

In this thesis, it has been questioned which technological, economic, and political factors influence the transformation of the Duisburg steel industry towards the new production concept of green hydrogen and what challenges and chances emerge with regard to the region, its residents, businesses, and the government. The result has revealed a tightly coupled multi-level system. In other words, Duisburg is not alone with the transformation of the steel industry but is part of a European energy and climate system.

Starting at the EU level, the most important drivers are the reformed EU ETS, and the Fit-55 package, the Carbon Border Adjustment Mechanism, the EU Taxonomy and innovative funding tools such as the Innovation Fund and hydrogen-related IPCEIs. These measures impose strong decarbonization pressure on conventional blast-furnace steel, secure against carbon leakages, and steer investments towards "green" investments. These instruments turn hydrogen-based direct reduction from a technological option into a politically preferred pathway. This provides Duisburg with the chance to stake out a pioneering role within the first European flagship project on green steel and hydrogen logistics. On the other hand, high costs due to CO2, tight sustainability standards, and complexity of state-aid procedures expose considerable risks. Weakening, delays, and inconsistencies within the framework of climate and industrial policy and the policy agenda on the EU level endanger the Duisburg business case, which is currently underpinning Duisburg’s transformation.

At the national level (Germany), important factors are the hydrogen and industry strategies of the German federal government, planning and implementation of the national hydrogen core grid, the paths of electricity and hydrogen prices, and dedicated support measures such as industry and infrastructure support programs. These measures partly offset the extraordinarily high investment costs and risk premia of hydrogen-based steel production and indicate the government’s intention to co-create markets rather than regulate them. In technology, the adoption of the transitional, natural gas-based phase (NG-DRI) is an essential enabler, giving companies the possibility to start the transition before hydrogen is generallyavailable. In companies and the regions view, it is a phase offering a chance to optimize the integrated Duisburg site rather than drifting into unmanaged decline. The main challenge is the chicken-and-egg dilemma where hydrogen actors wait for clarity that there is going to be enough demand for a high volume hydrogen supply, and industrial actors wait for a the security of a high volume hydrogen supply for their investments. Changes regarding funding, regulatory, and energy prices, or delays regarding core grid expansion, will instantly influence investment decisions, Duisburg site and regional competitive prospects, and employment. At the German national level, Duisburg, is a case to prove the feasibility of ambitious climate and industry policy governmental agendas regarding one of Germany's most energy-intensive basic industries.

At the regional and local level (Duisburg, Ruhr Region, NRW), the transformation is driven most importantly by the presence of the existing integrated steel cluster surrounding Thyssenkrupp, the location benefits of Europe's largest inland port and logistics location, the location within planned cross-border hydrogen corridors, and a regional tissue of initiatives and networks. An important role is also played by the regional strong tradition of co-determination and social partnership, actively promoting the transformation and enabling skill transformation. These enable strong capabilities regarding the transformation of infrastructure, the setup of a hydrogen hub, and the integration of green steel into regional value chains. They also enable Duisburg and NRW to become a role-model region regarding basic materials and industrial decarbonization, with beneficial spillovers regarding innovation and employment. At the same time, it is evident what puts the region at risk: failure and delays affecting hydrogen infrastructure, overloaded permitting authorities, and failure of priority projects. Consequently, citizens and municipalities are affected on jobs, finances, and environmental conditions by the success and failure of the transformation into green industries.

In each of these levels, the most important finding is, first, that the Duisburg transition is policy- and infrastructural-driven, and not market-driven. Green steel today, under the Duisburg transition, is founded on a politically constructed business case, which varies with various decisions regarding climate and trade agreements by the EU, government funding and support infrastructure, regional coordination, and further supported by investments in hydrogen and electricity infrastructure. In each case, exposure to uncertainty is very high, becoming a risk first to businesses, and a new role to the government and policymakers to act and share risks as active market structurators, while to the region and working classes, it promises a changed and revamped steel industry.

In CORIS terminology, the Duisburg case may be described as a challenge-oriented reorientation process with transformative elements. Decarbonizing the steel sector is obviously defined as a societal challenge, and it is inducing an adaptation of existing firms, infrastructures and institutions rather than their wholesale replacement. In contrast, the extent of technological transition, steel sector energy and hydrogen systems transformation, restructurations of cross-border interconnections, and evolving changes of respective skills and employment structures also imply a certain transformative potential. Whether such a reorientation process will develop into a new regional trajectory rests on filling the remaining gaps regarding a synchronous infrastructure, policy orchestration, long-term market formation, and societal safeguarding.

7.2 Theoretical implications (CORIS, regional pathways)

The results largely support and also specify and develop the fundamental hypotheses postulated by the CORIS and regional pathways literature. Duisburg exemplifies how a regional innovation system can substantially implement a challenge-oriented approach if and when a low-carbon steel sector can be defined and supported by a densely layered policy framework. The regional case underlines how challenge orientation is, first and foremost, closely interlinked with business case-formation and market formation by the state. In other words, ETS, CBAM, financial support by IPCEIs, hydrogen core networks, and long-term risk-sharing arrangements are not merely part of the surrounding context but are constituent elements of such an innovation system. The above argumentation bears considerable implications regarding assumed CORIS hypotheses, which propose and explore the importance of policy mix formation and, most importantly, the active role of the state and market formation.

Second, policy needs to actively foster and secure demand for hydrogen-based products, such as green steel, in Duisburg and, more generally, on the market. With respect to the Duisburg region, this could involve green public procurement and mandatory shares of low-carbon steel used, for example, in the building and infrastructure sector, as well as pushing initiatives regarding long-term offtake agreements between steel companies and large customers (such as automotive, machinery, and construction companies). If on the demand side, abundant (green) hydrogen infrastructure is paired with high and stable demand regarding hydrogen-based steel and other materials, the companies in Duisburg and, more generally, companies operating in analogous industrial areas, will face the right conditions to follow up on their transformation.

7.3 Policy and practice recommendations

The most important policy implication of this thesis is, therefore, that a successful transformation of the steel industry of Duisburg, and of other industrial areas generally, is possible only if hydrogen supply and hydrogen demand are developed simultaneously.

First, policy needs to aim to support high up-front investment in hydrogen infrastructure so that companies can finally begin to start transforming their production. In the case of Duisburg and the Rhine-Ruhr region, this will mean very early and secure integration into cross-border pipelines, import facilities, and storage as part of the German national hydrogen core infrastructure, so that high volumes of hydrogen are accessible at an attractive price. In the first phase, the hydrogen produced is not necessarily supposed to be 100% green, provided there is a clear road map defined by regulatory policy to step by step increase the maximum carbon intensity limits to zero, and provided what matters is not the origin but the cost and baselines of supply. In support of such a ramp-up of hydrogen infrastructure, procedures for permitting, planning, and approval of hydrogen pipelines, facilities, and hydrogen storage and grid investments have to finally accelerate and harmonize.

Second, policy needs to actively foster and secure demand for products based on hydrogen, such as green steel. As far as the specific case of the Duisburg region is concerned, this could occur by promoting green public procurements and quotas of low-carbon steel used in relevant areas such as the construction sector, and by fostering long-term take-off agreements between steel producers and relevant customers (such as car manufacturers, machine builders, and the construction industry, to name a few). In more general terms, it is also necessary to establish strong standards, marking, and buying regulations concerning the relevant industrial products, such that hydrogen-based products are highlighted and made economically attractive. If a robust and increasingly green hydrogen infrastructure is provided, and strong and stable demand is secured with regard to products such as hydrogen-based steel, industries operating in a region such as Duisburg, and more generally, will face the right conditions to implement the transition.

7.4 Limitations and future outlook

This thesis also has several limitations, which have to be named. Starting with the empirics, it is dedicated to a specific regional case, Duisburgs steel cluster and more specifically, to Thyssenkrupp Steel, which represents the most important incumbent. Other companies and other industrial policy paths are covered indirectly. The sample of interviews is also limited in number. More importantly, it did not include any representatives of political decision-making institutions on a municipal, regional, or federal level, due to unavailability.

Consequently, the finding of the thesis is based on how others assess and understand political paths, and not on policy-makers self-assessment. Moreover, the selection of experts, which mainly involves individuals with a specific strategic stake in the regional continuity of industrial presence, couldalso imply a potential bias towards a specific transformation path, potentially underrepresenting more critical voices on the specific issue of primary steel production viability in Germany.

Moreover, it is necessarily tied to a specific time frame within a policy sector which is changing thoroughly and very quickly, such as orientations, funding tools and regulatory frameworks regarding hydrogen support schemes, and infrastructure planning. This are variables and could develop significantly during the next several years. In concept, it is necessary to stress that the thesis sets out to apply CORIS and regional route-ways on an interpretable and qualitative basis and could not contain quantitative modeling of systems. Thus, macroeconomic global phenomena, such as the global import of green iron produced by world-regions rich in renewable resources, could merely be treated on a qualitative basis, not on a modeling level.

These constraints also raise several ways of future investigation. Comparative analysis could explore the extent to which Duisburg is unique and could generalize findings on the high capability, high lock-in transformation. Research could explore how policy mixes, hydrogen infrastructure, market creation tools, and social support evolve, given the very dynamic political surrounding, and what implications such paths may have regarding investment, and employment. Research should also integrate more the perceptions of policy makers, employees, citizens, and representatives of civil society, to further develop just transition assessment departing not only from the viewpoint provided by companies, trade unions, and experts, but also placing greater attention to more globally institutionalized perceptions.

References

Agora Industrie, FutureCamp, Wuppertal Institut, & Ecologic Institut. (2023). Klimaschutzverträge für die Industrietransformation: Aktualisierte Analyse zur Stahlbranche [Climate protection contracts for industrial transformation: Updated analysis of the steel sector] (Version 2.1). https://www.agora-industrie.de

Agora Industrie, FutureCamp, Wuppertal Institut, & Ecologic Institut. (2022). Klimaschutzverträge für die Industrietransformation: Kurzfristige Schritte auf dem Pfad zur Klimaneutralität der deutschen Grundstoffindustrie [Climate protection contracts for industrial transformation: Short-term steps on the path to climate neutrality for the German basic materials industry] (Version 1.0) [Study]. https://www.agora-industrie.de

Åhman, M., Nilsson, L. J., & Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. Climate Policy, 17(5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., & Zhang, Q. (2017). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. Journal of Cleaner Production, 163, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097

Aslam, S., Rani, S., Lal, K., Fatima, M., Hardwick, T., Shirinfar, B., & Ahmed, N. (2023). Electrochemical hydrogen production: Sustainable hydrogen economy. Green Chemistry, 25(23), 9543–9573. https://doi.org/10.1039/D3GC02849F

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. Renewable Energy, 177, 915–931. https://doi.org/10.1016/j.renene.2021.05.149

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. Energies, 13(3), 758. https://doi.org/10.3390/en13030758

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

Binti Che Ibrahim, N. S., Ramakrishan, S., Rezan, S. A., Binti Baharun, N., Alizadeh, R., & Roohi, P. (2015). Non-Isothermal Kinetic Modelling for Hydrogen Reduction of Ferric Oxide Using Matlab. Materials Science Forum, 819, 3–8. https://doi.org/10.4028/www.scientific.net/MSF.819.3

Birat, J.-P., Patisson, F., & Mirgaux, O. (2021). Hydrogen steelmaking, part 2: Competition with other net-zero steelmaking solutions – geopolitical issues. Matériaux & Techniques, 109(3–4), 307. https://doi.org/10.1051/mattech/2021023

Blöcker, A. (2022). «GRÜNER STAHL» – WIE GEHT DAS?

Bolz, S., Thiele, J., & Wendler, T. (2024). Regional capabilities and hydrogen adoption barriers. Energy Policy, 185, 113934. https://doi.org/10.1016/j.enpol.2023.113934

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bräuninger, M., Stiller, S., & Teuber, M.-O. (2022). Regionale Wasserstoffpotenziale. Wirtschaftsdienst, 102(10), 808–810. https://doi.org/10.1007/s10273-022-3304-3

Buchner, J., Menrad, K., & Decker, T. (2025). Keep it local and safe: Which system of green hydrogen production in Germany is accepted by citizens? Renewable Energy, 241, 122366. https://doi.org/10.1016/j.renene.2025.122366

Bugge, M. M., Andersen, A. D., & Steen, M. (2022). The role of regional innovation systems in mission-oriented innovation policy: Exploring the problem-solution space in electrification of maritime transport. European Planning Studies, 30(11), 2312–2333. https://doi.org/10.1080/09654313.2021.1988907

Cloete, S., Ruhnau, O., & Hirth, L. (2021). On capital utilization in the hydrogen economy: The quest to minimize idle capacity in renewables-rich energy systems. International Journal of Hydrogen Energy, 46(1), 169–188. https://doi.org/10.1016/j.ijhydene.2020.09.197

Conte, M., Rinaldi, L., Tonini, F., Fumagalli, T., Lorenzin, G., Piras, P., Sommariva, G. G., Rocco, M. V., & Colombo, E. (2022). Investigating the economic and environmental impacts of a technological shift towards hydrogen-based solutions for steel manufacture in high-renewable electricity mix scenarios for Italy. IOP Conference Series: Earth and Environmental Science, 1106(1), 012008. https://doi.org/10.1088/1755-1315/1106/1/012008

Digiesi, S., Mummolo, G., & Vitti, M. (2022). Minimum Emissions Configuration of a Green Energy–Steel System: An Analytical Model. Energies, 15(9), 3324. https://doi.org/10.3390/en15093324

Doucet, F., Blohm, M., Von Düsterlho, E., & Bannert, J. (2024). Green Hydrogen for the Energy Transition in Germany—Potentials, Limits, and Priorities. 2024 20th International Conference on the European Energy Market (EEM), 1–6. https://doi.org/10.1109/EEM60825.2024.10609015

Emonts, B., Reuß, M., Stenzel, P., Welder, L., Knicker, F., Grube, T., Görner, K., Robinius, M., & Stolten, D. (2019). Flexible sector coupling with hydrogen: A climate-friendly fuel supply for road transport. International Journal of Hydrogen Energy, 44(26), 12918–12930. https://doi.org/10.1016/j.ijhydene.2019.03.183

European Commission. (2022). The just transition dimension of industrial decarbonisation plans across the EU. Just Transition Platform.

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. Journal of Cleaner Production, 84, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063

Fløysand, A., Sjøtun, S. G., Jakobsen, S.-E., Njøs, R., Tvedt, H. L., Gjelsvik, M., & Aarstad, J. (2022). Institutional work, regional key actors, and green industrial restructuring. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography, 76(1), 14–28. https://doi.org/10.1080/00291951.2022.2040586

FNB Gas. (n.d.). Wasserstoff-Kernnetz [Hydrogen core network]. https://fnb-gas.de/wasserstofftransport/wasserstoff-kernnetz/

Gajdzik, B., Wolniak, R., & Grebski, W. (2023). Process of Transformation to Net Zero Steelmaking: Decarbonisation Scenarios Based on the Analysis of the Polish Steel Industry. Energies, 16(8), 3384. https://doi.org/10.3390/en16083384

Ganter, A., Gabrielli, P., Goericke, H., & Sansavini, G. (2024). Minimum-regret hydrogen supply chain strategies to foster the energy transition of European hard-to-abate industries (No. arXiv:2407.05988). arXiv. https://doi.org/10.48550/arXiv.2407.05988

Geels, F. W. (2022). Conflicts between economic and low-carbon reorientation processes: Insights from a contextual analysis of evolving company strategies in the United Kingdom petrochemical industry (1970–2021). Energy Research & Social Science, 91, 102729. https://doi.org/10.1016/j.erss.2022.102729

Grillitsch, M., & Hansen, T. (2019). Green industry development in different types of regions. European Planning Studies, 27(11), 2163–2183. https://doi.org/10.1080/09654313.2019.1648385

Guevara Opinska, L., Mahmoud, M., Bene, C., & Rademaekers, K. (2021). Moving towards zero-emission steel: Technologies available, prospects, timeline and costs (PE 695.484). Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament. http://www.europarl.europa.eu/supporting-analyses

Hildingsson, R., Kronsell, A., & Khan, J. (2019). The green state and industrial decarbonisation. Environmental Politics, 28(5), 909–928. https://doi.org/10.1080/09644016.2018.1488484

Isaksen, A., Trippl, M., & Mayer, H. (2022). Regional innovation systems in an era of grand societal challenges: reorientation versus transformation. European Planning Studies, 30(11), 2125–2138.

Jacobasch, E., Herz, G., Rix, C., Müller, N., Reichelt, E., Jahn, M., & Michaelis, A. (2021). Economic evaluation of low-carbon steelmaking via coupling of electrolysis and direct reduction. Journal of Cleaner Production, 328, 129502. https://doi.org/10.1016/j.jclepro.2021.129502

Jakobsen, S.-E., Uyarra, E., Njøs, R., & Fløysand, A. (2022). Policy action for green restructuring in specialized industrial regions. European Urban and Regional Studies, 29(3), 312–331. https://doi.org/10.1177/09697764211049116

Jesse, B.-J., Kramer, G. J., Koning, V., Vögele, S., & Kuckshinrichs, W. (2024). Stakeholder perspectives on the scale-up of green hydrogen and electrolyzers. Energy Reports, 11, 208–217. https://doi.org/10.1016/j.egyr.2023.11.046

Jiang, X., Wang, L., & Shen, F. M. (2013). Shaft Furnace Direct Reduction Technology—Midrex and Energiron. Advanced Materials Research, 805–806, 654–659. https://doi.org/10.4028/www.scientific.net/AMR.805-806.654

Käckenhoff, T., & Heine, F. (2024, November 25). Thyssenkrupp to cut 11,000 jobs at steel division in major corporate shakeup. Reuters. https://www.reuters.com/markets/commodities/loss-making-thyssenkupp-steel-slash-5000-jobs-by-2030-2024-11-25/

Kurrer, C. (2020). The potential of hydrogen for decarbonising steel production (EPRS Briefing, PE 641.552). European Parliamentary Research Service. https://www.europarl.europa.eu/thinktank

Lim, K. F., & Limbach, K. (2023). From the city of steel to Germany's 'China City': Economic restructuring, the EU–China transcontinental railway and infrastructure-led development in Duisburg. Regional Studies, 57(9), 1731–1746. https://doi.org/10.1080/00343404.2022.2149727

Liu, W., Zuo, H., Wang, J., Xue, Q., Ren, B., & Yang, F. (2021). The production and application of hydrogen in steel industry. International Journal of Hydrogen Energy, 46(17), 10548–10569. https://doi.org/10.1016/j.ijhydene.2020.12.123

Moritz, M., Schönfisch, M., & Schulte, S. (2023). Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. International Journal of Hydrogen Energy, 48(25), 9139–9154. https://doi.org/10.1016/j.ijhydene.2022.12.046

Mostafa, M., Ashabi, A., Hryshcenko, A., O'Callaghan, I., Bruton, K., & Sullivan, D. T. J. O. (2024). Green Hydrogen Penetration in Steel Industry Operations: A Year-long Modeling Case Study. E3S Web of Conferences, 566, 03003. https://doi.org/10.1051/e3sconf/202456603003

Muslemani, H., Liang, X., Kaesehage, K., Ascui, F., & Wilson, J. (2021). Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products. Journal of Cleaner Production, 315, 128127. https://doi.org/10.1016/j.jclepro.2021.128127

Nilsson, L. J., Bauer, F., Åhman, M., Andersson, F. N. G., Bataille, C., De La Rue Du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., Van Sluisveld, M., & Vogl, V. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. Climate Policy, 21(8), 1053–1065. https://doi.org/10.1080/14693062.2021.1957665

Njøs, R., Sjøtun, S. G., Jakobsen, S.-E., & Fløysand, A. (2020). Expanding Analyses of Path Creation: Interconnections between Territory and Technology. Economic Geography, 96(3), 266–288. https://doi.org/10.1080/00130095.2020.1756768

Oliver Wyman, & IW Consult. (2024). Die Stahlindustrie am Scheidepunkt: Wegbereiter für Transformation und gesamtwirtschaftliche Resilienz [The steel industry at a turning point: Paving the way for transformation and overall economic resilience]. Wirtschaftsvereinigung Stahl.

Pimm, A. J., Cockerill, T. T., & Gale, W. F. (2021). Energy system requirements of fossil-free steelmaking using hydrogen direct reduction. Journal of Cleaner Production, 312, 127665. https://doi.org/10.1016/j.jclepro.2021.127665

Radloff, R., Abdelshafy, A., & Walther, G. (2023). An integrative and prospective approach to regional material flow analysis: Modeling the decarbonization of the North Rhine-Westphalian steel industry. Journal of Industrial Ecology, 27(3), 662–675. https://doi.org/10.1111/jiec.13387

Rampai, M. M., Mtshali, C. B., Seroka, N. S., & Khotseng, L. (2024). Hydrogen production, storage, and transportation: Recent advances. RSC Advances, 14(10), 6699–6718. https://doi.org/10.1039/D3RA08305E

Rechberger, K., Spanlang, A., Sasiain Conde, A., Wolfmeir, H., & Harris, C. (2020). Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. Steel Research International, 91(11), 2000110. https://doi.org/10.1002/srin.202000110

Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088. (2020). Official Journal of the European Union, L 198, 13–43.

Ringsgwandl, L. M., Schaffert, J., Brücken, N., Albus, R., & Görner, K. (2022). Current Legislative Framework for Green Hydrogen Production by Electrolysis Plants in Germany. Energies, 15(5), 1786. https://doi.org/10.3390/en15051786

Rodríguez-Pose, A., & Bartalucci, F. (2024). The green transition and its potential territorial discontents. Cambridge Journal of Regions, Economy and Society, 17(2), 339–358. https://doi.org/10.1093/cjres/rsad039

Rootzén, J., & Johnsson, F. (2016). Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. Energy Policy, 98, 459–469. https://doi.org/10.1016/j.enpol.2016.09.021

Schlemme, J., Schimmel, M., & Achtelik, C. (2020). Energiewende in der Industrie: Potenziale und Wechselwirkungen mit dem Energiesektor. Branchensteckbrief der Eisen- und Stahlindustrie [Energy transition in industry: Potentials and interactions with the energy sector. Sector profile of the iron and steel industry]. Navigant Energy Germany GmbH.

Schoppengerd, S. (2024). Hydrogen corporatism and working time reduction: Union strategies in the transformation of German primary steel manufacturing.

Simic, A. K. (2022). H2-Transformation der Stahlindustrie und des Energieanlagenbaus.

Simões, F. L. D., & Santos, D. M. F. (2024). A SWOT Analysis of the Green Hydrogen Market. Energies, 17(13), 3114. https://doi.org/10.3390/en17133114

Sovacool, B. K., Herman, K. S., Iskandarova, M., & Hall, J. K. (2024). "Oh Yes! Net-Zero": Sociotechnical capabilities and regional innovation systems for British industrial decarbonization. Environmental Innovation and Societal Transitions, 51, 100852. https://doi.org/10.1016/j.eist.2024.100852

Stadt Duisburg. (n.d.). Wasserstoffstandort Duisburg | Wirtschaftsprojekte und Akteure [Hydrogen location Duisburg | Economic projects and actors]. https://www.duisburg.de/microsites/wirtschaft/projekte-themen/Kompetenzregion-Wasserstoff.php

Suer, J., Ahrenhold, F., & Traverso, M. (2022). Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. Journal of Sustainable Metallurgy, 8(4), 1532–1545. https://doi.org/10.1007/s40831-022-00585-x

Sutherland, B. R. (2020). Accelerating Green Steel in the EU. Joule, 4(9), 1860–1861. https://doi.org/10.1016/j.joule.2020.08.018

Tang, J., Chu, M., Li, F., Feng, C., Liu, Z., & Zhou, Y. (2020). Development and progress on hydrogen metallurgy. International Journal of Minerals, Metallurgy and Materials, 27(6), 713–723. https://doi.org/10.1007/s12613-020-2021-4

Tettamanzi, P., Gotti Tedeschi, R., & Murgolo, M. (2023). The European Union (EU) green taxonomy: Codifying sustainability to provide certainty to the markets. Environment, Development and Sustainability, 26(11), 27111–27136. https://doi.org/10.1007/s10668-023-03798-6 thyssenkrupp Steel Europe AG. (n.d.). Klimaneutraler Stahl – Unsere Strategie [Climate-neutral steel – Our strategy]. Retrieved December 6, 2025, from https://www.thyssenkrupp-steel.com/de/unternehmen/nachhaltigkeit/klimastrategie/klimastrategie.html

thyssenkrupp Steel. (2021). Transformation der Stahlindustrie: Die klimaneutrale Zukunft von thyssenkrupp Steel [Transformation of the steel industry: The climate-neutral future of thyssenkrupp Steel] [Position paper].

thyssenkrupp Steel. (2022, December 22). Creating facts for the transformation: Air Liquide completes hydrogen pipeline to thyssenkrupp Steel in Duisburg [Press release]. https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/air-liquide-completes-hydrogen-pipeline-to-thyssenkrupp-steel-in-duisburg.html

Tödtling, F., Trippl, M., & Desch, V. (2022). New directions for RIS studies and policies in the face of grand societal challenges. European Planning Studies, 30(11), 2139–2156. https://doi.org/10.1080/09654313.2021.1951177

Toktarova, A., Göransson, L., & Johnsson, F. (2021). Design of Clean Steel Production with Hydrogen: Impact of Electricity System Composition.

Trippl, M. (2023). Challenge-oriented regional innovation systems and strategies for sustainability transitions. In S. Schwaag Serger, L. Soete, & K. Stierna (Eds.), The Square: Putting place-based innovation policy for sustainability at the centre of policymaking (pp. 62–69). Publications Office of the European Union.

Trippl, M., Benner, M., & Baumgartinger-Seiringer, S. (2024). Regionale Innovations- und Wirtschaftspolitik in Zeiten transformativen Wandels: Der CORIS-Ansatz als Orientierungsrahmen. Standort, 48(4), 286–292.

Vilela, N. B., Castihlos, D. S., Murphy, A., & Oplotnik, Ž. J. (2024). EU's "Fit for 55" plan, its economic impact and intergovernmental perspective. Journal of Infrastructure, Policy and Development, 8(9), 8445. https://doi.org/10.24294/jipd.v8i9.8445

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production, 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279

Vogl, V., Åhman, M., & Nilsson, L. J. (2021). The making of green steel in the EU: A policy evaluation for the early commercialization phase. Climate Policy, 21(1), 78–92. https://doi.org/10.1080/14693062.2020.1803040

Vogl, V., Rootzén, J., & Svensson, O. (2019, June). A just transition towards a coal-free steel industry: Perspectives from labour [Conference presentation]. Nordic Environmental Social Science Conference (NESS 2019), Luleå, Sweden.

Voß, J.-P., Smith, A., & Grin, J. (2009). Designing long-term policy: Rethinking transition management. Policy Sciences, 42(4), 275–302. https://doi.org/10.1007/s11077-009-9103-5