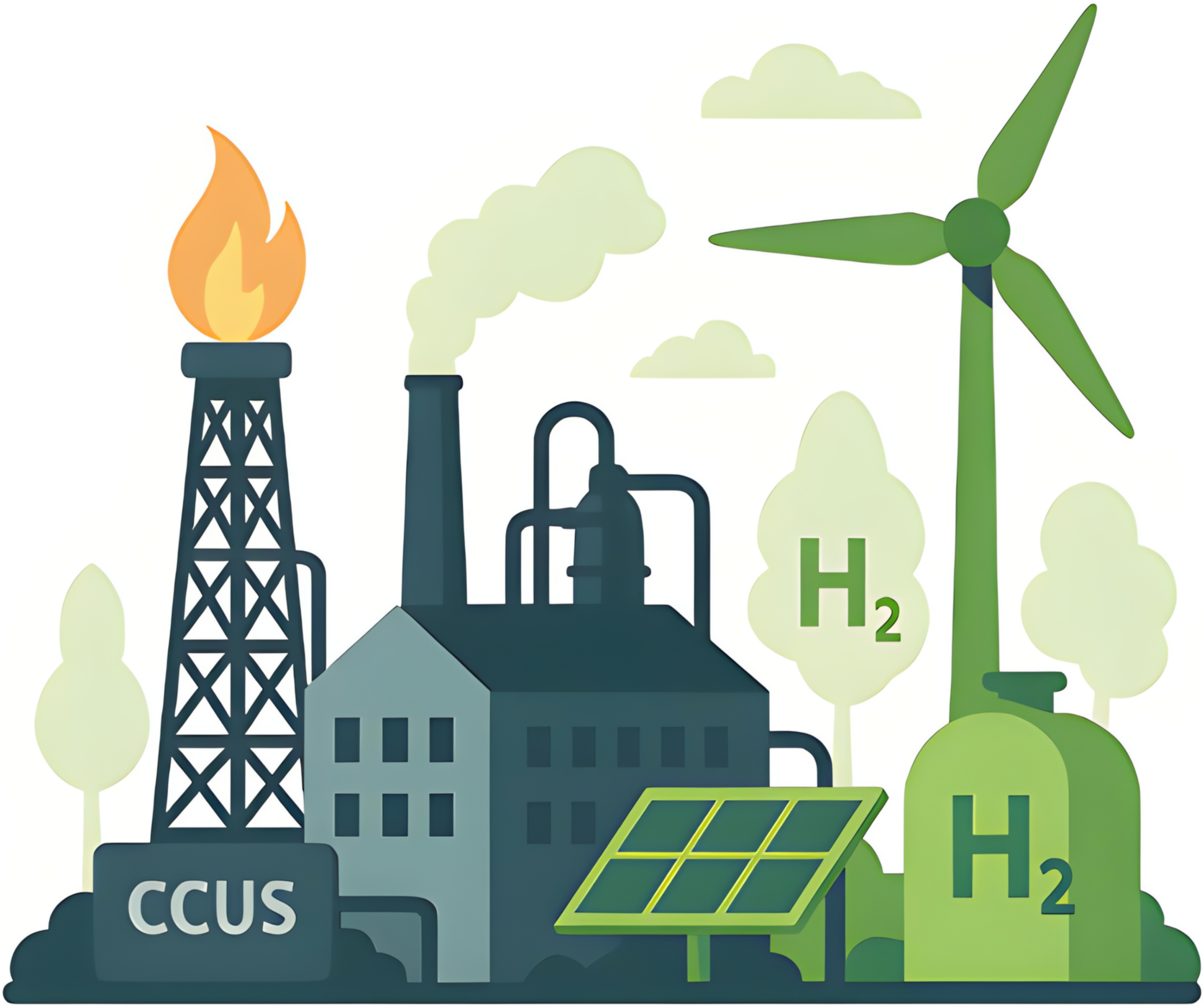
From fossil to green:

Driving the de-carbonization of energy-intensive industries



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Y.C. Wind

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TU Delft

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Ylse Wind
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Executive summary

Since 1990, global Carbon dioxide (CO_2) emissions have risen by nearly 50%, with energy-intensive industries playing a major role in this upward trend. In response, the 2015 Paris Agreement mobilized international efforts to limit global warming to a maximum of 2°C, preferably to 1.5°C. This has spurred ambitious climate policies worldwide. At the European level, the Green Deal and the "Fit for 55" package set binding goals: climate neutrality by 2050 and at least a 55% reduction in emissions by 2030. These targets place significant pressure on heavy industries such as steel, cement, chemicals, and refining to fundamentally transform their operations. These sectors are not only responsible for a large share of global emissions, but also face unique challenges in de-carbonization due to their reliance on fossil fuels, high-temperature processes, and capital-intensive infrastructure. While technological solutions like electrification, carbon capture, and green hydrogen are being developed, their successful deployment requires more than innovation alone. It demands deep changes in how these industries are organized, operated, and maintained on a day-to-day basis.

Among these sectors, steelmaking is especially critical, both for its economic importance and its high carbon footprint. This thesis examines how such a transformation can unfold in practice by focusing on a leading case: Tata Steel IJmuiden. While much public and academic attention is given to breakthrough technologies and national policies, this research shifts focus to the practical dimension of transition. Specifically, it explores how de-carbonization strategies are translated into organizational routines, systems, and responsibilities at the micro plant level while considering the meso- and macro- contextual factors in which the transition takes place. Using Tata Steel's Green Steel plan as a case study, the research investigates what Operations and Maintenance (O&M) shifts are needed to ensure that de-carbonization efforts are not only technologically possible but also organizationally sustainable and safe.

To address this, the study poses the following main research question: *"How can large energy-intensive industries transition towards de-carbonization in practice?"* Although the main research question focuses on large energy-intensive industries in general, all sub-questions specifically examine Tata Steel IJmuiden as the case on which the results are based:

- **Sub-question 1**: *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden entail?"*
- **Sub-question 2**: *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"*
- **Sub-question 3**: *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"*
- **Sub-question 4**: *"What changes in Operations & Maintenance are required to support Tata Steel's de-carbonization transition?"*

To explore these questions, the study used a qualitative narrative case study design, combining a literature review with semi-structured expert interviews and thematic analysis through a hybrid coding approach. Data was triangulated across academic sources, technical documentation, and first-hand perspectives from within the organization. In addition, expert knowledge synthesis and integration played a role in the analysis of the data. This involved synthesizing the tacit, experience-based insights of academic and industry supervisors into the interpretive process through reflective dialogue and supervision. Furthermore, the case was studied through a strategy-as-practice lens, which allowed close attention to how strategic transformation unfolds through everyday operational decisions and practices.

The case study research revealed that Tata Steel's de-carbonization strategy is centered around the substitution of old technologies by phasing out blast furnaces and introducing hydrogen-based Direct Reduction Plant (DRP) and Electric Arc Furnace (EAF) technologies. The strategy consists of two phases: by 2030, one DRP and EAF unit will be installed, allowing the shutdown of a major blast furnace and coking plant, and by 2037, a second unit will complete the transition. This transformation at the micro plant level, expected to reduce CO_2 emissions by 8.8 million tonnes annually, is deeply influenced by meso- and macro-level conditions such as the availability and cost of green hydrogen and electricity, regulatory frameworks, financial support, spatial constraints, and environmental requirements. These meso and macro drivers significantly shape the technical, operational, and organizational design of the transition.

The study highlights that O&M is not a passive function supporting technology change, but a core enabler that ensures the new green infrastructure operates reliably, safely, and efficiently. In the future hydrogen-based plant, O&M practices will be built around Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE) principles. Time- and condition-based maintenance will replace legacy routines, and a closer integration between O&M teams will be required, especially as systems are less automated and more reliant on real-time human interventions. Safety becomes a dominant concern, particularly with the introduction of hydrogen. New protocols, extensive retraining, and strict oversight through specialized hydrogen safety bodies will be necessary. The study also outlines key organizational changes, including new partnerships with Original Equipment Manufacturer (OEM), a new hydrogen committee, restructured maintenance contracts, and an expanded role for digital asset management systems to accommodate tens of thousands of new equipment components. A shift in operator roles, from passive monitoring to active process control, marks a major transformation in how labor is structured, trained, and managed.

Importantly, the analysis shows that industrial transformation cannot proceed through isolated or linear actions. Instead, it depends on the careful coordination of multiple interdependent strategies. Substitution of old technologies, while not a de-carbonization strategy in itself, plays a critical enabling role. By reshaping the technical, operational, and digital foundations of the industrial system, it allows for the integration of other low-carbon pathways such as hydrogen use, electrification, and carbon capture. In doing so, it initiates a series of ripple effects across organizational domains, triggering new safety risks, operational routines, skill demands, and digital infrastructures that must be actively managed through adapted O&M.

In sum, the thesis identifies three pillars essential to the success of this de-carbonization transition in practice: (1) technical adaptation and digitalization to accommodate new technologies, (2) workforce safety and competency transformation to operate and maintain high-risk systems, and (3) organizational restructuring and stakeholder integration to align the complexity of the transition across internal and external actors. These findings suggest that achieving climate neutrality in heavy industry is not only a matter of technological readiness but also of deep operational transformation. By examining the steel industry's transition at the plant level through a narrative case study, this research offers insights that can guide other energy-intensive sectors pursuing similar de-carbonization strategies. It highlights that success depends not only on what technologies are adopted but on how Operations & Maintenance adapt to make those technologies work, safely, reliably, and sustainably. Future experiments in industrial de-carbonization would benefit from early integration of O&M considerations into the planning and implementation of green transitions.

Keywords: De-carbonization, energy-intensive industries, steel industry, hydrogen, operations and maintenance, Strategy-as-Practice, narrative case study

Acronyms

AE Alkaline Electrolyzer

AER Activities Environmental Regulations

AI Artificial Intelligence

BER Building Environmental Regulations

BF Blast Furnace

BOF Basic Oxygen Furnace

CAPEX Capital Expenditure

CBM Condition-Based Maintenance

CC Carbon Capture

CCS Carbon Capture and Storage

CCU Carbon Capture and Utilization

CCUS Carbon Capture Utilization and Storage

CH_4 Methane

CO Carbon monoxide

CO_2 Carbon dioxide

H_2O Water

CS Crude Steel

DRP Direct Reduction Plant

DRI Direct Reduced Iron

EAF Electric Arc Furnace

EIA Environmental Impact Assessment

EPCM Engineering, Procurement and Construction Management

ECSC European Coal and Steel Community

ETS Emission Trading System

Fe Iron

Fe_2O_3 Iron ore

FMECA Failure Mode, Effects, and Criticality Analysis

GDP Gross Domestic Product

GDPR General Data Protection Regulation

H_2 Hydrogen

HAZOP Hazard and Operability Study

HREC Human Research Ethics Committee

IoT Internet of Things

LOCH Liquid Organic Hydrogen Carrier

MoT Management of Technology

MTBF Mean Time Between Failures

N_2 Nitrogen

NDA Non-Disclosure Agreement

NOx Nitrogen Oxides

O_2 Oxygen

OEM Original Equipment Manufacturer

O&M Operations and Maintenance

OPEX Operational Expenditure

PAH Polycyclic Aromatic Hydrocarbons

PDCA Plan-Do-Check-Act

PEME Proton Exchange Membrane Electrolyzer

PHA Preliminary Hazard Analysis

PFD Process Flow Diagram

P&ID Piping and Instrumentation Diagram

RAMSHE Reliability, Availability, Maintainability, Safety, Health and Environment

RBM Risk-Based Maintenance

RCA Root Cause Analysis

RCM Reliability-Centered Maintenance

R&D Research and Development

SAP Systems, Applications, and Products

SasP Strategy as Practice

SMR Steam Methane Reforming

SOE Solid Oxide Electrolyzer

SR Steam Reforming

SRQR Standards for Reporting Qualitative Research

TRL Technology Readiness Level

ZZS Zeer Zorgwekkende Stoffen (highly concerning substances)

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1 Introduction

Since 1990, global CO_2 emissions have increased by nearly 50%, with the fastest growth between 2000 and 2010 (Cordonier Segger, 2016). In response, the Paris Agreement was adopted in 2015, committing 197 countries to limit global warming well below 2°C, preferably to 1.5°C, compared to pre-industrial levels (UNFCCC, 2016). This landmark accord has driven ambitious climate policies worldwide. The European Union's response includes the European Green Deal ("European Green Deal", n.d.), aiming for climate neutrality by 2050, and the "Fit for 55" package, which raises the 2030 emissions reduction target to at least 55% ("Fit for 55", n.d.). Key mechanisms such as the EU Emission Trading System (ETS) incentivize emissions cuts in energy-intensive sectors, while policies promote renewable energy and the development of a hydrogen economy. These frameworks create strong drivers for industries to transition toward sustainability. Energy-intensive industries globally consume about 20% of total energy, with light industries adding another 15%, representing 35% of global energy demand, as displayed in Appendix A (International Energy Agency, n.d.).

Among these sectors, the iron and steel industry is the largest energy consumer within industry, accounting for 36% of industrial energy use in 2019 (International Energy Agency, n.d.). De-carbonizing steel production is uniquely challenging due to its reliance on coal, extremely high temperature processes, and long plant lifecycles. Despite efforts to improve energy efficiency, the sector remains one of the top global CO_2 emitters, necessitating a fundamental shift toward new technologies like green molecules. Beyond its environmental footprint, steel production is critical to the global economy, directly employing over six million people and supporting 40 million jobs worldwide (J. Kim et al., 2022). The sector's outputs underpin many other industries, amplifying the impact of decarbonization efforts. In the European context, steel remains a strategically vital product, essential for infrastructure, defense, energy systems, and manufacturing. The sector provides millions of jobs and supports a wide industrial ecosystem, making its sustainability crucial not only for climate goals but also for economic and geopolitical resilience.

In the Netherlands, the importance of steel production is deeply rooted in history. During both World Wars, disrupted steel imports compelled the country to establish its own steelmaking capacity to ensure self-sufficiency in this critical material. Post-war, the Dutch steel industry became a pillar of European cooperation through the European Coal and Steel Community (ECSC), which aimed to secure peace and economic stability by integrating essential industries (Elderkamp, 2023). Today, Tata Steel IJmuiden produces approximately 7 million tonnes of steel annually and plays a major economic role. It employs 9,200 people directly and supports around 86,000 jobs nationwide, about 1% of total employment in the Netherlands, and contributes roughly 6% to the national Gross Domestic Product (GDP) (Tata Steel, n.d.-b; Van den Berg et al., 2022). However, this industrial footprint also comes with considerable environmental challenges. Tata Steel is one of the biggest sources of CO_2 emissions in the Netherlands and has come under growing criticism for the air pollution it causes and the negative effects on the health of people living nearby (Koster, 2023).

At the same time, geopolitical tensions, disrupted global trade, and increased focus on strategic autonomy have reignited discussions around the importance of maintaining domestic steel production. While closing the plant might end active emissions and pollution, it would leave behind a legacy of heavily contaminated soil, with cleanup costs estimated in the billions, a burden likely to fall on taxpayers (Beetsma, 2025; van Tulder, 2025). Therefore, rather than phasing out the industry, it is essential to explore how steel production can become greener, cleaner, and more circular. Tata Steel's announcement of the Green Steel plan marks a step in this direction (Green Steel Plan, n.d.).

This thesis explores a crucial yet often under-examined dimension of the steel industry's transition: the O&M transformations required when shifting from fossil-based processes to green molecules such as hydrogen by replacing old technologies. While much attention is given to technological innovations and policy frameworks, the day-to-day functioning of plants, how they are run, maintained, and adapted during the transition, plays a vital role in achieving long-term climate neutrality. By focusing on Tata Steel IJmuiden as a case study, this research aims to uncover how large energy-intensive facilities can effectively manage this transformation in practice, ensuring operational resilience, safety, and sustainability throughout the journey towards a green future.

1.1. Research questions

Building on the focus of this thesis, how O&M practices must evolve as energy-intensive industries shifts from fossil-based processes to green alternatives like hydrogen, this section outlines the central questions guiding the research. While technological innovation is critical, the success of the transition also depends on how day-to-day operations are adapted and sustained during and after this shift. This study looks beyond just production technologies, exploring how energy-intensive facilities like Tata Steel IJmuiden can navigate the broader, interconnected changes required to become net-zero by 2050. It places the transition into the broader context by looking at the contextual factors that influence the transition, such as the hydrogen supply and infrastructure, permits and the costs of green steel, as well as linking the case study findings back to other industries. The research aims to provide practical, grounded recommendations that consider both internal operations and external factors influencing the transition. The main research question and sub-questions are as follows:

Research question: *"How can large energy-intensive industries transition towards de-carbonization in practice?"*

Although the main research question is focused on large energy-intensive industries in general, all sub questions specifically focus on the O&M of Tata Steel IJmuiden as a case study. This plant is used as the case on which the results are based. Within this case study the practice on which will be focused is O&M.

Sub question 1: *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden entail?"*

Sub question 2: *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"*

Sub question 3: *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"*

Sub question 4: *"What changes in Operations & Maintenance are required to support Tata Steels de-carbonization transition?"*

By addressing these questions, this research aims to support the de-carbonization of other energy-intensive plants in practice. The insights gained have broader applicability for companies integrating hydrogen or new technologies into their operations, ultimately accelerating the transition to climate neutrality by 2050. The results of the sub questions contribute to answer the research question as depicted in Figure 1.1.

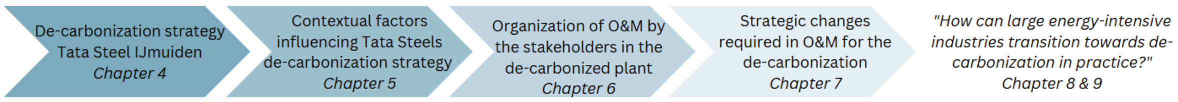

Figure 1.1: Visualisation of the literature review and sub questions leading to an answer on the main research question.

1.2. Focus of the study

This thesis adopts a systematic approach to explore how large energy-intensive industrial plants can transition toward de-carbonization in practice, with a specific focus on O&M. The research is structured around a single in-depth case study: Tata Steel IJmuiden. To analyze the complexity of the transition, the system is examined across three interrelated levels: micro, meso, and macro.

The framework of macro-meso-micro levels, derived from the SasP literature and particularly from Jarzabkowski and Whittington, 2008, is employed to structure the analysis. This approach allows for a nuanced examination of how strategic intent (macro), organizational structures and inter-organizational networks (meso), and day-to-day operational practices (micro) interact and influence each other during large-scale industrial transitions. For a more detailed discussion of the Strategy-as-Practice framework and its relevance to this study, see Section 2.4. Although these levels provide analytical clarity, it is recognized that they are not always sharply delineated in practice; overlaps and cross-level interactions are common and have been considered in the analysis. The framework is therefore used as a guiding heuristic to examine the interdependencies across scales rather than as a rigid categorization.

To support this structure, Figure 1.2 visualizes the multi-level analytical framework used in this thesis. It shows how the macro, meso, and micro levels are interrelated and how the sub-questions and corresponding chapters are distributed across these levels. This figure serves as a guide to understand how the research systematically addresses each dimension of the de-carbonization transition.

- The **macro** level addresses de-carbonization strategies of energy-intensive industries and Tata Steel's overarching de-carbonization strategy in particular. It also includes the broader institutional, regulatory, and societal context. This includes permitting procedures, national and European climate policy, and public expectations, all of which influence the direction and pace of the transition.

- The **meso** level concerns the Tata Steel site and its position within the broader steel value chain. It considers contextual factors such as the integration of new supply chains (e.g., hydrogen and electricity), spatial constraints, and interactions with other industrial actors. In this thesis, the meso level is understood not only in terms of intra-organizational processes and routines but also includes inter-organizational dynamics such as supply chains, infrastructural dependencies (e.g., hydrogen networks), and spatial-industrial integration. While the meso level is not the primary focus, it helps contextualize how external infrastructural and organizational conditions influence the feasibility of operational change.

- The **micro** level focuses on the practice and praxis of O&M as performed by the practitioners at the Tata Steel plant. It investigates how internal operational practices, such as maintenance routines, technical processes, operations and organizational roles, must evolve to align with the de-carbonization goals.

First, the theoretical background in Chapter 2 examines general macro-level de-carbonization strategies in energy-intensive industries. The remainder of the research, including the sub-questions, is structured as follows:

1. The first sub question, *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden look like?"*, and Chapter 4 explore the macro-level de-carbonization strategy of Tata Steel's transition, focusing on the planned technological and organizational transformation, particularly the shift from the current production process to a hydrogen-based Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF) system.

2. The second sub question, *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"*, and Chapter 5 links the macro and meso contextual factors with the micro-level by investigating how institutional, infrastructural, and organizational factors; such as permitting, supply chains, spatial constraints, and energy infrastructure, affect the realization of the de-carbonization strategy and the O&M practices.

3. The third sub question, *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"*, and Chapter 6 examines how O&M is being reimagined in the future steelmaking process, including the roles and responsibilities of the stakeholders involved in O&M at the micro plant level.

4. The fourth question, *"What changes in Operations & Maintenance are required to support Tata Steels de-carbonization transition?"*, and Chapter 7 continues at the micro level, analyzing the required changes in routines, skills, tools, and coordination necessary for maintaining the new production technologies and supporting the de-carbonization strategy.

The main research question focuses on how de-carbonization strategies are operationalized in practice within energy-intensive industries. Specifically, it examines how high-level strategic ambitions are translated into tangible changes in the daily practices of O&M. By exploring this process, the thesis aims to bridge the gap between policy-level objectives and plant-level execution. Through the case of Tata Steel IJmuiden, it investigates how such transitions are experienced, managed, and structured within real industrial environments. Ultimately in Chapter 8 & 9, the findings from this case are used to reflect back on the macro industry level, offering insights into how micro-level practices can support broader de-carbonization strategies across all energy-intensive industries.

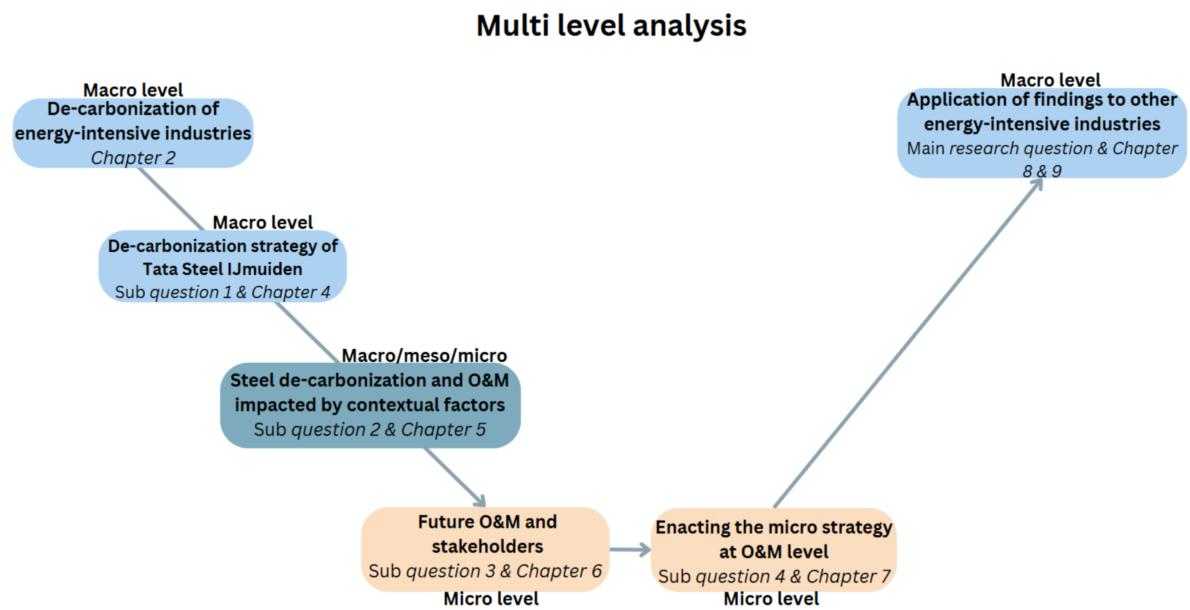

Figure 1.2: Visualization of the multi level analysis throughout the thesis with the dedicated chapters indicated.

1.3. Changing context

The transition towards de-carbonized steel production is taking place in an increasingly uncertain and rapidly changing global context. These challenges significantly influence the progress of green steel initiatives. For instance, in early 2025, the United States announced the introduction of tariffs on steel imports, a decision that is expected to impact the European steel industry. In Germany, ThyssenKrupp recently stated that it intends to revise its plans due to the technical, economic, and political uncertainties of the current time. Similarly, ArcelorMittal in France declared that it would only proceed with investments if the EU provides greater clarity on key issues affecting the steel industry's future, such as high energy prices and the availability of hydrogen (Directoraat-generaal

Bedrijfsleven & Innovatie, 2025).

The European steel industry is under considerable pressure and faces challenges such as increased energy costs and competition from increased steel imports from China. In addition, the German automotive sector, one of the largest consumers of Tata Steel products, is experiencing significant difficulties due to import tariffs and stricter environmental regulations. These factors put Tata Steel Netherlands in a challenging position, requiring the company to reduce costs to maintain its operations while continuing its investments in green transitions and efforts to mitigate pollution in the surrounding environment (Directoraat-generaal Bedrijfsleven & Innovatie, 2025). Given this dynamic and uncertain context, this thesis focuses on Tata Steel Netherlands' green steel plan as announced in November 2023 (Green Steel Plan, n.d.). Even if the plans evolve during the course of this research, the November 2023 green steel plan remains the central case under investigation.

1.4. Arcadis

This thesis was conducted in collaboration with Arcadis, an international design and engineering firm active in projects related to infrastructure, environmental services, and industrial transformation. Arcadis supports clients in navigating complex sustainability challenges, particularly those involved in transitioning toward lower-emission, more resilient operations. The focus on O&M is closely aligned with Arcadis' broader interest in improving the performance and sustainability of industrial systems. O&M plays a crucial role in ensuring that new technologies and processes are not only implemented, but also effectively integrated into day-to-day practice. Well-designed O&M strategies can extend asset lifetimes, increase efficiency, reduce emissions, and improve safety, making them a key lever in achieving sustainability goals. This research contributes to Arcadis' internal knowledge on how energy-intensive industries, such as steelmaking, can adapt their O&M models in response to new environmental standards and technological developments. More broadly, it offers insights into how O&M can support system-level transitions, providing value beyond the immediate case. The findings may help future projects on sustainable industrial transitions, contributing to wider efforts to align operational practices with long-term climate and environmental objectives. Furthermore, the business unit at Arcadis where the internship and thesis research were conducted has no active business relationship with Tata Steel. This organizational distance helped ensure that the research was not steered by commercial interests, allowing for independent analysis and maintaining the integrity of the findings.

1.5. Groeien met Groen Staal

This thesis contributes to the mission of the Dutch national consortium *Groeien met Groen Staal*, which aims to develop a circular, de-carbonized, and high-tech steel industry in the Netherlands by 2050. The consortium brings together Dutch universities, including TU Delft, research institutes, and industrial partners such as Tata Steel, to collaboratively accelerate the transition to green steel through an integrated approach. This includes not only technological innovation, but also changes in the value chain and the societal changes required to support system-wide transformation. The research presented in this thesis aligns with this mission by using Tata Steel IJmuiden as a case study, this work contributes to knowledge on the micro plant-level operational dynamics and their connection to the broader macro system change, this thesis supports the consortium's goal of maintaining international technological leadership and economic competitiveness. Moreover, the involvement of two thesis supervisors who are also part of the consortium ensures close alignment and relevance to ongoing collaborative research efforts.

1.6. Positionality

My background as a student at TU Delft, combined with my Dutch upbringing and internship at Arcadis, shaped the lens through which I approached this research. TU Delft's academic environment provided a solid foundation in systems thinking and sustainability, especially through my Bachelor's degree in Molecular Science & Technology, which emphasized quantitative methods and analytical rigor. During my Master's in Management of Technology, I built on this technical foundation and engaged with interdisciplinary topics in innovation, policy, and systems design. Although this was my first time conducting qualitative research, including interviews and observations, I had previous experience with independent research projects and was introduced to qualitative research methods through my MSc coursework.

Throughout this thesis, I alternated between two roles: that of a student and that of an intern. In academic settings, I emphasized learning and inquiry, which encouraged openness and information sharing from stakeholders. In professional contexts, I aligned with Arcadis' strategic objectives, demonstrating a practical and solution-driven mindset that helped foster trust and cooperation. Culturally, growing up in the Netherlands influenced my preference for direct communication, collaboration, and a pragmatic approach to problem-solving. At the same time, my international study and work experiences helped me develop adaptability in diverse cultural and organizational contexts. This flexibility proved especially valuable in navigating a research topic situated at the intersection of social, political, and technical complexity.

I also recognize that my positioning may have introduced certain biases. My association with Arcadis could have influenced me to emphasize organizational perspectives or to frame findings in ways that align with consultancy-driven approaches. My technical and systems-oriented academic background may have predisposed me toward solution-focused thinking over political or community-based framings. Furthermore, entering the steel industry and industrial research contexts as a newcomer meant that I had to invest additional effort in understanding industry-specific language, dynamics, and sensitivities. To mitigate these potential biases, I actively aimed for a diversity of stakeholder perspectives, maintained transparency in data handling and interpretation, and continuously reflected on my own assumptions throughout the research process. By acknowledging and navigating my positionality, I aimed to produce research that is not only methodologically robust but also socially relevant.

1.7. Thesis outline

This thesis is structured to guide the reader through the complex transition of Tata Steel's IJmuiden plant toward a sustainable and low-carbon future. Each chapter builds upon the previous one to deepen understanding, starting with a theoretical foundation, moving through the practical case study, and concluding with analysis and reflection. This helps to contextualize the challenges, strategies, and operational changes required for a successful transition. The research is informed by a multi-level analytical framework that distinguishes between micro, meso, and macro levels of analysis, which is included throughout the different chapters of the thesis as displayed in Figure 1.2. These levels provide an integrated lens through which to understand the multi-level nature of industrial transformation and how site-specific decisions are embedded in wider structural contexts.

Chapter 2 provides the theoretical background on de-carbonization strategies in energy-intensive industries at the macro level. This chapter introduces the core concepts, technologies, and O&M practices that frame Tata Steel's de-carbonization transition. It situates the case study within a broader academic discourse, enabling later findings to be grounded in existing literature. It also introduces the SasP framework as the lens through which this research will be analyzed. Chapter 3 explains how the research was designed and conducted methodologically. This chapter is key to establishing the scientific rigor of the thesis by transparently describing the research design, the literature review, interviews, the synthesis and integration of expert knowledge, and considerations of validity and reliability. It builds confidence in the robustness of the results. The chapter concludes with the used tools and software with a reflection on the use of Artificial Intelligence (AI).

Chapter 4 presents the Tata Steel case as a practical example of an energy-intensive industry undergoing a de-carbonization transition. This chapter is the base for the remaining of the research since it explores the de-carbonization strategy at the macro level as planned by Tata Steel. It translates theoretical concepts into a real-world setting, revealing the complexity and uncertainties inherent in such industrial transformations. Chapter 5 focuses on meso- and macro-level factors influencing the transition at the micro plant level, including hydrogen and green electricity supply, costs, regulations, safety, and operational management. Understanding these external factors is critical because they define the environment within which strategic decisions are made and affect the feasibility of the transition. This chapter places the case in a wider context and shows how external pressures shape operational realities.

Chapter 6 explores future operational management practices at the micro plant level. This chapter is vital because it highlights the concrete adaptations by the stakeholders and new routines necessary to enable the de-carbonization transition, bridging the gap between strategy and day-to-day operations. Chapter 7 analyzes the differences between current and future operational management and discusses required changes in strategy at the micro plant level. This analysis is important for identifying the organizational and technical challenges that must be addressed for successful implementation.

Chapter 8, the discussion, links the findings of the case study back to the macro level of the analysis by looking other energy-intensive industries and their potential de-carbonization strategies. It examines the implications for O&M as practice within different de-carbonization strategies, it looks at possible interactions amongst de-carbonization strategies. It discusses the potential barriers to de-carbonization transitions as well as the contradictions and uncertainties in de-carbonization transitions.

After this broader contextualization, Chapter 9, synthesizes the main findings related to the sub-questions and provides a conclusive answer to the main research question: *"How can large energy-intensive industries transition toward de-carbonization in practice?"* This final chapter integrates the insights across all analytical levels and highlights the practical and theoretical contributions of the study. After answering the main research question, a reflection on the interviews and the researcher's role and potential biases enhances the transparency and the credibility of the thesis. Furthermore, the chapter discusses the contributions of this research to science and practice. After which the chapter states the limitations of this research and the thesis concludes with recommendations for practice and future research directions. Together, the chapters offer a comprehensive perspective on the technical, organizational, and contextual challenges of sustainable industrial transformation.

1.8. Relevance for Master Management of Technology

This thesis is highly relevant to the Master in Management of Technology (MoT), as it examines a large-scale technological transition in a complex industrial setting, focusing on the role of O&M in the de-carbonization of industries. The work reflects the central themes of the MoT program, such as managing technological innovation, understanding systemic change, and aligning technological developments with organizational strategy and operational execution. The research explores how the adoption of a de-carbonized steelmaking practice affects not only the core production technology but also the wider organizational and operational context. It highlights the challenges and implications of transitioning from fossil-based to hydrogen-based steelmaking, a shift that is embedded in broader societal, regulatory, and environmental dynamics. This aligns with the program's emphasis on understanding how technological change is influenced by, and in turn influences, actors, institutions, and external environments. By investigating how a major firm like Tata Steel manages uncertainty, coordinates complex planning processes, and adapts its operational practices, the thesis contributes to insights on how firms respond to emerging technologies and shifting stakeholder expectations. This perspective resonates with the program's focus on strategic technology management and long-term thinking in innovation processes.

In conducting this research, scientific methods were applied to investigate real-world problems in a corporate context. Through qualitative research, interviews, and document analysis, the thesis provides a structured and evidence-based analysis of a technological transition, demonstrating the ability to operationalize abstract innovation challenges into concrete organizational implications. Overall, this thesis exemplifies how MoT graduates are trained to analyze complex technological systems, understand innovation dynamics, and develop actionable recommendations for organizations navigating transitions. It contributes to the core mission of the program: preparing professionals who can manage technology in a way that addresses pressing societal challenges while delivering value to businesses.

2

Theoretical background

To effectively address the research question, "*How can large energy-intensive industries transition towards de-carbonization in practice?*", the research has been divided into three core areas. These areas served as the foundation for the literature search, ensuring that each component of the question was explored and adequately addressed as shown in Figure 2.1.

The first Section (2.1) focused on identifying potential de-carbonization strategies in energy-intensive industries. This is done in order to get a broad overview of which technologies can be used to de-carbonize industries, as well as an overview of the barriers and benefits for such a transition as well. The second Section (2.2) zooms in on understanding the de-carbonization of the steel industry as a specific energy-intensive industry, with a particular focus on Tata Steel in the Netherlands as a case study. The steel industry is one of the most energy-intensive sectors, and its environmental impact makes it a significant contributor to Carbon dioxide (CO_2) emissions. Literature exploring the production processes, emissions sources, and case-specific studies of Tata Steel was prioritized. Key technologies discussed include several de-carbonization methods, such as the use of green hydrogen, ammonia-based solutions, and Carbon Capture and Storage (CCS). Literature addressing these innovations and their applicability to the steel industry was included. The third explored area, Section 2.3, zooms in even further, on the role of Operations and Maintenance (O&M), as a practice at the micro-plant level, in enabling the de-carbonization strategies. O&M practices are critical for ensuring the efficiency, reliability, and safety of new technologies, particularly in large energy-intensive plants.

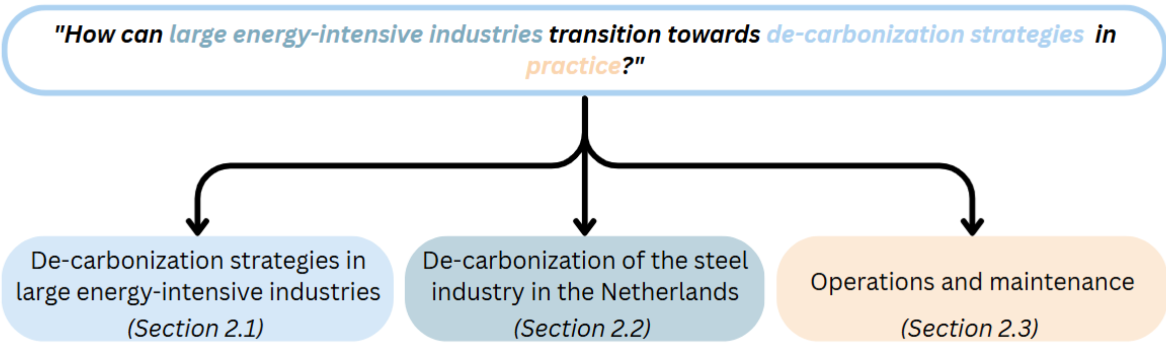

Figure 2.1: Overview of the literature review topics aimed at identifying relevant areas of research to address the research question.

To study how strategic decisions around O&M are made during such transitions, this thesis drew on the Strategy as Practice (SasP) perspective, elaborated in Section 2.4. This approach emphasizes the day-to-day practices, routines, and micro-level actions through which strategic change is enacted. Following this literature review and theoretical framing, this chapter discusses the knowledge gap addressed in this research in Section 2.5 and outlines its scientific contribution in Section 2.6.

2.1. De-carbonization strategies in large energy-intensive industries

The reviewed literature highlights a broad array of strategies, barriers, and benefits associated with de-carbonizing energy-intensive industries, providing valuable insights into opportunities and challenges. All the reviewed articles with their de-carbonization strategies, barriers and benefits are summarized in Appendix B, Table B.1. This section will discuss the main de-carbonization strategies found, as well as barriers to de-carbonization and the benefits of de-carbonizing industries.

2.1.1. De-carbonization strategies

Energy-intensive industries employ a variety of strategies to reduce carbon emissions, as summarized in Table B.2. Among the most frequently mentioned approaches, energy efficiency stands out as a universal strategy, cited in 9 out of 10 articles. Industries optimize processes to minimize energy consumption, showcasing the widespread applicability of this method. Another widely discussed strategy is Carbon Capture Utilization and Storage (CCUS), mentioned in 8 articles. This technology is considered a key pathway for reducing industrial emissions across all sectors. Recycling and reuse of materials also emerged as a significant approach, cited in 8 articles, though it is less relevant to the oil refining industry. The integration of hydrogen into industrial processes is another prominent strategy, highlighted in 8 articles. Hydrogen serves as a versatile de-carbonization tool, either as a combustion agent for heating or as a reduction agent in processes requiring high temperatures, such as steel production. Waste heat recovery and heat management were identified in 6 articles as effective strategies for improving energy efficiency. Similarly, electrification and the use of renewable energy sources were both mentioned in 5 articles, emphasizing the shift away from fossil fuels to cleaner energy options. Less frequently mentioned strategies include circularity, digitization, substitution of outdated technologies, raw material optimization, bio-energy with CCS, use of by-products, novel formulas, batch preheating, and sustainable packaging. These approaches, although cited less often, provide additional avenues for de-carbonization tailored to specific industrial needs.

2.1.2. Barriers to de-carbonization

Despite the availability of effective strategies, industries face several challenges in implementing de-carbonization measures, as outlined in Table B.3. The most prominent barriers are financial and economic challenges, mentioned in 9 articles. High upfront costs for implementing new technologies often deter industries from transitioning to low-carbon processes, especially in sectors with low profit margins. Organizational and managerial barriers were identified in 7 articles, highlighting resistance to change within industrial organizations. Successful de-carbonization requires managerial alignment and workforce training to overcome inertia and foster adoption of new practices. Technological barriers remain significant, mentioned in 4 articles. Many de-carbonization technologies are still in the demonstration phase and lack proven scalability for large production processes. Performance uncertainties and integration challenges further hinder adoption. In addition, behavioral barriers, such as resistance to change and cultural challenges, were noted in 4 articles. These barriers often arise from longstanding industry traditions and a lack of awareness about the benefits of de-carbonization. Infrastructural barriers, cited in 3 articles, include limitations in hydrogen infrastructure, renewable energy grids, and heat recovery systems at industrial sites. Other barriers mentioned less frequently include institutional barriers, regulatory and policy inconsistencies, political obstacles, lack of knowledge and technical expertise, end-use constraints, and the complex nature of industrial operations.

2.1.3. Benefits of de-carbonization

The literature also underscores the substantial benefits of de-carbonization across environmental, economic, and social dimensions. Environmental benefits are the most frequently mentioned, with reduced greenhouse gas emissions playing a pivotal role in mitigating climate change. Improved energy efficiency and process optimization lead to significant cost savings, making de-carbonization economically attractive for industries. Beyond direct savings, de-carbonization fosters economic spillovers, such as job creation, technological innovation, and broader economic development, extending benefits beyond the industry itself. Additionally, cleaner production processes contribute to human health improvements and higher worker satisfaction, creating safer and healthier work environments.

2.2. De-carbonization of the steel industry in the Netherlands

This section of the literature review zooms in on the iron and steel industry in general as an energy intensive industry, with its current and de-carbonized production methods. Subsequently it zooms in on a steel plant in the Netherlands, Tata Steel IJmuiden, as it is the case on which this study is based. It shortly discusses the specific plans of Tata Steel in their de-carbonization transition. Before mapping out the required changes in practice, it is necessary to dive into the literature about the strategic change in making de-carbonized iron and steel.

2.2.1. Current general iron and steel production

The iron and steel industry has a significant contribution to CO_2 emissions, accounting for over 5% of the EU's total emissions in 2021. De-carbonizing this sector is challenging due to the high heat required for steel and iron production (Boldrini et al., 2024). Before the de-carbonized practice of making steel can be analyzed, the current processes must be analyzed. The current practice of making steel consists of two options, the Blast Furnace (BF)-Basic Oxygen Furnace (BOF) and Direct Reduced Iron (DRI)-Electric Arc Furnace (EAF) as shown in Figure 2.2. In the BF-BOF process, iron ore is processed into sinter or pellets at 1000°C using natural gas and coal, then reduced to iron at 1400°C in the BF, emitting significant amounts of CO_2. The resulting hot metal is further processed in the BF-BOF to produce crude steel. Some plants have optimized this process and there is not much room for further optimization to save energy, but major changes are needed to emit emissions (Somers, 2022).

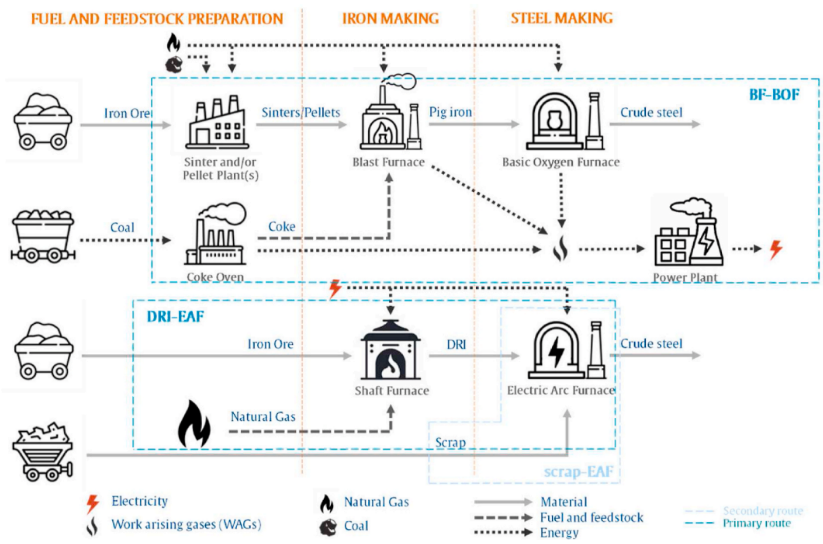

Figure 2.2: Visual representation of the iron and steel production. Figure obtained from Boldrini et al., 2024.

In the DRI-EAF process, Iron ore (Fe_2O_3) is reduced to DRI in the shaft furnace using syngas and natural gas (Methane (CH_4)). Syngas is created by reforming that natural gas: CH_4 + Water (H_2O) → Carbon monoxide (CO) + 3 Hydrogen (H_2) (El-Kadi et al., 2024). The reduction of iron ore happens in two reactions: 1) $Fe_2O_3 + 3\ H_2 \rightarrow 2$ Iron (Fe) + 3 H_2O, and 2) $Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$. This process emits less CO_2 than BF-BOF. The DRI is melted in the EAF at 1600°C, often combined with recycled scrap, which can also be directly heated in the EAF to produce Crude Steel (CS) (Somers, 2022). Currently, the BF-BOF process emits generally 1.9 tCO_2/tCS, and the DRI-EAF process 0.9 tCO_2/tCS (Boldrini et al., 2023).

2.2.2. General de-carbonized iron and steel production

To de-carbonize the practice of making steel, three key strategies can be pursued. First, the use of recycled materials can be increased. Second, transitioning to a de-carbonized steel production from iron ore can be achieved by using alternative fuels. Third, residual emissions can be captured and stored by using CCUS techniques (Boldrini et al., 2024). These three de-carbonization strategies are displayed in Figure 2.3.

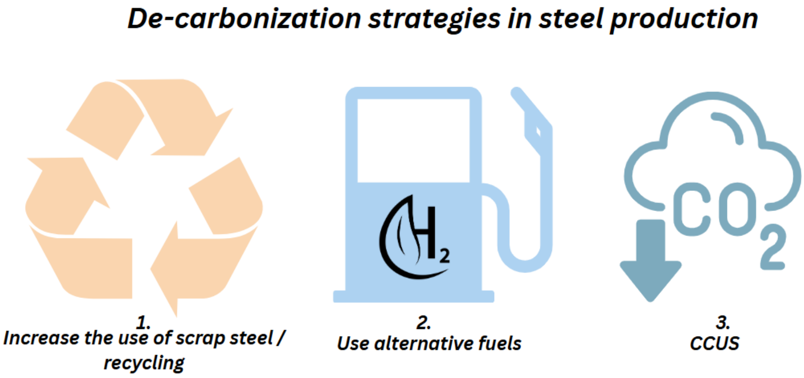

Figure 2.3: Visual representation of the three main de-carbonization strategies in the steel industry.

As described and shown in the figure, increasing the use of scrap steel in the production process is the first approach to lowering carbon emissions in the practice of making steel. Scrap can be added in the DRI-EAF process in which it is melted in the EAF as shown in Figure 2.2. This process causes CO_2 emissions of 0.2-0.3 t/tCS. While recycling steel reduces emissions, new steel production is necessary to maintain high-quality standards. Achieving a zero-carbon process is essential for further emission reductions (Boldrini et al., 2023).

The second strategy is transitioning to a zero-emission process using alternative fuels such as green hydrogen. Green hydrogen, produced via water electrolysis, reacts with iron ore to produce iron and water ($Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$). This process, utilized in Direct Reduction Plant (DRP)'s, significantly reduces CO_2 emissions, when the hydrogen used is produced in a zero-emission process (Somers, 2022). 90% of all hydrogen is currently produced by using fossil fuels, which can be classified as Grey Hydrogen. Blue hydrogen is hydrogen that has been produced by using gas, but the emitted CO_2 has been stored again. Green hydrogen indicates that renewable power was used during the water electrolysis, so no CO_2 is emitted during the production process. In this process the H_2O molecules are split into H_2 and Oxygen (O_2). Besides a reducing agent, it can also be used as a fuel to heat the process (Griffiths et al., 2021). Green ammonia is another alternative fuel that can be used for steel making. It can be made from hydrogen and nitrogen under high pressure (100-250 bar) using renewable electricity and the Haber-Bosch process. It can replace a limited amount of coke and natural gas in the BF-BOF process, reducing CO_2 emissions by up to 9.8%. In the DRI-EAF process, ammonia serves as both a reducing agent and fuel, further cutting emissions as shown in Figure 2.4 (El-Kadi et al., 2024).

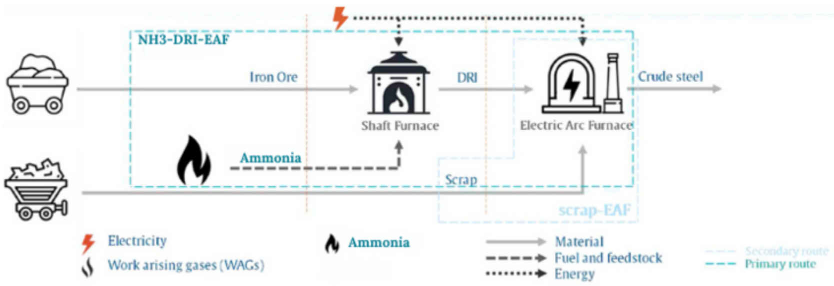

Figure 2.4: Visual representation of the de-carbonized iron and steel production with ammonia. Information obtained from El-Kadi et al., 2024 and design obtained from (Boldrini et al., 2024).

Hydrogen and ammonia are both often not yet produced sustainably, ammonia is produced via Steam Reforming (SR) and hydrogen is predominantly produced (96%) from fossil fuels through Steam Methane Reforming (SMR), with only 4% produced via electrolysis (Arsad et al., 2023; Morlanés et al., 2020). Ammonia production is as efficient as hydrogen production, and offers logistical advantages. When ammonia reacts with iron ore, it forms a nitride layer that protects against water corrosion. Typically, porous iron ore is highly reactive with oxygen and water, posing transport risks due to heat release. Hydrogen-based steel production lacks this protective layer, requiring compaction into hot briquette iron for safer transport (Ma et al., 2023). Although not all iron might need to be transported before it is processed into steel. However, Morlanés et al. (2020) highlights challenges in ammonia use in steel production. Burning ammonia produces harmful emissions, and its toxicity raises safety concerns. Hydrogen offers several advantages, its transport infrastructure is more developed, potentially lowering costs, and it results in lower emissions than ammonia. Hydrogen's explosiveness necessitates strict safety measures (Arsad et al., 2023). Dijkstra (2024) recommends integrating ammonia into a broader hydrogen system. Since hydrogen can be produced more cost-effectively, it is preferred, with ammonia used for specific applications where hydrogen falls short.

The third de-carbonization option for the steel industry is CCUS. CCUS technologies aim to reduce CO_2 emissions by capturing carbon dioxide from industrial processes and either storing it underground CCS or using it as a raw material Carbon Capture and Utilization (CCU) for chemical production. These methods enable traditional processes, like the BF-BOF steelmaking route, to operate with lower environmental impact. There are three main CO_2 capture strategies: pre-combustion, post-combustion, and oxyfuel combustion (see Figure B.1).

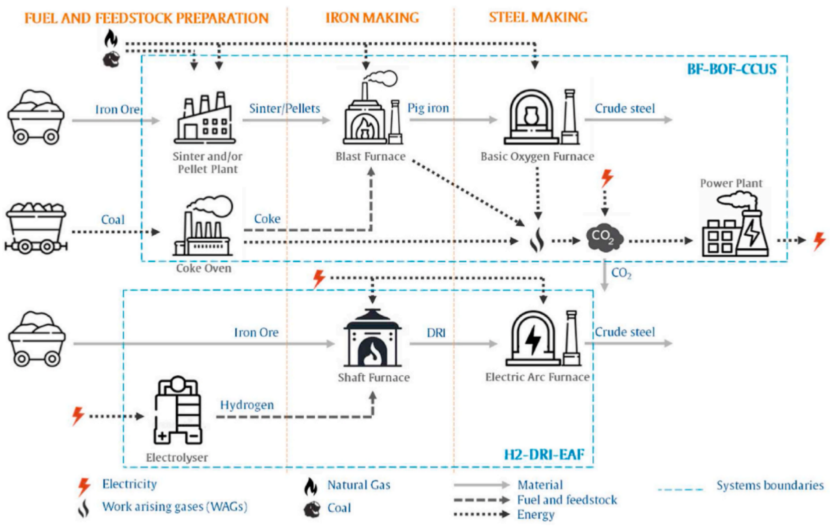

Figure 2.5: Visual representation of the de-carbonized iron and steel production with carbon capturing in the BF-BOF or hydrogen in the DRI-EAF. Figure obtained from (Boldrini et al., 2024).

Among these strategies, post-combustion capture is the most mature and widely used, capable of removing 95–99% of CO_2 by passing flue gases through separation units, then liquefying the CO_2 for transport or storage (Hoeger et al., 2021; Song et al., 2018). Post-combustion methods include absorption (e.g., amine solutions), adsorption (solid materials capturing CO_2 on their surfaces), and membrane separation (selective gas permeation). Absorption is common but energy-intensive; membranes are efficient but sensitive to impurities (McLaughlin et al., 2023). Pre-combustion capture removes CO_2 before fuel combustion by gasifying fuels into syngas, separating CO_2, and using hydrogen as clean fuel. While effective and commercially used in some sectors, this is less suited to steelmaking due to carbon's role in the alloying process (McLaughlin et al., 2023). Oxyfuel combustion burns fuel with pure oxygen, producing flue gas rich in CO_2 and water vapor, simplifying capture and reducing equipment costs (Song et al., 2018). Captured CO_2 is transported via pipelines or ships to storage or utilization sites. Pipelines are cost-effective for large volumes and short distances, while ships offer flexibility over longer distances. In the Netherlands and Norway, projects aim to store CO_2 under the North Sea, requiring significant infrastructure (McLaughlin et al., 2023).

2.2.3. Current iron and steel production Tata Steel

The iron and steel industry has a significant contribution to CO_2 emissions, accounting for over 5% of the EU's total emissions in 2021 (Boldrini et al., 2024). It is even accountable for 7% of the world wide emissions as well as in the Netherlands (Elderkamp, 2023). De-carbonizing this sector is challenging due to the high heat required for steel and iron production. At this moment there are two routes to produce steel at the Tata Steel plant. In the primary way the iron ore is reduced to iron and formed into steel in the BF by the use of coal. The secondary way is by the use of scrap metal, which is melted down in the EAF as shown in Figure 2.6.

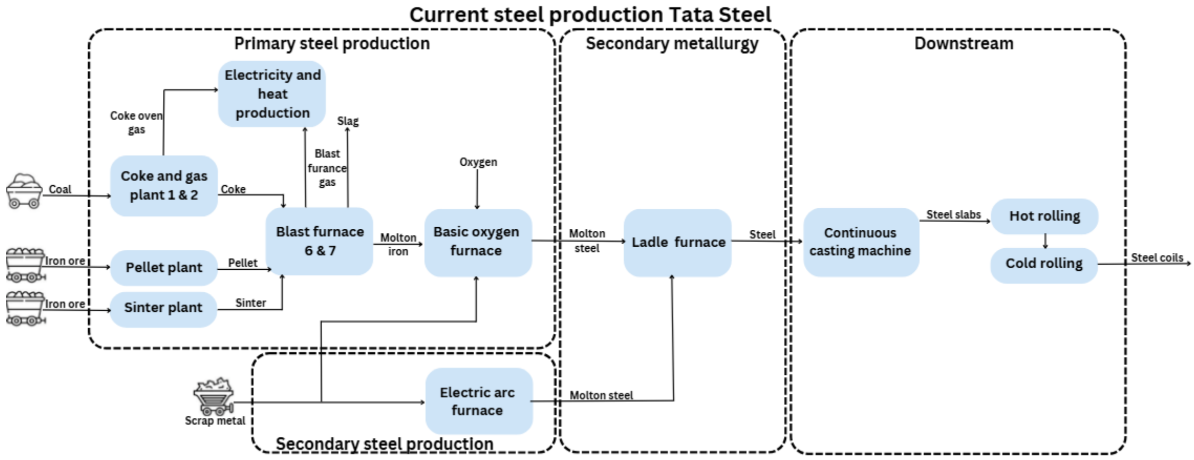

Figure 2.6: Visual representation of the current production process at the Tata Steel IJmuiden plant. Figure based on Elderkamp, 2023.

In primary steel production, coal is processed into coke in a coke and gas plant. During this process, coal is heated in oxygen-free ovens, which releases gases such as H_2, CH_4, CO_2, and CO. These gases are then transferred to a unit for electricity and heat generation. The resulting coke is a hard material with a high carbon concentration, which is essential for the subsequent metal production process. Simultaneously, iron ore is processed into pellets and sinter in the pellet or sinter plant. Pellets are small, spherical particles, while sinter is a porous, clumpy material. These forms allow air to pass through, which is crucial for the reduction process in steel production. The Fe_2O_3, in the form of sinter or pellets, is reduced by coke in the BF according to the following reaction: $Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$. This stage of the process emits a significant amount of CO_2. While many plants have optimized this process to improve energy efficiency, further reductions in emissions will require major technological changes rather than incremental optimizations (Somers, 2022).

After the iron is melted and reduced in the blast furnace, the molten iron is transported to the BOF. The molten iron contains a high concentration of carbon, which is reduced in the BOF. During this process, carbon reacts with oxygen, releasing CO and CO_2. The intense heat generated during this reaction necessitates the addition of scrap metal to lower the temperature. However, the amount of scrap that can be added is limited due to the presence of impurities in the scrap and the requirement to maintain sufficient temperatures. Typically, this primary steel production process emits approximately 2 tonnes of CO_2 per tonne of steel produced, although in highly efficient systems, emissions can be reduced to 1.8 tonnes of CO_2 per tonne of steel as in the case of Tata Steel IJmuiden (Elderkamp, 2023).

In contrast, the secondary steel production route emits significantly less CO_2, as it primarily involves melting down scrap steel, which has already undergone reduction. This route emits approximately 0.2-0.3 tonnes of CO_2 per tonne of steel (Boldrini et al., 2023). Scrap steel is melted in the EAF. Additional heat is often generated by using gas. The EAF is tilted to pour the molten steel (or hot metal) into a steel ladle, a large and heat-resistant refractory-lined container used to hold and transport molten steel between processes within the steel plant. Although secondary steel production emits substantially less CO_2 compared to the primary production process, it cannot fully replace primary production. This limitation is due to the insufficient availability of scrap steel to meet the ever-increasing global demand for steel. Furthermore, the quality of steel produced from scrap is often lower due to impurities present in the recycled material (Elderkamp, 2023).

After the molten scrap steel is melted and the carbon concentration in the molten iron is reduced, both materials undergo further processing in the ladle furnace. This stage, considered the refining step, involves fine-tuning the steel's composition and purity, as well as adding alloying elements to meet specific quality requirements. While the processes for primary and secondary steel differ, the equipment used in this stage is similar. In the final step of steel production, the liquid steel is solidified into a usable form using a casting machine. This process occurs near the melting temperature of the steel and produces either flat products or long products. For flat products, the molten steel is cast into steel slabs, which are then rolled into sheets or plates. Long products, on the other hand, are produced by casting the molten steel into billets or blooms. After casting and rolling, the steel may receive a final coating or paint layer based on customer specifications (Elderkamp, 2023). Figure 2.7 shows that in the BF-BOF process, which is currently most used in steel production, the coke production and the reduction to iron in the BF emits the most CO_2 (Keys et al., 2019).

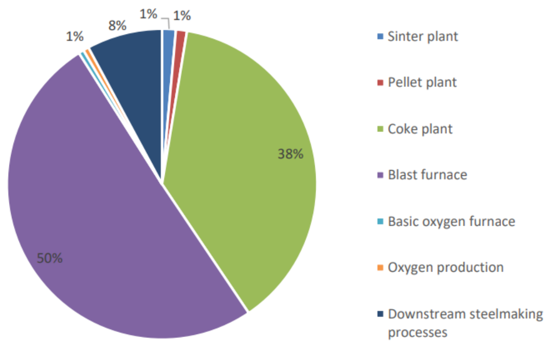

Figure 2.7: Distribution of energy consumption in the BF-BOF steel production process. Figure obtained from (Keys et al., 2019).

2.2.4. Tata Steel's transition

After examining how the steel industry can de-carbonize in general, this section will focus on the specific transition of Tata Steel IJmuiden as it is the case on which this study is based. To improve its sustainability, Tata Steel focuses mainly on the three de-carbonization strategies mentioned in the previous section: increasing the amount of scrap metal, using hydrogen as an alternative fuel and therefore replacing old technologies and using CCUS.

If the amount of scrap metal is increased as the first de-carbonization strategy, it saves the use of raw materials. Every ton of scrap metal leads to an CO_2 reduction of 1.6 tons. Tata Steel plans on increasing the use of scrap metal from 17% to 30% by 2030 (Green Steel Plan, n.d.). Besides that, Tata Steel has announced plans to transition its IJmuiden plant to a DRI facility that utilizes hydrogen instead of fossil fuels to achieve de-carbonization. One BF will stop operating in 2030. This BF will be replaced by a DRP installation and an EAF. This replacement will reduce the CO_2 emissions of Tata Steel by 40%, which is 5 Mton of CO_2. The other BF has just been renovated and will continue operating until 2035. Tata Steel will also implement some measures that should limit the emission of harmful substances from BFs while they are still operating. After 2035 the second BF will also be replaced by DRP installations and EAF.

Further measures will be taken to make Tata Steel IJmuiden CO_2-neutral by 2045 such as using CCUS. Until sufficient hydrogen supply is available, the DRP will operate with natural gas. The change to DRI with natural gas will already lead to a significant reduction in emissions reduction compared to the traditional BF-BOF process and it will have less negative impact on the surrounding area than the current production process has. The expectation is that there will be enough hydrogen available to run the DRI process in 2030. There are plans to make a windmill park at sea close to the

Tata Steel plant to generate enough electricity for the production of Green Steel (Green Steel Plan, n.d.). The different stages in this transition are shown in Figure 2.8.

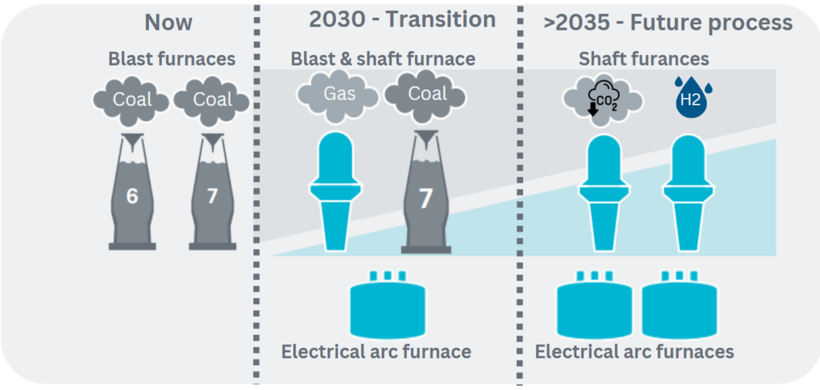

Figure 2.8: Visual representation of the de-carbonized iron and steel production with carbon capturing and hydrogen. Figure based on (Tata Steel Nederland & FNV, 2021).

2.3. Operations and maintenance

The literature on O&M presents a comprehensive overview of the evolution and categorization of maintenance strategies in industrial operations. A recurring theme across the studies is the classification of maintenance into two primary types: reactive and proactive maintenance. Reactive maintenance, also referred to as corrective or breakdown maintenance, is performed after equipment failure. It is characterized by minimal upfront costs but can lead to high downtime and unexpected production losses. Despite its disadvantages, this strategy remains widely used due to its simplicity and applicability in non-critical systems (Merkt, 2020).

In contrast, proactive maintenance encompasses a variety of strategies designed to prevent equipment failures. These include preventive maintenance, which is based on time or usage and relies on scheduled interventions. Proactive maintenance also includes predictive maintenance, such as Condition-Based Maintenance (CBM), which depends on real-time monitoring of equipment conditions to detect deviations. Predictive maintenance uses historical and live data along with algorithms to forecast failures. Prescriptive maintenance recommends optimal actions based on predictive insights. The reactive and proactive maintenance strategies are displayed in Figure 2.9. These approaches are increasingly adopted in industrial settings due to their potential to improve equipment reliability, reduce unplanned downtime, and optimize operational costs (Bouabid et al., 2024; Errandonea et al., 2020; Gawde et al., 2022).

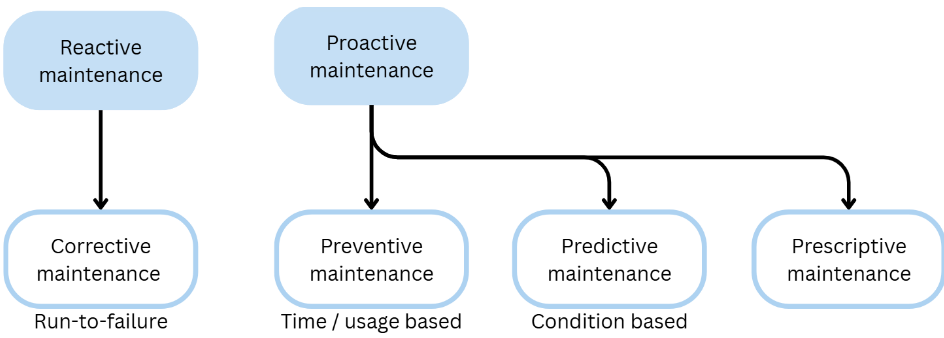

Figure 2.9: Visualisation of the reactive and proactive maintenance strategies.

The literature also identifies advanced strategies that build upon core maintenance concepts. Opportunistic maintenance is highlighted as a cost-effective approach that capitalizes on existing downtimes to maintain related components, reducing resource waste and downtime overlap. Risk-Based

Maintenance (RBM), which prioritizes interventions based on the likelihood and severity of equipment failure, is particularly useful for assets critical to safety or production continuity. Another commonly discussed approach is Reliability-Centered Maintenance (RCM), a structured methodology that systematically analyzes equipment functions, failure modes, and their consequences to prioritize maintenance actions based on operational risk (Bouabid et al., 2024; Merkt, 2020) In addition, the literature emphasizes the growing role of digital technologies, Artificial Intelligence (AI), Internet of Things (IoT) , and Digital Twins, in supporting predictive and prescriptive maintenance. These technologies enable real-time monitoring, pattern recognition, and simulation-based decision-making. IoT-sensors collect operational data, AI-models analyze it to detect anomalies and predict failures, and Digital Twins simulate real-world operations to recommend and validate maintenance actions. Together, these tools are transforming traditional maintenance practices by enhancing precision, adaptability, and energy efficiency (Rojas et al., 2025).

O&M are closely interconnected functions essential for ensuring safety, reliability, and productivity in industrial settings. Errandonea et al., 2020 highlight that integrating digital twins into maintenance enhances both maintenance effectiveness and operational decision-making by providing real-time equipment insights, promoting a proactive approach that boosts overall efficiency. Bouabid et al., 2024 stress that preventive maintenance strategies, such as time-based and condition-based maintenance, must consider operational factors such as usage patterns and environmental conditions to maintain continuous and safe production, especially in high-risk industries. Gawde et al., 2022 emphasize the role of multi-sensor data fusion in fault diagnosis, showing that understanding operational parameters is crucial for accurate maintenance planning. Similarly, Merkt, 2020 notes that integrating operational data improves predictive maintenance models, aligning maintenance schedules with actual equipment use to minimize downtime. These studies highlight that effective maintenance depends on accurate operational data, and reliable operations require properly maintained equipment. Implementing intelligent, data-driven strategies enhances this synergy by enabling real-time monitoring and proactive decision-making, ultimately improving performance and sustainability. The literature consistently supports a transition from reactive to proactive maintenance approaches. While reactive maintenance is still used in certain situations, proactive maintenance strategies are increasingly recognized as essential for reducing risks, lowering costs, and boosting reliability in modern industries.

These insights underscore that O&M are not isolated technical domains but are deeply embedded within broader organizational transformations. At Tata Steel, the macro level de-carbonization strategy introduces significant technological changes at the micro plant level, such as modifications to BF operations and shifts in energy inputs, that directly impact O&M activities. These changes require adjustments not only in maintenance routines and operational protocols but also in how various stakeholders interact, coordinate, and make decisions on the ground. As such, understanding how strategic change unfolds at the micro level involves more than tracking new technologies or procedures; it calls for close attention to the everyday practices, roles, and interpretations that shape how these macro-level objectives are translated and enacted within the local operational context.

2.4. Strategy-as-Practice: A theoretical framework

Strategic change within large, complex organizations like Tata Steel often unfolds across multiple levels, ranging from high-level policy formulation to daily operational decisions on the ground. Understanding this dynamic requires more than analyzing strategic plans or performance outcomes; it demands attention to the actual practices and actors that bring strategy to life. The Strategy-as-Practice (SasP) framework offers a valuable lens for capturing this process by shifting the analytical focus from strategy as an abstract product to strategizing as a situated, social activity. Rather than viewing strategy solely as something organizations have, the SasP approach examines what people do when they engage in strategy work (Whittington, 2006). This section first reviews relevant empirical studies that illustrate how strategic change is experienced at the micro level within organizations. It then discusses the theoretical development of the SasP framework and its core concepts, before detailing how the framework is applied within this thesis to investigate the operational implications of Tata Steel's transition.

2.4.1. Empirical foundations: Case studies on strategic change at the micro level

Several previous case studies have investigated how macro-level strategies are enacted in practice at the micro level within organizations. Pelletier et al., 2020 examined strategic transformation in small modular enterprises undergoing digitization. Their study explored how strategy unfolded through the interplay of praxis (e.g., IT investments), practitioners (e.g., leadership, suppliers), and practices (e.g., coordination routines). It demonstrated how innovation can emerge even in conservative industries when strategy is enacted through day-to-day interactions and adaptations. Similarly, Löwstedt, 2010 conducted an interpretive case study in a large construction firm undergoing organizational change. His findings showed that strategy was often experienced as fragmented and emergent, shaped more by individual sense-making and informal actions than by formal strategic plans. This highlighted the importance of attending to the lived, social dimensions of strategizing, particularly in complex and hierarchical environments. What both studies underscore is that strategic transformation is not simply imposed from the macro level; rather, it is shaped, negotiated, and enacted by a variety of actors through ongoing practices. This micro-level view of strategizing provides a compelling entry point for understanding how top-down initiatives like Tata Steel's macro de-carbonization strategy are experienced and translated at the micro plant level. To systematically investigate this dynamic, this thesis draws on the SasP framework.

2.4.2. From strategic planning to strategic practice

Strategic management research has long been influenced by various conceptual lenses that offer different assumptions about how strategy is formulated and implemented. Whittington, 1996 identified four foundational perspectives: policy, planning, process, and practice. The policy view emphasizes strategic decision-making as a top-down process led by senior executives. The planning perspective frames strategy as a rational, analytical exercise, often conducted by dedicated units using models and forecasting tools. The process view shifts attention to how strategy unfolds over time through routines, bounded rationality, and political negotiation.

In contrast, the practice perspective, developed into the SasP approach, asks a fundamentally different set of questions: How is strategy actually done? By whom, using what tools, in what contexts? (Whittington, 2006). Rather than viewing strategy as a static plan or outcome, SasP explores strategy as a lived, socially embedded activity. It highlights how strategizing is performed by individuals in their day-to-day work, bringing attention to micro-level interactions and practices often overlooked by traditional strategic management research. Central to the SasP framework are three interrelated elements: practitioners, practices, and praxis (Jarzabkowski & Spee, 2009).

- **Practitioners** are the actors involved in shaping and carrying out strategy. These may include managers, consultants, engineers, frontline workers, or external stakeholders.
- **Practices** are the tools, routines, procedures, norms, and technologies that guide strategic activity. Examples include strategic frameworks, planning tools, monitoring systems, or operating procedures.
- **Praxis** refers to the stream of activities through which strategy is enacted in practice. This can involve formal meetings, informal negotiations, daily work routines, and other forms of situated action.

This triadic model allows researchers to capture how individuals interact with tools and each other to enact strategy in specific contexts. It positions practitioners as key intermediaries who translate, reinterpret, and adapt strategic intent through their daily actions. While the SasP perspective has gained traction as a corrective to more deterministic views of strategy (Carter et al., 2008), applying it in empirical research remains challenging. As Da Silveira Santos et al., 2020 argue, many conventional methods fall short in capturing the tacit, situated, and often emergent nature of strategizing. Consequently, scholars have called for more nuanced and innovative methodological approaches that can engage deeply with the social and interpretive dimensions of strategy work. Narrative inquiry has emerged as a particularly promising approach in this regard. Because it centers on how individuals make sense of strategy through storytelling, metaphor, and projection, it aligns well with the interpretive orientation of SasP (Brown et al., 2008; Webster & Mertova, 2007). Especially in contexts of organizational change or uncertainty, narratives offer rich insight into how strategy is constructed, negotiated, and enacted by different actors. This is particularly important in pluralistic or complex organizations where strategic alignment is not given but must be continually constructed through communication and interpretation (Da Silveira Santos et al., 2020). Recent SasP research has also emphasized the need to better integrate macro-level institutional dynamics with micro-level strategy practices (Gurbuz et al., 2022). Strategy is not developed in a vacuum; it is embedded in broader structural, technological, and socio-political contexts. Jarzabkowski and Spee, 2009 stress this point through their multi-level model of praxis, distinguishing between micro (plant level), meso (organizational), and macro (institutional or societal) levels of analysis.

2.4.3. Inclusion of the framework in this thesis

This thesis adopts the Strategy-as-Practice framework to investigate Tata Steel's de-carbonization transition. This is a top-down, macro-level strategy, which is still in the planning phase, but already being enacted through everyday practices at the micro level. The research specifically explores how this strategy is translated and experienced within the localized setting of a production plant, emphasizing the role of practitioners such as maintenance engineers, operations staff, safety managers, and executives. Strategic practices in this context include technical planning, digital monitoring systems, and performance optimization procedures, while praxis is reflected in routine activities such as equipment inspections, troubleshooting, incident reporting, and report generation. Crucially, the de-carbonization strategy introduces technological shifts, such as replacing the BF operations and energy inputs, that directly reshape O&M strategies. These changes extend beyond technical tasks to influence how practitioners interact, share knowledge, and coordinate their roles, making this transition a valuable case for studying strategy as an ongoing, situated, and negotiated practice.

The thesis follows a multi-level structure to address these dynamics. The emperical research starts in Chapter 4, which focuses on the macro-level de-carbonization strategy and how it is shaping the *praxis* through planning and preparation. Chapter 5 examines the meso- and macro-contextual factors, such as regulatory constraints, infrastructure requirements, and societal expectations, that influence both the strategy introduced in Chapter 4 and the micro-level practices and praxis addressed in Chapters 6 and 7. These latter two chapters analyze how O&M is reimagined and reorganized at the micro plant level, addressing changes in both *praxis* and *practice* as experienced by the *practitioners* responsible for enacting the transition. This structure highlights the interconnectedness of strategy formulation, contextual constraints, and everyday operational realities in shaping industrial de-carbonization. The multi-level analysis was described and illustrated in Section 1.2. Figure 2.10 demonstrates how praxis, practice, and practitioners are integrated throughout the research.

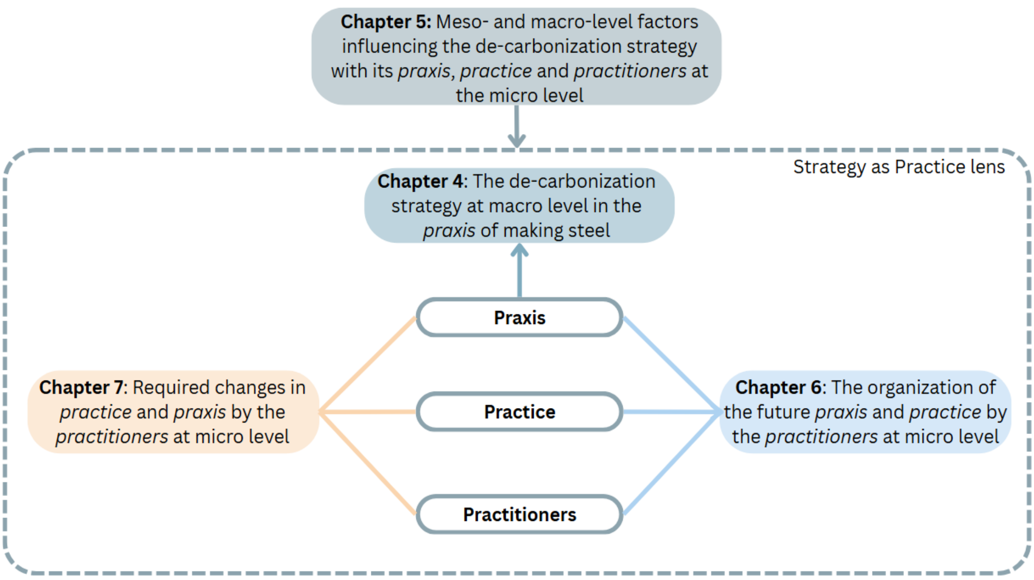

Figure 2.10: Visualisation of the inclusion of the *praxis*, *practice* and *practitioners* in the research, studied through a SasP lens.

2.5. Knowledge Gap

Despite a growing body of research on the de-carbonization of energy-intensive industries, significant knowledge gaps remain in the context of integrating hydrogen into large-scale industrial operations, particularly with respect to O&M practices. Although considerable literature exists on the use of hydrogen in de-carbonized steel production, few studies investigate the operational implications of this transition, such as the adaptation of maintenance routines, including the safety considerations tied to hydrogen handling, or the skills and training required for personnel. Furthermore, there is limited insight into how these practical concerns are managed during a staged transition, where legacy systems and new technologies co-exist over time. At the same time, the European Commission calls for concrete, sector-specific transition pathways that bridge strategic ambition with local implementation (European Commission, n.d.). Yet, the majority of existing work focuses either on macro-level policy frameworks or on macro-level technical system design, often neglecting the "how" of implementation on the ground at the micro plant level. To the researcher's knowledge, no existing studies have fully explored the intersection of three key domains: de-carbonization strategies, steel production, and O&M. This thesis addresses that gap, visualized in Figure 2.11.

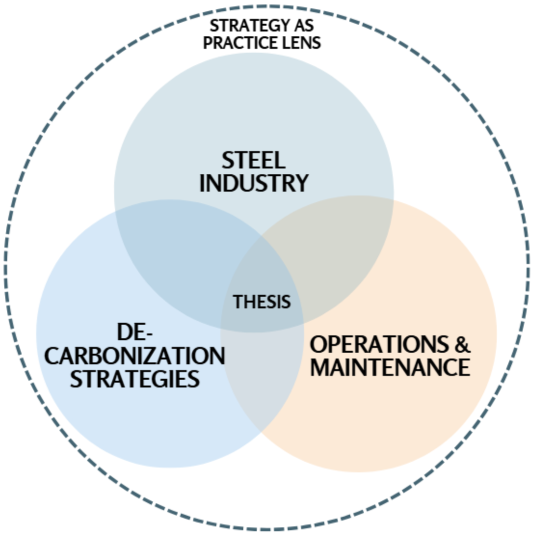

Figure 2.11: Visualisation of the knowledge gap between the literature about the steel industry, sustainable transition and O&M studied through a SasP lens.

Although overlaps exist between these individual areas of literature, integrated research that connects all three remains notably absent. In particular, the micro-level realities of how O&M practices are transformed during a transition to de-carbonized steelmaking have not been sufficiently studied. By focusing on the case of Tata Steel and its ongoing transition to DRI-EAF technology using hydrogen, this thesis provides a grounded understanding of the operational challenges and maintenance transformations that accompany industrial de-carbonization efforts. In addition, this study contributes to the theoretical and methodological development of the SasP literature. By analyzing how individuals engage with strategy in their day-to-day work, the research provides insight into the social and emergent nature of strategic transformation, especially within industrial and high-risk organizational contexts. Furthermore, it responds to calls for methodological approaches that capture the interplay between micro-level practices and macro-level pressures, including societal expectations, regulatory demands, and environmental imperatives. Using a narrative and interpretive approach, the study explores how de-carbonization strategy is not only planned but also performed and made sense of in real-world settings of technological change. This perspective helps uncover how strategic direction is practically negotiated and enacted within the operational core of industrial organizations.

2.6. Scientific contribution

This thesis contributes to academic and practical debates in several important ways. First, it offers a novel empirical focus on the O&M implications of de-carbonization within the steel sector, an area characterized by high carbon intensity but limited scholarly attention to day-to-day transition practices. Through the case study of Tata Steel IJmuiden, the research identifies specific O&M challenges posed by hydrogen and new technology integration, including maintenance of new equipment, safety protocols, and workforce retraining. Second, and methodologically, this thesis contributes to the SasP literature by extending its application to the context of industrial de-carbonization, an area that remains underexplored despite its strategic complexity and societal relevance. It demonstrates how SasP can be employed to study strategy not as a finalized outcome but as an emergent and situated activity unfolding at multiple organizational levels. Specifically, it captures how strategic intent, such as Tata Steel's hydrogen-based transformation, is interpreted and operationalized by diverse practitioners including engineers, safety managers, and frontline staff. By examining how these actors engage with new technologies, planning tools, and coordination routines, the research advances understanding of how macro-level strategies are translated into concrete actions and local adaptations in high-risk, technologically complex environments.

Furthermore, this thesis offers a methodological contribution by combining narrative inquiry and interpretive analysis to access the often tacit and evolving nature of strategizing. It responds to ongoing calls in SasP literature for methods that can bridge micro-level practices with macro-level institutional pressures, such as regulatory change, environmental mandates, and societal expectations. In doing so, the thesis not only enriches the conceptual utility of the SasP framework but also enhances its applicability in studying real-world transitions where strategic ambiguity and operational complexity intersect. By integrating O&M into the broader de-carbonization literature and applying the SasP lens to industrial transformation, the thesis responds directly to the EU's call for actionable, context-specific transition pathways. It also contributes to theory by demonstrating how O&M, typically seen as peripheral or technical concerns, play a central role in shaping the trajectory and feasibility of sustainability transitions.

3 Methodology

This chapter outlines the methods used to investigate how Operations and Maintenance (O&M) practices are evolving in the context of energy-intensive industrial de-carbonization, with a focus on Tata Steel's transition toward hydrogen-based steelmaking. It starts in Section 3.1 with introducing the overall research design, including the execution plan which highlights subsequently how the research was carried out in practice. It continues with describing how the dual research approach, specifically the literature review in Section 3.2 and the semi-structured interviews in Section 3.3, were conducted. Afterwards it describes the synthesis and integration of expert knowledge in Section 3.4. This chapter continues with a reflection on the validity and reliability of the research in Section 3.5 and it concludes with a description of the tools and software used in this study in Section 3.6.

3.1. Research design

This thesis adopts a qualitative research design centered on a case study of Tata Steel, a large energy-intensive steel plant in the Netherlands. The aim is to explore how Tata Steel plans to de-carbonize, with a specific focus on the changes in O&M this transition entails in practice. In particular, the study examines how the strategic change affects the operations, safety risks, hydrogen integration, and the roles of the stakeholders as practitioners. Ultimately, the research seeks to provide practical recommendations to support the steel industry, and other energy-intensive industries, in their shift toward more sustainable production processes.

The research employs a dual-method approach that combines a literature review with expert interviews. This integration of data sources strengthens the research by providing both theoretical grounding and practical insights. The literature review identifies existing knowledge and reveals gaps concerning the influence of de-carbonization strategies on O&M practices. Meanwhile, the interviews surface practitioner perspectives, offering real-world insights into the strategic and operational challenges of de-carbonizing a complex industrial system like Tata Steel.

The research was shaped by a collaboration that balanced academic and professional perspectives. The academic guidance provided by TU Delft supervisors ensured a strong theoretical foundation and methodological rigor, while the pragmatic outlook of Arcadis enhanced the relevance and applicability of the findings. This dynamic supported a research process that actively bridged scientific literature with industrial realities, resulting in a thesis that combines conceptual depth with practical utility.

The definition of the research problem itself emerged through a process of co-creation between the author, academic supervisors at TU Delft, and professionals at Arcadis. This iterative dialogue helped refine the scope and focus of the study, ensuring that the research question addressed both academically relevant knowledge gaps and pressing real-world challenges faced by practitioners working on industrial de-carbonization. This collaborative approach strengthened the relevance, clarity, and practical resonance of the study from its inception.

Given the real-world complexity of sustainability transitions, this study adopts a transdisciplinary research perspective. Transdisciplinarity bridges academic knowledge with practical expertise, acknowledging that systemic societal problems, like industrial de-carbonization, cannot be addressed through disciplinary knowledge alone. This approach integrates insights from engineering, environmental science, organizational studies, and industrial practice, enabling a more holistic and actionable understanding of the challenges and pathways in question (Pohl et al., 2017).

The research process was intentionally iterative and inclusive. The literature review did not rely solely on academic sources retrieved via systematic database searches; it was also enriched by the interview process. Interviewees pointed to relevant gray literature, internal reports, and technical documents, which enhanced the comprehensiveness and contextual relevance of the review. This iterative exchange between literature and stakeholder insights allowed for a deeper, more grounded exploration of operational change in the context of de-carbonization.

The research progressed through a sequence of structured phases, illustrated in Figure 3.1. This visual representation highlights the clear flow from data collection to analysis and reporting, supporting the effective achievement of the research objectives.

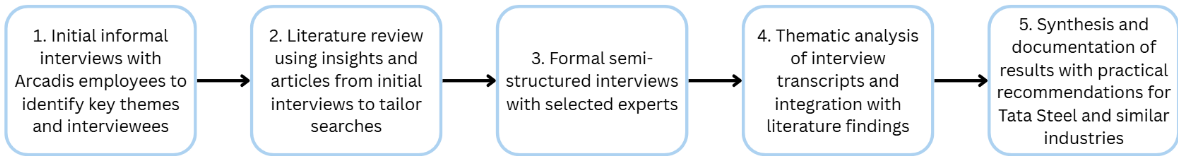

Figure 3.1: Visualisation of the research flow applied during this thesis.

3.2. Literature review

To support the investigation into environmental sustainability transitions and the evolving role of O&M in de-carbonization strategies in energy-intensive industries and Tata Steel in particular, a literature review was conducted. The goal was to capture the multidisciplinary knowledge base relevant to industrial de-carbonization, with a particular focus on the steel industry. The review strategy combined structured database searches, citation tracking, and expert-informed inclusion of gray literature. The literature was organized around three thematic areas central to the research question:

- De-carbonization strategies for energy-intensive industries
- De-carbonization of the steel industry, with specific focus on Tata Steel
- O&M strategies that facilitate sustainable industrial transitions in practice

Searches were primarily conducted in the Scopus database using predefined queries tailored to each theme. A two-step screening process was applied: first, titles and abstracts were reviewed for relevance; second, selected papers were read in full to ensure substantive contribution. Citation tracking helped identify additional influential works, while expert input, gathered through interviews and informal consultation, led to the inclusion of corporate reports, technical documentation, and other relevant gray literature. To maintain focus and consistency, the following inclusion criteria were applied:

- Published in or after 2015, aligning with the post-Paris Agreement period
- English or Dutch language
- Relevant to industrial de-carbonization, green steelmaking, or industrial O&M
- Accessible full text

Studies were excluded if they focused on unrelated sectors, outdated technologies, or lacked practical relevance. By drawing on both academic sources and practitioner knowledge, the literature review provided a robust foundation for identifying key themes, informing interview design, and guiding the overall analysis. Further details on the search queries and reviewed materials are provided in Appendix C.

3.3. Interviews

This section describes the semi-structured interviews conducted during the research as well as their analysis, data quality and the data management.

3.3.1. Semi-structured interviews

To complement the literature findings, semi-structured expert interviews were conducted to explore practitioner perspectives and organizational realities that are not well documented in academic sources. Interviewees were purposively chosen for their expertise in Tata Steel's transition strategy, de-carbonization strategies in general, hydrogen technology, or O&M practices. Purposive sampling allows researchers to select participants who meet specific criteria of interest, thus ensuring a balance between those with deep knowledge of the subject matter and those offering diverse viewpoints (Adeoye-Olatunde & Olenik, 2021). Initial exploratory interviews with Arcadis professionals helped refine the research scope and inform the development of the interview guide. Subsequent formal interviews were carried out with experts from Tata Steel, Arcadis, other industry experts and academia. A snowball sampling technique was applied to identify additional participants with relevant experience. Interviews were conducted both in person and via video calls, depending on participant availability and location. Conducting interviews via video conferencing had the added benefit of offering greater accessibility and ease of recording (Adeoye-Olatunde & Olenik, 2021). All interviews were audio or video-recorded, and automatic transcription tools were used to generate transcripts for analysis. The semi-structured format allowed the interviews to follow a consistent set of questions while enabling flexibility to explore emerging topics of relevance. This structure is particularly suitable for complex research inquiries, such as understanding operational transformations in the context of industrial de-carbonization, because it allows interviewers to probe into issues as they arise during the conversation (Adeoye-Olatunde & Olenik, 2021). Participants represented a range of technical and strategic roles. A total of nine expert interviews (n=9) were conducted, aiming to achieve a comprehensive understanding of the transition's operational implications, as shown in Table 3.1.

Interview #	Participant	Topic
1	Energy transition specialist, Rabobank	General aspects of Tata Steel's transition and plans
2	Arcadis consultant, risk and opportunity management	Safety challenges and risks during transition
3	Former Dutch Member of Parliament	Tailored agreements
4	Assistant professor, University of Calgary	CCUS
5	Arcadis consultant, compliance and permits	Permit application process
6	Arcadis business developer, hydrogen	Hydrogen technology aspects
7	Arcadis engineer, energy and carbon	CCUS and hydrogen integration
8	Tata Steel employee, operational sustainability	O&M future outlook and transition
9	Tata Steel employee, asset management and development	O&M future outlook and transition

Table 3.1: Overview of conducted interviews including details of the participants and topics covered.

3.3.2. Data analysis

Interview data were analyzed using thematic analysis. A hybrid coding strategy was applied, combining deductive themes derived from existing literature with inductively developed codes that emerged during engagement with the interview transcripts (Adeoye-Olatunde & Olenik, 2021). This approach enabled a structured yet adaptable analysis, grounded in theory while remaining receptive to novel insights from practitioners.

All quotes cited in the thesis were originally spoken in Dutch, except for quotations from interview 4, and have been translated into English by the author. Appendix H.1 provides an overview of selected examples, demonstrating how these translations were carried out to ensure accuracy and clarity while preserving the intent and nuance of the original statements. To protect participant confidentiality, all transcripts were anonymized and stripped of personally identifiable information. Quotes are referenced using neutral, non-descriptive identifiers (e.g., Interview 1, Interview 2). This process ensured an ethically responsible and methodologically robust exploration of practitioner perspectives on operations management O&M transformation and industrial de-carbonization. Additional details on the analysis procedure are provided in Appendix H.2.

3.3.3. Data quality

The quality of the data collected for this thesis is shaped by both the strengths and limitations inherent in its qualitative methodology. Central to the research were interviews with professionals from Tata Steel and other key stakeholders involved in industrial de-carbonization. While these participants provided valuable insights grounded in practical experience, the nature of their institutional affiliations introduces potential biases. Participants may have consciously or unconsciously presented strategically favorable or selectively framed narratives aligned with organizational interests.

To ensure the robustness and reliability of the findings, several measures were implemented to enhance data quality. These included the triangulation of sources, critical cross-verification of interview responses, and transparent reflection on the researcher's role in data interpretation. Nonetheless, the involvement of institutional partners may have influenced the prioritization of certain themes or interpretations. These limitations are acknowledged, and efforts were made to mitigate their impact through rigorous methodological safeguards and adherence to principles of academic integrity and critical independence.

3.3.4. Data management

This research complies with TU Delft's ethical standards and the General Data Protection Regulation (GDPR) to ensure secure and responsible data handling. Data collected for this thesis include interview recordings, transcriptions, research notes, and documents used in the semi-systematic literature review. The participants received a participant information sheet and provided informed consent for their interviews. This sheet is included in Appendix F.

The consent process clarified how their data would be used, stored, and anonymized, and included their right to withdraw at any stage. Personally identifiable information, such as names, roles, or affiliations, was only collected for logistical purposes and are deleted upon project completion. Interview recordings were transcribed and anonymized by removing any identifying details. Participants were also given the opportunity to review and edit their interview summaries. All data are stored on secure, encrypted devices and institutional storage systems, with access limited to the researcher. Anonymized transcripts and summary data may be retained for academic use, but do not contain any personally identifiable information. This data management plan has been reviewed and approved by TU Delft's Human Research Ethics Committee (HREC), and all ethical protocols regarding confidentiality, voluntary participation, and secure data management have been followed.

3.4. Expert knowledge synthesis and integration

In addition to structured interviews and the literature review, this research employed a method of reflective and theoretical synthesis grounded in expert-practitioner experience (Marshall, 2019). Reflection here is understood as an active process, involving conscious and deliberate intent to make sense of experiences and ideas. This method is also integrative, as it explores and synthesizes multiple perspectives to construct a coherent and meaningful narrative.

Åsvoll, 2014 discusses the roles of abduction, deduction, and induction in interpretative case studies. Åsvoll emphasizes that induction in qualitative research often depends on intuitive knowledge, where the researcher's tacit understanding and reflective practice are crucial. Thus, synthesizing expert intuition alongside structured data enhances the rigor and depth of analysis, supporting a transparent and robust inquiry process. Moreover, Åsvoll, 2017 highlights the significance of reflective intuitive knowing within innovation management, arguing that intuition is not irrational but an essential complement to analytical thinking. Innovation processes, especially under conditions of complexity and uncertainty, rely heavily on practitioners' tacit knowledge and intuitive judgments. Incorporating these elements systematically enriches the research, enabling a more nuanced understanding that bridges formal methodologies and practical expertise.

Therefore, throughout the research process, insights from interviews and literature were not only analyzed independently but also interpreted and enriched through reflective synthesis with the tacit knowledge of academic and industry supervisors. Through regular supervision sessions, the researcher was able to draw on the professional reflections of supervisors and actively integrate their experiential knowledge into the narrative sense-making approach. This enabled the conscious incorporation of practitioners' tacit knowledge into the analysis.

The main contribution from one supervisor involved guidance on structuring a table to analyze the interaction between different de-carbonization strategies as displayed in Chapter 8. The supervisor suggested, during a super vision session, to structure interactions between the de-carbonization strategies in a tabular format to clarify how different approaches interact practically. Building on this suggestion, the researcher independently designed and developed a detailed table that mapped the relationships between de-carbonization strategies, incorporating insights from the case study and literature.

This integrative approach, combining structured methodologies with the synthesis of expert knowledge, not only enhanced the depth and clarity of the analysis but also underscored the researcher's capability to synthesize complex information into a coherent and insightful framework, ultimately contributing to a more nuanced understanding of de-carbonization strategies.

3.5. Validity and reliability

To ensure methodological rigor and transparency, the design, conduct, and reporting of this qualitative research were guided by the Standards for Reporting Qualitative Research (SRQR) as proposed by O'Brien et al. (2014). These standards informed the development of research questions, the approach to data collection, reflexivity, and the process of thematic analysis. By applying SRQR, the study ensures clarity in the interpretation of data and credibility in the presentation of findings.

To further strengthen the credibility of the research, multiple strategies were implemented. Triangulation of data from multiple sources, academic literature, technical documentation and expert interviews were used to validate emerging insights. A transparent and well-documented research process, as displayed in Appendix C supports the reliability and replicability of findings. Careful tracking of research decisions, including interview protocols and coding schemes as displayed in Appendix G, further enhances methodological transparency.

3.6. Used tools and software

The following tools and software were utilized during the research process to support data collection, analysis, documentation, and presentation:

- **Overleaf**: An online LaTeX editor used for writing and formatting the thesis, ensuring consistency and facilitating collaboration.
- **Microsoft Teams**: Employed for recording interviews and generating initial transcripts, provid-

ing a reliable platform for remote communication.

- **Microsoft Excel**: Used for organizing and analyzing interview data, available under a license from Delft University of Technology.
- **Microsoft Word**: Utilized for drafting, editing, and preparing supplementary documents, also licensed by Delft University of Technology.
- **Canva**: Applied to design and enhance visualizations, including figures and diagrams presented in the thesis.
- **Artificial Intelligence (AI)**: Chat GPT and Arcadis GPT were used for refining texts.

During the development of this thesis, two artificial intelligence tools, ChatGPT and Arcadis GPT, were used to enhance various stages of the research and writing process. These AI applications were primarily employed for rewriting and refining textual content to improve clarity, coherence, and overall readability. Additionally, they were used to translate anonymized interview quotations, ensuring that the original meaning was preserved while adapting the language appropriately. Beyond language refinement, the AI tools supported restructuring of written materials, helping to optimize the logical flow and organization of arguments and findings. During the design phase, AI-assisted brainstorming and idea generation provided creative input and alternative perspectives that complemented the researcher's own insights. Additionally, ChatGPT was also used to generate the front page illustration. Furthermore, the AI platforms facilitated the conversion and formatting of textual data into LaTeX code, streamlining the integration of content into the thesis document. Throughout this process, the researcher maintained a critical stance toward all AI-generated outputs. Every response produced by the AI was thoroughly reviewed and evaluated for accuracy, relevance, and alignment with the research objectives. This careful oversight ensured that the final content reflected the researcher's original analysis and academic rigor. The use of AI tools thus functioned as an aid to enhance productivity and quality, without supplanting the essential role of human judgment and expertise in the research.

4

On-sight transition Tata Steel

This chapter aims to address the first sub question of this research: *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden entail?"* This chapter presents a narrative of the strategic transition at the macro level, focusing on how Tata Steel IJmuiden is planning to de-carbonize its steel production. It outlines the overarching planned strategy, key decisions, and technological substitutions that shape the transition path. To answer this sub-question, the chapter first explores the preparation phase of the strategic de-carbonization transition with the phases of planning and design in Section 4.1. Next, the phases of the planned transition are described in Section 4.2. Furthermore, the de-carbonization strategies involving the use of alternative fuels with its adoption of new technologies and the replacement of legacy systems are discussed in Section 4.3, including the implementation of Direct Reduction Plant (DRP), Electric Arc Furnace (EAF), and Carbon Capture Utilization and Storage (CCUS) as another de-carbonization strategy. Since recycling as a de-carbonization strategy does not require major changes in the prodution process, this aspect is not part of the main analysis. Finally, concluding remarks that synthesize the findings and directly address the sub-question are provided in Section 4.4.

4.1. Phases of planning and design

The strategic de-carbonation starts of with several phases of planning and design. The planning and design process consists of several distinct phases, beginning with the decision on technology, which includes the selection of DRP and EAF systems. During the basic engineering phase, a Process Flow Diagram (PFD) is developed, with the Original Equipment Manufacturer (OEM) calculating the process flows and determining the gas quantities. In addition to the PFD, a more detailed Piping and Instrumentation Diagram (P&ID) is created. The P&ID includes critical details such as flow rates in cubic meters per hour, average pipe velocities, pipe diameters, and specifications for pipe lengths, T-joints, and fittings. Pressure loss calculations account for every meter of pipe, as well as elbows and T-joints, facilitating the determination of pump capacity. Following the basic engineering phase, detailed engineering is carried out by the Engineering, Procurement and Construction Management (EPCM) contractor. The decision to work with an EPCM contractor highlights a strategic practice designed to manage operational uncertainty and complexity. This phase involves refining the design to include all components, down to individual bolts and nuts. Once detailed engineering is completed, the execution phase begins, followed by the start-up phase and, ultimately, the operational phase. (Interview 9) According to interview 1, basic engineering typically includes the development of a plot plan and a preliminary 3D plan, which serve as a semi-definitive version of the design. Detailed engineering further elaborates the pipeline designs, ensuring all components are specified in detail for construction.

The transition to green steel production began with the design phase in 2022 as shown in Figure 4.1, which was followed by the engineering phase that concluded at the end of 2024. Currently, the construction preparation phase is underway, and completion is expected in 2026. This phase includes obtaining necessary permits and preparing the construction site. Construction is scheduled to begin in 2026, with the start-up phase expected in 2029, during which Blast Furnace (BF) 7 and Coal and Gas Factory 2 will be decommissioned (Tata Steel, 2025c). This early planning and design work not only sets technical parameters but also constitutes a form of strategizing that shapes future praxis in the present.

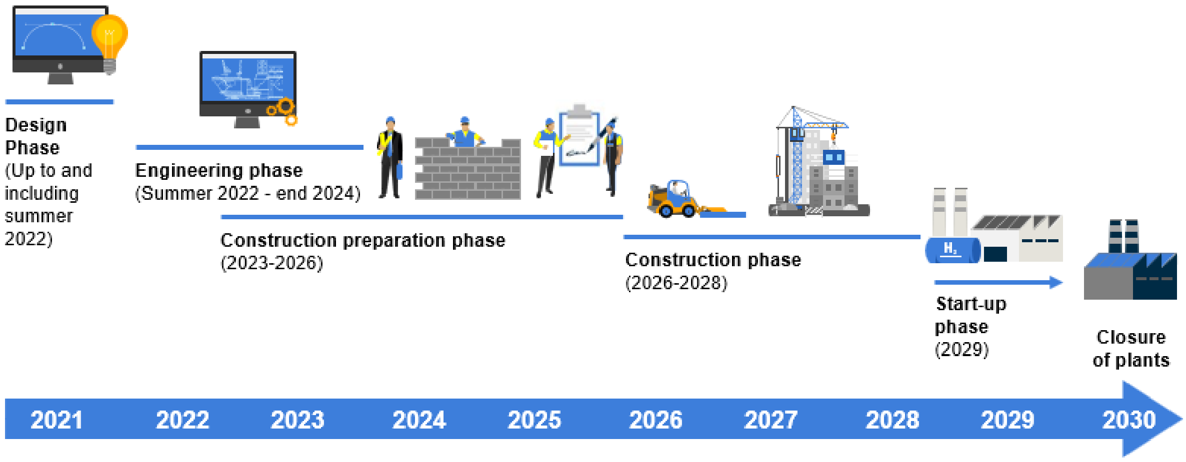

Figure 4.1: The planning of the first phase of Tata Steels transition. Figure obtained by Tata Steel, 2025c.

4.2. Phased transition towards a de-carbonized plant

Following the design and planning stages, Tata Steel Netherlands will begin transitioning away from its current setup, two BFs, BF 6 and BF 7, which together produce 7 million tonnes of Crude Steel (CS) per year (Keys et al., 2019). These furnaces generate a combined total of 12.6 Mton of Carbon dioxide (CO_2) emissions annually, as shown in Figure D.1. Specifically, BF 6 produces 2.5 Mton of molten iron and emits 3.9 Mton of CO_2, while BF 7 produces 3.8 Mton of molten iron and emits 6 Mton of CO_2 (Interview 8). The de-carbonization process will unfold in two phases, led by an EPCM firm. The first phase includes the construction of the initial DRP and EAF, scheduled between 2028 and 2030. This plant will replace BF 7 and Coke and Gas Plant 2, leading to an expected annual emissions reduction of 5 Mton CO_2 while producing 2.5 Mton of CS.

> *"We are now moving towards a reduction of 5 million tons of CO_2 because we are shutting down BF 7, the largest one. That 5 million tons reduction will already be achieved with 100% natural gas. It's a huge step. Imagine: coal consists of 90% carbon, 10% hydrogen, and some other components. Natural gas, on the other hand, consists of only 20% carbon, which makes a significant difference."* (Interview 8)

The second phase starts after the first DRP is fully operational, the second DRP will be built between 2032 and 2037, with a planned output of 3.5 Mton of CS and an additional 3.8 Mton CO_2 reduction if operated with natural gas (Tata Steel Nederland & FNV, 2021).

> *"If we shut down BF 6, the reduction will be around 3.8 million tons. So, if you look at the current situation, we are at 12.6 million tons of CO_2 emissions. With the first step, where we reduce 5 million tons, we'll reach approximately 7.6 million tons. Then, if you add the additional 3.8 million tons reduction from shutting down BF 6, there will still be around 4 million tons of CO_2 emissions remaining."* (Interview 8)

Initially, the DRP will operate on natural gas until sufficient hydrogen becomes available, at which point the fuel mix will gradually shift. The use of natural gas already yields significant CO_2 savings compared to coal. The phased emission reductions are visualized in Figure 4.2. By 2030, the first Direct Reduced Iron (DRI) system (DRP + EAF) will operate alongside BF 6. The decommissioning of BF 7 and Coke and Gas Plant 2 will yield a 40% reduction in CO_2 emissions. From 2035 onward, production will rely solely on the DRI system, now fueled by a mix of natural gas and hydrogen. At this point, BF 6, the sinter plant, and Coke and Gas Plant 1 will also shut down, achieving a further 30% emission reduction. The goal is to achieve a zero-emission process by 2045 through increased hydrogen usage and carbon capture.

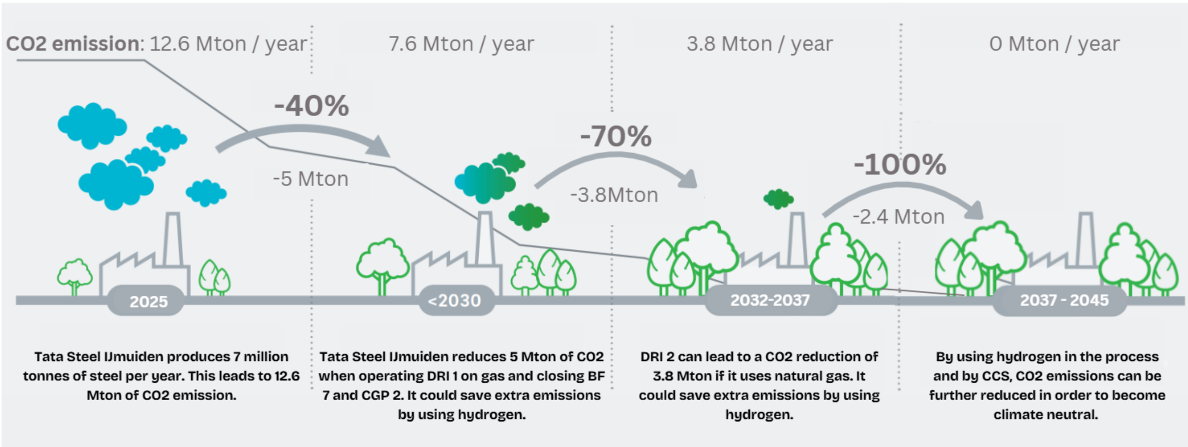

Figure 4.2: Visual representation of the transition timeline in lowering emissions. Figure based on data from FNV, n.d.

4.2.1. Phase 1: The transition period (2025–2030)

In the first phase, referred to as the transition period, DRI 1 will be constructed while regular operations continue. This phase exemplifies strategic praxis, requiring continuous coordination and adaptation to balance legacy systems with new infrastructure. Figure 4.3 illustrates this transition: once shaft furnace or DRP 1 (indicated in green) is fully constructed and operational, Coke and Gas Factory 2 and BF 7 will be decommissioned (both indicated in red).

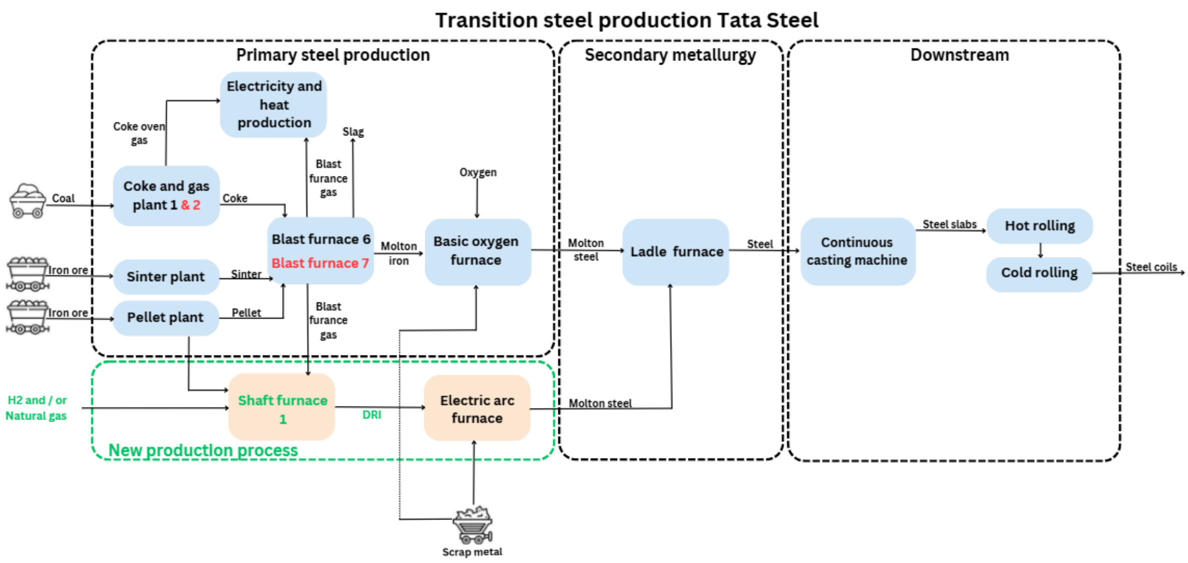

Figure 4.3: Visual representation of the transition phase of Tata Steel IJmuiden. New installations are indicated in green, decommissioned installations in red, and the new production line in orange.

BF 7, having the highest production capacity and emitting 6 Mton CO_2 annually, will be closed first to maximize emissions reduction. Coke and Gas Plant 2, considered the most harmful to the surrounding community, will also be shut down ahead of Coke and Gas Plant 1 (Interview 8). This transition is further depicted in Figure D.2.

DRI 1 is expected to produce 2.5 Mton of steel annually, whereas BF 7 currently produces 3.5 Mton of pig iron. During the transition, Tata Steel will need to import 1 Mton of pig iron to maintain output levels. Initially, the DRI process will rely primarily on natural gas due to limited hydrogen availability. Once hydrogen becomes more accessible, the plant will operate on a mix of 80% hydrogen and 20% natural or green gas. Green gas is purified biogas with a quality equivalent to natural gas. This carbon input remains necessary, as steel is an alloy that requires carbon in the production process (Tata Steel Nederland & FNV, 2021).

Beyond technological transformation, the transition period also presents significant logistical and operational challenges. The DRP plant must be constructed and gradually commissioned within a densely built, active industrial site. This dual-task operation, building while running, requires careful coordination to avoid disrupting existing processes. One of the most pressing constraints is physical space. The IJmuiden site has no surplus land comparable to "football fields," as noted in Interview 1; space must be created by relocating or dismantling existing infrastructure before new facilities can be installed. This limitation affects construction layout, logistics, and materials handling. All major components for the new plant must be delivered, stored, and assembled on-site, requiring temporary staging areas, crane access, and safe movement paths, all coexisting with active steel production.

> *"We want to make that transition while remaining in operation, and that's like open-heart surgery."* (Gasunie, n.d.)

Operating in this high-risk, high-density environment demands tight sequencing of activities. Most construction coordination will be led by an EPCM firm, while Tata Steel will support by providing necessary resources and interfaces (Interview 9).

Integrating the new DRI facility into existing logistics also presents challenges. For example, liquid iron from the BF is currently transported by train to the steel plant. Connecting the new plant to this rail network involves strict safety constraints and precise alignment. Track design must avoid too sharp curves and maintain safe buffers, influencing facility orientation (Interview 1). Another key challenge is production synchronization during the switchover. If the new DRI line produces too much or too little material relative to downstream needs, bottlenecks or underutilization may occur. Tata Steel aims to minimize underproduction while maintaining continuity across the value chain (Interview 8).

This transition is not simply a technical upgrade but a complex logistical transformation, requiring spatial optimization, interconnectivity, and careful orchestration of existing and new systems. During this period, two fundamentally different factories will operate in parallel, demanding operational safeguards to prevent human error.

> *"If you use two materials that are both necessary for your process but have different properties, and you use them simultaneously, you must ensure that operators from plant A never work in plant B. If you put people in a situation where they have to work with A today and B tomorrow, there is a chance that something might go wrong."* (Interview 2)

4.2.2. Phase 2: The future state

By approximately 2035, BF 6 will be replaced by the second DRI plant, referred to as DRI 2. This facility, shown in Figure D.3, will have a production capacity of 3.5 Mton of steel annually. Alongside BF 6, the sinter plant and Coke and Gas Factory 1 will also be decommissioned. This transition will significantly reduce emissions: BF 6 currently emits 3.9 Mton CO_2 per year. If DRI 2 operates on natural gas, it will reduce emissions by approximately 3.8 Mton CO_2 annually. Hydrogen-based operation would lead to even greater reductions. Furthermore, DRI 1 will be able to rely more heavily on hydrogen, no longer depending on residual gases from BF 7. The commissioning of DRI 2 and EAF 2 will enable the full phase-out of BF 6, Coke and Gas Factory 1, and the sinter plant, as illustrated in Figure 4.4. However, the sinter plant plays a vital role in Tata Steel's internal circularity. Investigations are ongoing to determine whether sinter can be used in the DRI process, allowing the sinter plant to continue supporting resource recirculation:

> *"A large part of the residual materials produced on site is currently reused through the sinter plant. If you shut it down, you remove an important link in the recirculation process or circularity. For the time being, however, we still need the sinter plant for the one remaining BF. [. . .] Sinter simply*

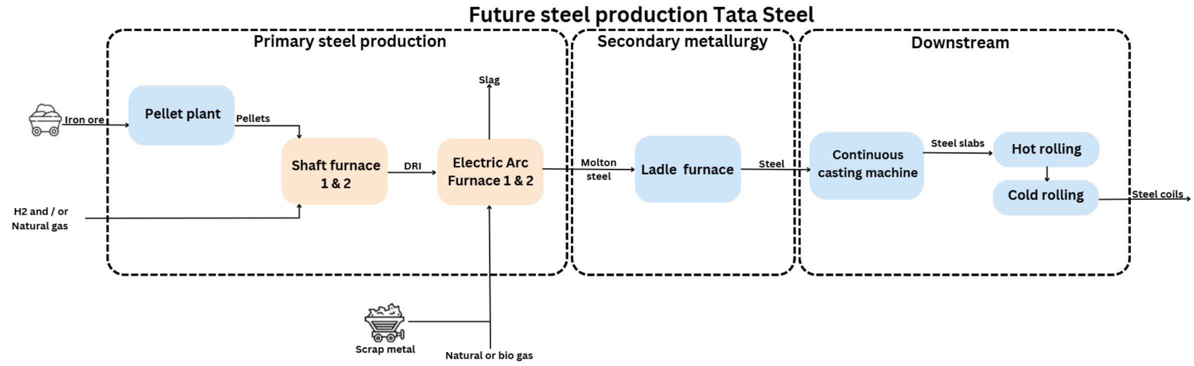

Figure 4.4: Visual representation of de-carbonized steel production. New installations indicated in orange.

> *flows less smoothly than pellets, which move through the system more like marbles. So I don't think it's easily possible, but we do need to investigate it. Otherwise, we'll have to find another solution for our circularity."* (Interview 8)

Natural gas-based DRI production is a proven technology, but hydrogen-based steelmaking remains in its infancy and has only been demonstrated at small scales. To reach full CO_2 neutrality, all natural gas must eventually be replaced. The final 20% carbon content may be substituted with biogenic green gas, and any remaining emissions can be captured and stored, as discussed later in this chapter. Hydrogen may also be used as a fuel in downstream processes to further de-carbonize the steel value chain (Tata Steel Nederland & FNV, 2021).

In addition to the DRP and EAF, numerous other installations will be required. A HYTEMP tower will pneumatically transfer hot DRI using nitrogen gas to avoid cooling losses. The nitrogen will be reheated and re-pressurized in the HYTEMP tower (HYTEMP | Energiron, n.d.). Transporting DRI between installations generates dust, necessitating washing and dust collection systems (Interview 9). Additional requirements include DRI storage units for cold product, water treatment facilities, a CO_2 treatment plant, a gasholder, and a humidifier, all essential components for the future low-carbon plant. These systems and more are shown in Figure D.4.

4.3. De-carbonization strategies

The main de-carbonization strategies chosen by Tata Steel IJmuiden involves switching to alternative fuels (hydrogen and natural gas) and therefore the replacement of old technologies. Secondly CCUS will be included as a de-carbonization strategy and lastly, more scrap will be used. However, increasing the amount of scrap steel will not require significant on site changes so therefore this chapter will focus on the new technologies that use the alternative fuels. The new technologies used in the future include the DRP-EAF production process. These technologies are already used on a large scale with gas as the fuel and reduction gas. Running the DRP on hydrogen is technically feasible, but has not yet been tested on a large scale (McKinsey & Company, 2020). The choice and configuration of technologies such as DRP and EAF reflect critical strategizing practices, as these decisions involve aligning environmental goals with operational feasibility and stakeholder expectations. In the DRP-EAF process, iron ore is first shaped into pellets, spherical particles that are transferred to the DRP, where they are reduced by either natural gas or hydrogen, after which the pellets are melted to steel in the EAF.

4.3.1. Direct Reduction Plant

The first new technology that Tata Steel is planning to implement is the DRP. The pellets, as described above, first enter the DRP to be reduced from iron ore to iron. DRP's are widely used in combination with natural gas, which offers a cleaner alternative to the coal-based BF-Basic Oxygen Furnace (BOF) process (Elderkamp, 2023). While the BF-BOF emits approximately 1.9 tCO_2/tCS, the DRP process reduces emissions to 0.9 tCO_2/tCS when natural gas is used as the reduction agent (Boldrini et al., 2023). This reduction is significant, but natural gas, being a fossil fuel, still emits CO_2 and is not renewable. To achieve a truly de-carbonized process, green hydrogen can be used as the fuel and reduction gas.

Hydrogen plays a key role in the DRI production process as a clean alternative to natural gas. The reduction of iron ore occurs through the reaction: Iron ore (Fe_2O_3) + 3 Hydrogen (H_2) $\rightarrow$ 2 Iron (Fe) + 3 Water (H_2O). In this reaction, hydrogen reduces the iron ore to pure iron while emitting only water (H_2O) as a byproduct, making it a zero-carbon reduction agent. However, while hydrogen can reduce iron ore, it does not provide the carbon needed for steel production. Steel is an alloy of iron and carbon, and carbon is essential to ensure the strength and hardness required for various applications. Since hydrogen does not contain carbon, additional steps are required to introduce carbon into the steelmaking process. A potential solution is to use a mixture of hydrogen and natural gas during the transition phase to address the carbon shortage. Carbon reduces the melting point of steel and supplies chemical energy through its oxidation, thereby decreasing the demand for electrical power (HELIOS, 2025).

In the traditional BF-BOF process, the molten iron from the BF is saturated with carbon as described in Chapter 2, which is then adjusted to desired levels (between 0.002% and 2.14%) in the BOF (Elderkamp, 2023). Tata Steel produces various types of steel with unique chemical compositions tailored for applications such as automotive, construction, and packaging (Tata Steel, n.d.-a).

Due to the essential function of carbon in steel, the low carbon content in DRI, based on hydrogen, is a key issue. In contrast to the carbon-saturated hot metal from a BF, hydrogen-based DRI lacks sufficient carbon to form proper steel, resulting instead in material closer to cast iron. As described in Interview 1, this creates a fundamental question for operations: where and when to reintroduce carbon into the process. While possible solutions exist, such as carbon injection during melting, they are not yet fully developed or tested at scale. Importantly, this limitation is not a showstopper. As explained in Interview 1, the industry will begin with a natural gas-based DRI setup and gradually introduce hydrogen, allowing for progressive development without halting construction. This staged approach aligns with how Tata Steel plans to transition: by incrementally increasing hydrogen content as supply and technology allow. Nevertheless, the timeline to achieve 100% hydrogen-based, zero-emission steel remains uncertain, and may range from 10 to 20 years depending on technological advances. In the initial phase natural gas will be the primary reduction gas due to insufficient availability of green hydrogen. As hydrogen supply increases, a mixture of hydrogen and natural gas can be used as an intermediate solution.

The DRI production process on natural gas operates as follows: iron ore is reduced to DRI in the shaft furnace using syngas at approximately 1000°C. Syngas is produced by reforming natural gas through the reaction Methane (CH_4) + H_2O $\rightarrow$ Carbon monoxide (CO) + 3 H_2 (El-Kadi et al., 2024). The reduction of iron ore with syngas occurs through two main reactions: 1) $Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe$ and $3\ H_2O$, and 2) $Fe_2O_3 + 3\ CO \rightarrow 2\ Fe$ and $3\ CO_2$. Which leads to a total reduction reaction with natural gas: $4\ Fe_2O_3 + 3\ CH_4 \rightarrow 8\ Fe + 3\ CO_2 + 6\ H_2O$. Although this process emits less CO_2 than the BF-BOF process, it is not entirely carbon-free (Somers, 2022). This reaction happens at 8 bar. Therefore charging the DRP with pellets is a challenge. Interviewee 9 described this process of charging the DRP with pellets without loosing the pressure in the vessel:

> *"That feeds into barrels, which then become pressurized, because above the reactor it is atmospheric. But in this barrel, a load of pellets is added again. Then the pressure in these barrels are equalized, so both are at 8 bar. Once there is no pressure difference anymore, a valve opens, and the pellets simply fall down into the reactor. Then the valve closes again, the pressure in the barrel is released, and the next batch is added."*

Tata Steel Netherlands chose the Energiron DRP provided by Danieli and Tenova (Danieli, 2024). This technology can operate on natural gas as shown in Figure 4.5, as well as on hydrogen as shown in Figure 4.6. This only requires small adjustments to the installation.

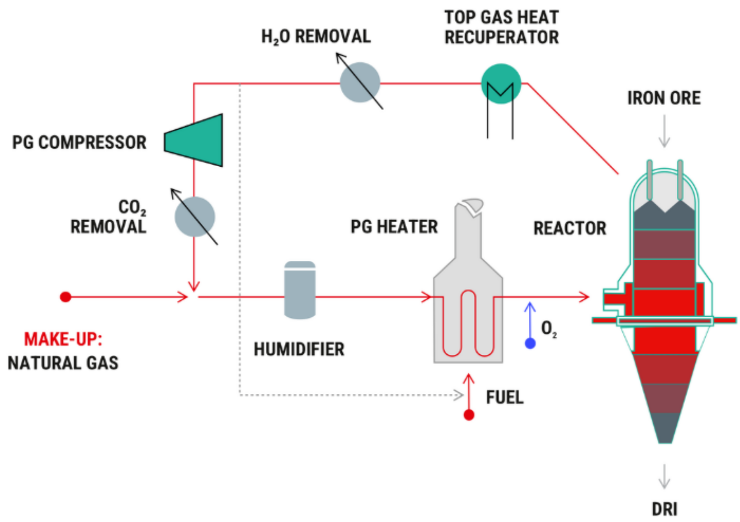

Figure 4.5: Visual representation of the Energiron DRI on natural gas. Figure obtained from Energiron, n.d.

The technology developers Tenova and Danieli state on their website that the DRP can run on 100% hydrogen:

> *"This shows that an Energiron plant is capable of handling high hydrogen content (virtually up to 100%) without major changes to its equipment, and it is a technology which is a step ahead toward a sustainable ironmaking future, rendering carbon direct avoidance a reality."* (Pauluzzi et al., 2021)

However according to one of the interviewees it is not possible to run the plant on 100% hydrogen:

> *"The DRI installation cannot operate entirely on 100% hydrogen without any carbon. A small amount of carbon is necessary to keep the metallurgical process running."* (Interview 8)

However, another interviewee stated that it could be theoretically possible, but it is not proven on a wide scale yet:

> *"The theory suggests that it is possible, but there are not many DRI installations that actually operate on 100% hydrogen yet. It presents an additional challenge because you are not adding carbon to the iron, but you need carbon to produce steel, as steel is an alloy of iron and carbon. So, if carbon is not added during the DRI process, it must be added during melting or in the steelmaking plant."* (Interview 1)

In the case of 100% hydrogen, the CO_2 removal or Carbon Capture (CC) can be missed as well as the humidifier. Hydrogen has been used as a reducing agent in the Energiron technology since 1957. Hydrogen has always been a main reducing agent in the DRI plants, since natural gas is a mixture of H_2 and CO. Energiron plants typically work with a H_2:CO ratio of 3:5. If hydrogen is the main reducing molecule, faster reduction can be achieved (Energiron, n.d.). The Energiron plant can transition between 100% gas and 100% H_2 and all the ratios in between without reducing plant productivity and steel quality. This switch does not take up much time, only the operational conditions need to be adjusted. The DRI operates at a high pressure of 6-8 bar, which increases the reactivity of hydrogen molecules for the reaction which enhances the efficiency. To generate enough thermal heath for the reaction, the DRI operates at a high temperature of approximately 1000°C. The mechanical sealings make sure that the system operates safely and efficient, by preventing gas leaks (Energiron, 2024).

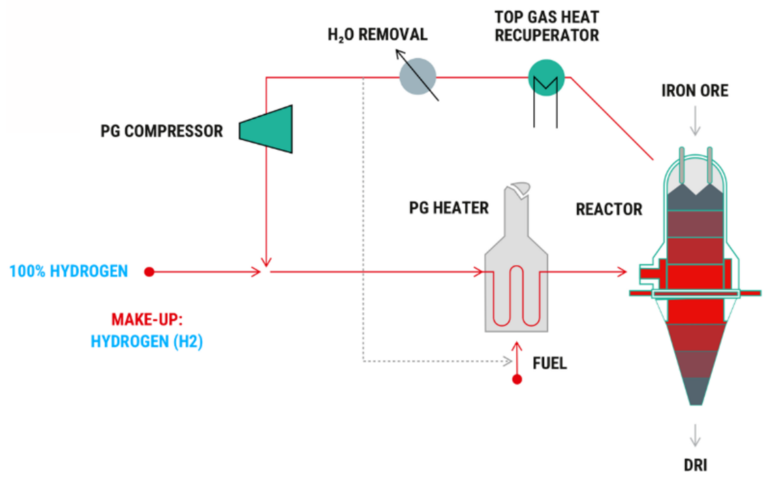

Figure 4.6: Visual representation of the Energiron DRI on hydrogen. Figure obtained from Energiron, n.d.

If hydrogen replaces 75% of the natural gas, the reformer or humidifier can be removed from the process as shown in Figure 4.6. The burners in the Process Gas Heater must be replaced to accommodate hydrogen as a fuel. If the DRI runs almost entirely on hydrogen, it can reach very low emissions of only 11 kg/tDRI. The remaining emissions are due to the needed carbon content in the steel and these emissions can be captured to eliminate all CO_2 emissions (AIST MENA Steel Forum, 2023). Tata Steel is implementing a DRP technology that is capable of producing hot and cold DRI (Interview 9). The hot DRI can be directly transferred to the EAF for immediate steel production, enhancing energy efficiency by utilizing the residual heat of the DRI. Conversely, the cold DRI is cooled and stored in inert nitrogen environments to prevent oxidation and degradation. This stored cold DRI can be used during periods when the DRP is offline or undergoing maintenance, ensuring continuous EAF operations, and thereby providing operational flexibility (Energiron, 2024).

4.3.2. HYTEMP and Electric Arc Furnace

From the DRP, the hot DRI is transported to the EAF in a HYTEMP system, which is a pneumatic transport system. The EAF and HYTEMP system are both new technologies that Tata Steel is implementing as part of their strategy as well. By transporting the DRI in the HYTEMP, the DRI stays warm (700 °C) and less energy is needed to heat the iron in the EAF. It uses gas as the conveying medium, which creates a force required to move the DRI particles through the pipeline (HYTEMP | Energiron, n.d.). The system is completely enclosed and insulated, minimizing heat loss and environmental impact during hot DRI transport. Non-oxidizing gas, typically Nitrogen (N_2), is used as the conveying medium to prevent oxidation of the hot DRI. The DRP and the HYTEMP tower are displayed in Figure 4.7 (HYTEMP | Energiron, n.d.).

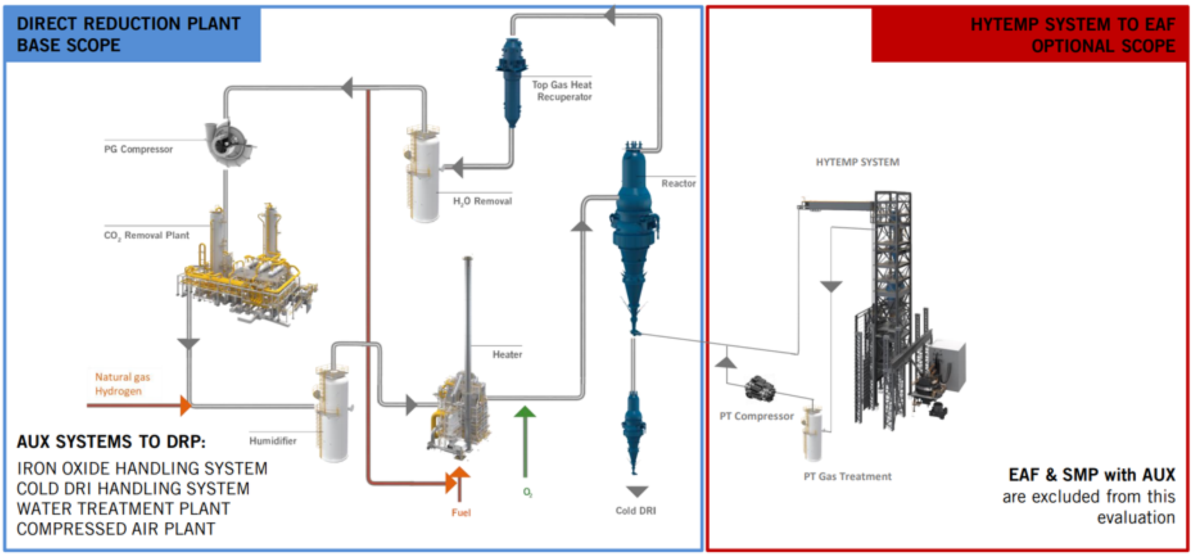

Figure 4.7: Visual representation of the Energiron DRP and HYTEMP tower. Figure obtained from Tata Steel, 2025c.

Coming from the HYTEMP system as solid pellets, the DRI is melted in the EAF, depicted in Figure D.5. EAF steelmaking is a batch-based process that allows for flexible combinations of feedstock, scrap steel and DRI. The process begins by lifting the roof of the EAF to allow for the introduction of scrap metal and DRI, typically using a charge bucket operated by an overhead crane. Once the charge is complete, the roof is closed, and three graphite electrodes are lowered into the furnace to generate an electric arc. This arc produces the extreme heat, approximately 1,600°C required to melt the metal mixture (NUCOR, n.d.).

Using a combination of recycled scrap and DRI provides environmental advantages. Scrap, when melted directly in the EAF, offers a low-emission steelmaking route with emissions of only 0.2–0.3 tCO_2/tCS (Somers, 2022). DRI, which is added during this melting phase, helps achieve the desired steel composition and compensates for scrap quality variations. When DRI is produced using 100% hydrogen, the resulting DRI contains zero carbon, leading to no direct CO_2 emissions during its production (Boldrini et al., 2023). However, since carbon is required to convert iron into steel, additional carbon must be introduced in the EAF. This is done either through the scrap itself or by injecting carbon-rich materials such as carbon powder (Energiron, 2024).

During the melting process, fluxing agents like limestone and dolomite are added to form slag, a byproduct that floats on the molten steel due to its lower density. Slag plays an important role by absorbing impurities, protecting the furnace lining from damage, and improving heat transfer within the furnace. Once the desired chemical composition and temperature are reached, the furnace is tilted to remove the slag. The purified molten steel is then tapped from the bottom of the EAF into a heat-resistant ladle. This ladle transports the liquid steel to downstream processing facilities, such as the casting plant, where the steel is formed and further refined before being sent to the direct sheet or hot rolling mills (NUCOR, n.d.). The EAF operates in a batch cycle, known as the "tap-to-tap" cycle:

> *"The EAF, it has a tap-to-tap time. So you empty it, then you add new material, start melting, and then you empty it again. That process consists of batches of about 300 tons each time."* (Interview 9)

4.3.3. Carbon Capture and Storage

The final main de-carbonization strategy and new technology that Tata Steel is implementing is CCUS. As long as the plant does not run on 100% hydrogen, there will still be some emissions of CO_2. As mentioned before, the remaining CO_2 emissions can be reduced by capturing the CO_2 from the gas leaving the shaft furnace for which an installation is needed as well. This capturing can be a build-in feature in the purchased shaft furnace of Energiron. This installation uses a post-combustion strategy. As shown in Figure 4.5, the CO_2 is captured after combustion takes place. The captured CO_2 needs to be be transported to a storage location such as empty gas fields in the north sea. Before Tata Steel developed the Green steel plan, they planned on capturing the CO_2 on sight and bringing it with pipelines to greenhouses and industries for use and transporting it to the north sea for storage. This project was called Athos and was a consortium between EBN, Gasuni, Port of Amsterdam and Tata Steel. The project had the potential to store 7.5 Mton CO_2 per year. However, this project was abandoned when Tata Steel announced the Green steel plan (CCUS Network, n.d.).

Tata Steel plans to utilize the CO_2 removal system integrated into the Energiron DRI technology. This system is equipped with a CC feature as part of the production process, ensuring efficient removal and handling of CO_2. The cost of storing CO_2 varies depending on the storage location, ranging from €1-7 per ton for onshore storage and €6-20 per ton for offshore storage (Song et al., 2018). In addition to the built-in CC system, Tata Steel ensures that the captured CO_2 gas is provided in a capture-ready state. This involves dehydrating the gas, removing sulfur content, and pressurizing it to meet transport and storage requirements. Furthermore, pipelines are constructed to deliver the CO_2 to the recipients desired location, such as ports or other facilities. As highlighted:

> *What we do is ensure that the gas (CO_2) is offered in a capture-ready state, meaning it is dehydrated, de-sulfurized, and pressurized. Additionally, we install pipelines up to the point where the party receiving it wants to take over. For example, from here to the port, after which it becomes their responsibility."* (Interview 8)

The selection of the most appropriate CC technology depends on the temperature of the flue gas as well as its concentration and pressure (Wanison et al., 2025). According to interviewee 4, there are three main technologies to consider. Firstly amine scrubbing, which involves absorption of CO_2 by amine-based solvents. This is, as previously described in Chapter 2, a technique used in the post-combustion strategy. However this solvent needs to be regenerated by using heat, requiring significant energy. This is a proven technology but needs large installations and equipment (Wanison et al., 2025).

> *"The most mature technology, which is the only commercial technology today, is aiming scrubbing, [...] You flow the flue gas through an absorption column where the amine bonds with the CO_2."* (Interview 4)

The second technology that can be considered, is the second most mature technology, is the use of solid sorbents. These systems use packed absorption columns filled with selective solid materials that adsorb CO_2 from flue gas. Once the solid sorbent becomes saturated with CO_2, the feed gas is switched to a fresh column, while the saturated column undergoes regeneration through various methods, such as temperature or vacuum. Since the technology captures CO_2 from the fluegas, it is a post-combustion technique as well. This method is potentially more space-efficient but not commercially widespread. It is not universally applicable, as their efficiency and capture costs can vary significantly depending on the specific characteristics of the flue gas and operating conditions (Interview 4).

> *"So I would say the next higher maturity technology in the Technology Readiness Level scale is a solid sorbant. [...] So now you have a selective solid sorbant that basically takes in CO_2 from the flue gas."* (Interview 4)

The last technology mentioned in interview 4, is cryogenic separation, this involves cooling the gas mixture to condense the CO_2. This technique is applicable if the CO_2 concentration in the gas is high. These systems work by cooling flue gas to extremely low temperatures, allowing CO_2 to condense into a liquid form while releasing the remaining components of the flue gas (Wanison et al., 2025).

> *"Cryogenic systems [. . .] have a process where you really cool down the gas to the point where you can collect liquid CO_2 and then release the rest of the flue gas. Which is price wise very competitive. Again, depending on the on the scale."* (Interview 4)

After the remaining CO_2 emissions will be captured, it needs to be stored or used. After capturing, it needs to be cooled if it is transported by ships. This would be the case if it is transported to Norway for storage. The CO_2 can be exported by ships, pipelines or trucks to the permanent storage location. This permanent location is a rock formation or under seas with more than one kilometer of depth.

In 2024, Tata Steel, ECOLOG, Horisont Energi, Port of Amsterdam, OCAP, the Norwegian bank DNB en ABN AMRO signed a collaboration agreement to establish a liquid hydrogen and CO_2 corridor between the Netherlands and Norway. The project focuses on importing liquid hydrogen from Norway to Tata Steel's plant in IJmuiden and exporting captured CO_2 from the plant to Norway. Gen2 Energy will produce hydrogen in Norway using hydropower, which will be liquefied for transport. ECOLOG ships will deliver the liquid hydrogen to the Port of Amsterdam, where it will be converted back into gas and transported via pipelines to the Tata Steel facility (Tata Steel, 2024). This cold energy can be used to liquify the CO_2 before transport. Horistont Energi will store the CO_2 underseas. They plan on storing 24 million tonnes of CO_2 per year, this project is called The Gismarvik CO_2 and this process is shown in Figure D.6. This would be the biggest CO_2 terminal of Norway. The CO_2 is shipped by ECOLOG, at 9 bar /-55 °C (CCUS - ECOLOG, 2024) as shown in Figure D.7. Afterwards it is processed in Norway by Horistont Energi and then stored underground transported in pipelines as shown in Figure D.8 (Horisont Energi, 2023).

Another possible option for Tata Steel could be the transport of CO_2 towards the port of Rotterdam by a pipeline. The CO_2 can be liquified there by CO_2 next and it will be transported to the empty gas fields in Norway (Terminal, 2025).

> *"You can keep your CO_2 as a gas and feed it into pipelines, which then transport it to a location where it is taken to a permanent storage site. Alternatively, you can bring your CO_2 to somewhere in the Port of Rotterdam, to the CO_2 Next hub, where it is liquefied, loaded onto a ship, and transported to Norway, where it is stored underground."* (Interview 7)

If Tata Steel liquifies the CO_2 themselves, they would need big installations for liquifying the CO_2:

> *"If you are going to liquefy CO_2 yourself, you'll need to install quite a bit at your own site to liquefy large amounts of CO_2."* (Interview 7)

4.4. Conclusion

This chapter addressed the first sub-question of this research: *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden entail?"* The de-carbonization strategy of the Tata Steel's plant in IJmuiden is characterized by a significant reduction in CO_2 emissions, facilitated primarily by the replacement of old technologies with new, low-carbon steelmaking routes to enable the use of alterative fuels. Initially natural gas and subsequently hydrogen will be used, recycling will be increased through the greater use of scrap steel. Finally CCUS, as a de-carbonization strategy, is implemented. The shift from traditional BF processes to a combination of DRP and EAF technologies marks a structural overhaul aligning Tata Steel with international climate targets and European sustainability directives. By 2030, the planned closure of BF 7 and Coke Gas Plant 2 will result in a reduction of 5 million tons of CO_2 emissions, followed by a further 3.8 million-ton reduction between 2032 and 2037 with the retirement of additional facilities. These milestones are essential for achieving the company's net-zero goals and contributing to the Dutch national climate strategy.

At the heart of this transition lies the integration of a DRP-EAF steelmaking route. The ability to flexibly use both hot and cold DRI, alongside recycled scrap steel, enables optimized energy use, continuous operations, and reduced dependence on fossil fuels. The use of hot DRI, transported through the HYTEMP pneumatic system, drastically lowers energy needs in the EAF by preserving thermal energy and preventing oxidation through nitrogen-based conveyance. The gradual shift from natural gas to hydrogen as a reducing agent further emphasizes Tata Steel's commitment to zero-carbon steel production. While hydrogen offers the potential for truly carbon-neutral steel, technical constraints, such as the metallurgical necessity of carbon in the EAF, mean that full hydrogen integration must be approached pragmatically. Consequently, carbon management strategies, including carbon injection and post-combustion CO_2 capture systems, are essential components of the roadmap.

Importantly, the transition is not without its challenges. Operating two parallel production systems during construction and ramp-up phases introduces logistical complexity and spatial constraints. To mitigate these risks, Tata Steel engaged an EPCM contractor for the new facilities' construction. Additionally, operational personnel should be assigned exclusively to either the BF-BOF or DRP-EAF lines to minimize cross-process errors. The future of the IJmuiden site will be characterized not only by clean ironmaking technologies but also by an ecosystem of supporting infrastructure, such as CC plants, water treatment systems, and gas handling installations.

In conclusion, Tata Steel's main de-carbonization strategy revolves around shifting to alternative fuels (initially natural gas and later hydrogen), and therefore having to replace old technologies, as well as increasing recycling to reduce raw material demand and CCUS. This strategic transformation represents a complex and significant step toward sustainable steel production. While uncertainties remain, particularly around hydrogen usage, carbon requirements, and market dynamics, the roadmap is clear: a future where Tata Steel produces high-quality steel with a drastically lower carbon footprint. This transformation is not only about the end outcomes but also about how practitioners, practices, and planning activities in the present actively shape future praxis. These situated actions and strategic decisions form an ongoing process of making and remaking strategy in real time, providing a valuable model for other energy-intensive industries aiming to de-carbonize.

5 Contextual factors in Tata Steels transition

This chapter addresses the second sub-question of this research: *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"* To answer this question, the chapter examines a range of contextual macro- and meso-contextual factors that impact the de-carbonization transition at the micro plant level as well as the micro plant practices of Operations and Maintenance (O&M). These contextual factors influence the strategic, operational, and organizational dimensions of Tata Steel's de-carbonization transition and are critical to understanding both the challenges and the pathways toward a successful transformation. All the determined factors influencing the de-carbonization transition of Tata Steel discussed in this chapter are displayed in Figure 5.1. The shift from conventional to green steel production at Tata Steel IJmuiden is not solely an engineering challenge. Rather, it is embedded within a complex web of systemic influences, including environmental mandates, public health imperatives, economic viability, labor dynamics, and societal expectations (Elderkamp, 2023). While technological innovation, such as the planned move from Blast Furnace (BF)'s to Direct Reduction Plant (DRP)-Electric Arc Furnace (EAF) systems, is central to the de-carbonization strategy, the implementation of these technologies depends on the alignment of a broad set of external conditions.

To capture the complexity of this transition, the chapter is organized into ten sections that address the meso- and macro- contextual factors shaping the transformation process, after which the uncertainties, contradictions and conclusions are discussed. These contextual factors were first identified through a review of academic literature, policy documents, news articles and industry reports. Subsequently, semi-structured interviews were conducted with stakeholders involved in or knowledgeable about the de-carbonization transition of Tata Steel IJmuiden or energy-intensive industries in general. By triangulating insights from literature with empirical findings from the interviews, a refined set of ten interrelated contextual factors was developed. These factors represent the most salient external influences that affect both the strategic direction and the practical implementation of Tata Steel's de-carbonization pathway.

Section 5.1 begins with an exploration of *environmental and social pressure*, including the need to reduce not only Carbon dioxide (CO_2), but also other harmful substances such as particulate matter and Nitrogen Oxides (NOx). Next, Section 5.2 delves into the role of *hydrogen*, its production, infrastructure, costs, and implications as a central element in the future steelmaking process. The third section (5.3) covers the essential need for *green electricity* to power both hydrogen electrolysis and plant operations. Following this, Section 5.4 examines challenges related to *construction and spatial planning*, addressing the limited physical and environmental space available for building new infrastructure. The fifth section (5.5) considers the role of *permitting procedures*. The sixth section (5.6) discusses the *costs of green steel production*, including its initial investment and operational costs. Section 5.7 includes the of *tailored agreements* to mitigate financial risk, as well as facilitating permits and necessary infrastructure. Section 5.8 considers the role of *labor*. Section 5.9 investigates *safety consider-*

ations, particularly the risks associated with hydrogen storage and use, the potential for human error, and necessary safety measures like increased distances and new protocols. Section 5.10 addresses changes in *O&M* practices, highlighting how the transition impacts workforce organization, smart maintenance, and the integration of O&M with other transformation aspects.

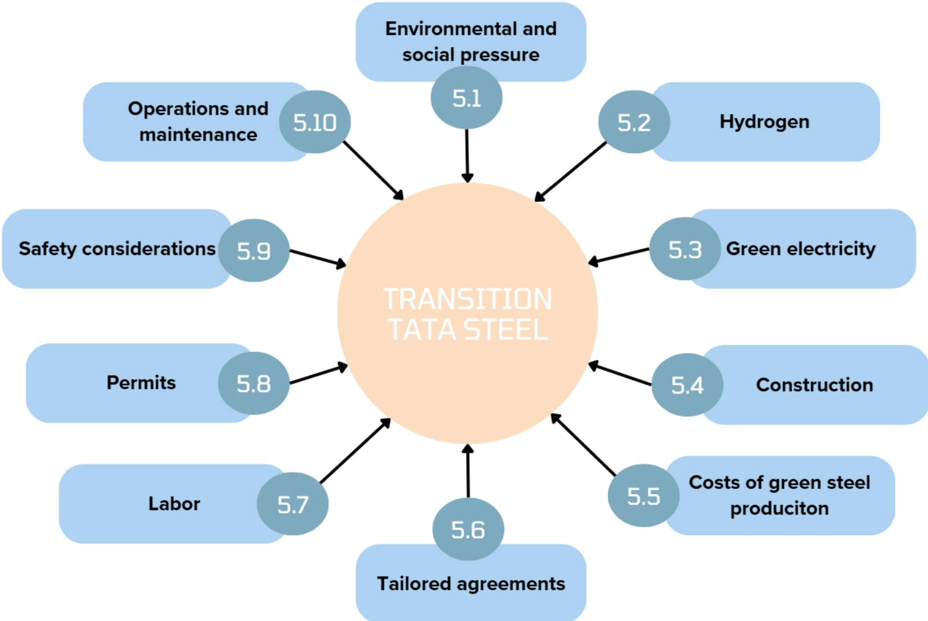

Figure 5.1: Visual representation of factors influencing Tata Steel's transition, with their corresponding sections within this chapter.

After exploring all the ten contextual factors influencing the de-carbonization strategy, the *uncertainties and contradictions* inherent in the transformation process are discussed in Section 5.11, including technological, regulatory, and societal tensions. Finally, the chapter concludes in Section 5.12, by synthesizing these findings into a broader understanding of how these interrelated factors collectively shape Tata Steel's path toward becoming a net-zero steel producer.

Together, these meso- and macro-contextual conditions form the external framework within which Tata Steel's transition must be understood, planned, and implemented. They highlight that while technological feasibility is crucial, the success of industrial de-carbonization is equally dependent on aligning environmental, infrastructural, economic, regulatory, and organizational factors. As such, this chapter serves as a bridge between the broader meso- and macro-level dynamics and the micro-level practices of de-carbonization and O&M, setting the stage for analyzing how external pressures translate into internal change.

5.1. Environmental and social pressure

While reducing CO_2 emissions is central to Tata Steel's de-carbonization efforts, it is not the only environmental concern shaping the company's transformation. Public scrutiny has intensified due to a growing body of evidence on the health and environmental risks associated with other harmful emissions, such as NOx, particulate matter, Polycyclic Aromatic Hydrocarbons (PAH), and heavy metals, released during conventional steel production (NOS, 2023). These emissions have become a central point of tension between Tata Steel and the surrounding communities. Research has shown that long-term exposure to these substances increases the likelihood of serious health outcomes, including respiratory illness, cancer, and developmental impairments in children (Geelen et al., 2023). Episodes of delayed emission reporting and environmental incidents have only amplified public concern. For example, in 2025, Tata Steel was fined €140,000 for failing to report two environmental incidents within the 15-minute regulatory window, reinforcing perceptions of insufficient environmental governance (NOS, 2025a).

These mounting pressures, rooted in public health concerns, environmental activism, and political scrutiny, have had a tangible influence on Tata Steel's corporate strategy. Initially, the company's de-carbonization plan focused on Carbon Capture and Storage (CCS) through its involvement in the ATHOS project. However, in September 2021, Tata Steel decided to withdraw from the project, effectively ending its participation in CCS development (Van Heiningen, 2024). This marked a significant turning point. In place of CCS, Tata Steel announced a more ambitious and integrated strategy aimed at producing green, clean, and circular steel (Tata Steel, 2022). This new vision explicitly prioritizes not only climate goals but also the urgent need to reduce the company's broader environmental footprint and its impact on surrounding communities. By transitioning from BF production to DRP-EAF technology, the company seeks to significantly cut CO_2 emissions while simultaneously addressing other forms of harmful pollution. The transition from coal to cleaner energy sources, such as natural gas and eventually hydrogen, brings significant environmental improvements. The removal of coal piles and coke ovens will eliminate major sources of pollution, including dust emissions and PAH's. Cleaner alternatives like natural gas, hydrogen, and electricity result in reduced pollution and are far less harmful to the environment.

> *When you take a broader perspective, you can see that the coal piles will disappear, replaced by natural gas and later hydrogen. This alone will lead to significant improvements. [...] Additionally, coal is currently used in the coke ovens to produce coke, which also generates pollution. By eliminating coal and coke ovens in the future, we will remove a major source of pollution.* (Interview 8)

Another notable advantage is the substantial reduction in NOx emissions, which is crucial for addressing nitrogen-related challenges in the Netherlands. Additionally, Zeer Zorgwekkende Stoffen (highly concerning substances) (ZZS) such as PAH's will significantly decline with the elimination of coal and coke ovens. However, the transition may slightly increase emissions of other substances, such as dioxins. Therefore, additional measures to mitigate the dioxins are needed. Although total dust emissions will decrease, certain activities will continue to generate dust, including the transport of iron ore and pellets, slag processing, and the coating of pellets with cement. To address this, various measures are being implemented in the future plant, such as installing filtration systems, covering conveyor belts, and equipping them with extraction systems to minimize dust generation. Noise emissions are expected to rise during the transition phase, and since there is no additional capacity to absorb these increases, supplementary measures will be required. Furthermore, water discharged from the installation will need to be treated in a comprehensive water purification system (Interview 8). Concrete measures in the current plant have already been introduced. Between 2019 and 2022, PAH emissions were reduced by 50% through process improvements at the sinter plant, cold rolling mill, and BFs. The company aimed to reduce visible dust in Wijk aan Zee by 65% by 2024, supported by infrastructural changes such as an 18-meter windscreen and enhanced dust management in storage areas. A De-NOx system at the Pellet Plant was expected to lower NOx emissions by 30% in 2025. Additionally, by the end of 2023, emissions of heavy metals have been cut by 55%, lead by 70%, and particulate matter by 35%, using advanced extraction and de-dusting technologies (Tata Steel Nederland, 2022). The timeline of these measures are displayed in Figure 5.2.

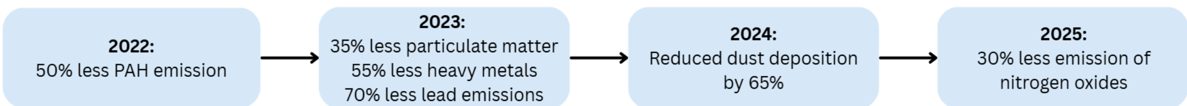

Figure 5.2: Visual representation of the transition timeline in lowering other harmful emissions.

These developments demonstrate how external environmental and social pressures have not merely influenced tactical adjustments but have fundamentally reshaped Tata Steel's strategic direction. The company's transition plan now reflects a broader commitment to aligning industrial operations with evolving societal values, regulatory expectations, and environmental imperatives.

5.2. Hydrogen

The availability of hydrogen is a key factor in Tata Steel's transition toward green steel production. Ensuring this availability requires careful consideration of various aspects, including potential hydrogen supply options. Tata Steel sees three options for obtaining green hydrogen. (Tata Steel, 2022).

The first options is by producing hydrogen on-site by using an electrolyzer. For this process is water and electricity needed as is further detailed in Section 5.2.1. The second option for obtaining hydrogen is through the national hydrogen backbone could supply hydrogen in gas state. This is a very efficient way transporting hydrogen and is further detailed in Section 5.2.2. The third and final option to obtain green hydrogen is by importing hydrogen internationally as is discussed in Section 5.2.3. This can be done by pipes or ships over large distances. These hydrogen supply options are displayed in Figure 5.3.

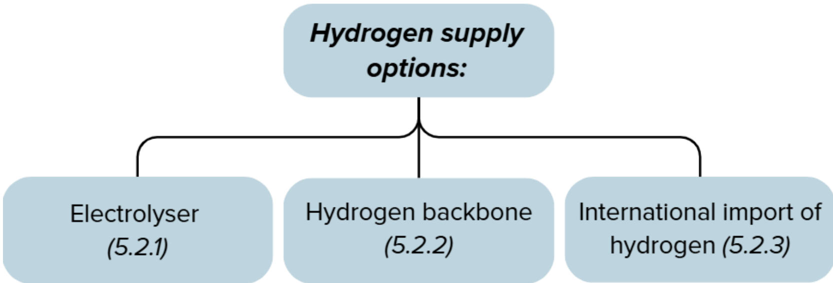

Figure 5.3: Visual representation of Tata Steel's hydrogen supply options.

According to interviewee 1 it does not matter for Tata Steel where they get the hydrogen from. Whether they need to import it or can get it through the backbone. As long as its green hydrogen and in a usable state:

> *"I think they don't really care, as long as the price is right. Yes, as long as it can be delivered to them in a form they can use, I think. In that sense, it's more of a commercial matter, looking at what contracts we can make."* (Interview 1)

Afterwards, other important factors such as hydrogen storage solutions will be described in 5.2.4, and the associated costs to the use of hydrogen will be described in 5.2.5.

5.2.1. Electrolyser

The first way in which Tata Steel can obtain hydrogen is by producing it on their own site by the use of an electrolyser. Industries commonly use three main types of electrolyzers: Alkaline Electrolyzer (AE)'s, Proton Exchange Membrane Electrolyzer (PEME)'s and Solid Oxide Electrolyzer (SOE)'s (Baum et al., 2022). There are different advantages for the different types of electrolysers:

> *"AE's are the most developed and most commonly used technology for green hydrogen production. They are slightly less efficient than PEME, they are less able to respond to intermittency. However, they are somewhat cheaper to purchase. PEME is the opposite of that: they are more expensive to purchase, the Technology Readiness Level (TRL) is slightly lower, they are less frequently applied. But they can handle intermittencies better and have a slightly higher efficiency, so you lose less energy in the conversion to hydrogen."* (Interview 7)

Electrolyzers produce hydrogen by splitting water into hydrogen and oxygen through the use of electricity. This process occurs through electrochemical reactions: oxidation takes place at the anode (the positive electrode), producing Oxygen (O_2). The reduction occurs at the cathode (the negative electrode), producing Hydrogen (H_2). An electrolyzer also contains a separator, which ensures the separation of H_2 and O_2 while facilitating the transfer of ions within the electrical circuit. The overall reaction can be represented as: Water (H_2O) $\rightarrow$ 1/2 O_2 + H_2 (Baum et al., 2022). The expectation is that Tata Steel IJmuiden will need 380 kton of hydrogen per year. To create this amount of hydrogen, a 4 GW electrolyzer is needed. Tata Steel cooperates in the H2ermes project with HyCC and Port of Amsterdam to create hydrogen by electrolyzing to lower emissions in the steel production. This facility would be 100 MW, producing up to 15500 tonnes of hydrogen, with scaling possibility up to 500 MW (H2Ermes - HYCC Project, n.d.). If a 4 GW electrolyzer is needed, it will not be enough to supply Tata Steel with enough hydrogen. If the plans for on- and offshore hydrogen production are combined, there is an expectation that the Netherlands will have a total electrolysis capacity of 11 GW in 2035.

For producing hydrogen in an electrolyzer, water is needed. This needs to be very pure water. For the 4 GW electrolyzer that is needed to produce enough hydrogen for Tata Steel IJmuiden, 3.6 - 7.6 million m^3/year water is needed. Besides the water for electrolysis, coolwater is needed to cool down the electrolyzer. Current electrolyzer technologies are 60-70% efficient, the remaining 30-40% results into heat. It can also be cooled down by air, this does not use water but needs a lot of energy and space (Ministerie van EZK & Ministerie van I&W, 2024). The H2ermes electrolyzer will have a capacity of 100 MW, with the potential to scale up to 500 MW. According to Ministerie van EZK and Ministerie van I&W, 2024, an electrolyzer typically requires one acre of land per 35–70 MW of production capacity, depending on design choices and the selected technology. This land requirement is not solely for the electrolyzer itself, which occupies approximately a quarter of the total space, but also includes area for cooling systems and infrastructure to convert electricity from high to low voltage. For a 100 MW electrolyzer installation, this translates to a land use of approximately 1.4–2.9 hectares. If scaled up to 500 MW, the land requirement could increase to as much as 14.3 hectares. Tata Steel IJmuiden has a total of 750 hectares of land available (Ministerie van EZK & Ministerie van I&W, 2024).

5.2.2. Hydrogen backbone

The hydrogen backbone is a pipeline network that will connect hydrogen production facilities, storage sites, and major consumers. The infrastructure in the Netherlands, is illustrated in Figure 5.4. The connection of Tata Steel to the backbone is indicated with number three.

Figure 5.4: Visual representation of the hydrogen backbone in the Netherlands. 1: Offshore wind energy, 2: High-voltage grid connection, 3: Connection to hydrogen backbone, 4: Importing or production of hydrogen, 5: Current gas infrastructure, 6: CCS in empty gas fields, port for importing hydrogen or exporting CO_2. Figure obtained by Tata Steel, 2025c.

Industries typically require hydrogen with a purity of approximately 98.5%. The hydrogen backbone is expected to deliver hydrogen with a purity between 98% and 99%. If Tata Steel requires higher purity levels, additional purification steps will be necessary. Furthermore, industries often use hydrogen at a pressure of 10 bar, while the hydrogen backbone is expected to deliver hydrogen at 30-50 bar. If Tata Steel cannot utilize hydrogen at 50 bar, they will need to install pressure regulation stations to reduce the pressure to suitable levels before use (Arcadis, 2025).

"Regulating stations are where the monitoring and measurement of how much natural gas you

consume takes place, and where the pressure is adjusted for the end user. If hydrogen is in the backbone, the design pressure is 66 bar. If you want to use it at your site, you first need to reduce the pressure further. And you have to keep track of how much you're taking, so it's essentially a full regulating station." (Interview 7)

Hynetwork plans to extend access to the hydrogen backbone for the region around Tata Steel by 2030. To become a customer of Hynetwork, companies must first sign a Non-Disclosure Agreement (NDA) and submit an Expression of Interest. For Tata Steel, this process also requires signing a connection study agreement, which costs €150,000. The subsequent steps include signing an investment agreement and a valve investment agreement. Once the connection agreement has been finalized, construction can begin (Hynetwork, n.d.). Gasunie implements most of the infrastructure needed for Tata Steel to access hydrogen from the backbone. The connection from the backbone to the Tata Steel plant is shown in Figure E.1. How this infrastructure needs to look like, heavily depends on the amount of hydrogen Tata Steel will use in their process. Tata steel needs to redistribute the hydrogen from the point where Gasunie's infrastructure stops (Interview 7).

5.2.3. International import of hydrogen

Hydrogen will also be imported by ships in Eemshaven, Amsterdam and Rotterdam as shown in Figure 5.4 as number seven. These importing stations are further connected by pipelines to the north western Europe network which is expected to be ready in 2035. The import of hydrogen in Amsterdam is expected to be around 1.5 million tons of hydrogen, in Rotterdam even double and in Groningen 0.75 million tons of hydrogen. Rotterdam will be the largest hydrogen import port in northern Europe. This north western Europe pipeline network provides access to hydrogen in the Netherlands, Belgium and Germany with the Port of Rotterdam as the biggest import location (TNO & Arcadis, 2025). The north western European hydrogen pipeline network is shown in Figure E.2. If hydrogen is imported over larger distances, it needs to be in a liquid state in order to be stable enough to be transported. It can be liquified by using ammonia, or by cooling it to -252,87 °C to reach its liquid state or lastly by the use of Liquid Organic Hydrogen Carrier (LOCH), which includes a chemical bound hydrogen to a liquid. But since the hydrogen needs to be bound to a liquid, it needs to be separated after transport, therefore this last method is less energy efficient. (Arcadis & DNV, 2023).

5.2.4. Storage of hydrogen

If Tata Steel plans to produce hydrogen themselves using an electrolyzer or import it via ships, they will require a storage tank. If Tata steel only wants to get hydrogen through the hydrogen backbone, they might not need a storage unit. However, according to an interviewee, a storage tank will always be needed:

"Theoretically, if you receive twenty-four-seven delivery from the backbone, you wouldn't need local storage. In practice, however, you always need some local storage, for example, during maintenance periods. [. . .] And national or European storage capacity is insufficient. So you're inevitably dealing with curtailment. Whether or not curtailment actually occurs depends on the measures we take to prevent it. Knowing that, according to current projections, curtailment is expected to occur regardless, this means you'll need more storage capacity." (Interview 6)

A storage tank can also be used to store hydrogen when the price is low, when the production price is low due to high availability of green electricity. In that way they can use the stored hydrogen when the hydrogen is more expensive in times of less availability of green electricity (Arcadis, 2025).

5.2.5. Costs of hydrogen

The estimated investment costs for producing green hydrogen are between €12 and €14 per kilogram. The cost per kilogram of hydrogen decreases as the size of the electrolyzer increases. For instance, with a 100 MW electrolyzer (such as the H2ermes project), the cost is estimated at €13.69 per kilogram. However, increasing the electrolyzer capacity to 500 MW could reduce the price per kilogram further (TNO, 2024). A research of Port Port of Amsterdam, 2024 showed that there is an expectation of €2.8-3.5/kg H_2 if hydrogen is imported into the Netherlands. The future prices will be determined in a market mechanism of hydrogen. The price depends on where you buy the hydrogen:

"The price depends on where you purchase it. It will also become a kind of free market when you buy low-carbon hydrogen. Initially, there are a number of importers in the North Sea Canal area, which is a point-to-point network if it is not yet connected to the backbone. And you will be dependent on that." (Interview 7)

The price of green hydrogen is strongly influenced by the cost of green electricity, which remains a key factor and therefore the expected prices range a lot since they depend heavily on the price of green electricity. Therefore the prices are very hard to estimate and very insecure. Investment costs for hydrogen electrolyzer projects are substantial and depending on the chosen technology, and electricity grid tariffs also have a significant impact on hydrogen pricing. These tariffs have risen in recent years, further increasing production costs. While certain factors, such as scaling up electrolyzer capacity, can help lower the price of green hydrogen, it will remain more expensive than natural gas (TNO, 2024). The scaling up of green hydrogen production remains a challenge due to insufficient demand. Large-scale production requires reliable customers such as Tata Steel, which could drive increased adoption of green hydrogen and ultimately lead to lower prices through economies of scale (Tata Steel Nederland & FNV, 2021).

5.3. Green electricity

Green electricity can be generated in offshore wind farms located in the North Sea, as depicted as number one in Figure 5.4. This electricity can also be utilized for local hydrogen production. Tata Steel is currently establishing a direct connection to the TenneT offshore wind farm, granting them direct access to green electricity (Tata Steel Nederland & Zeremis, 2023) which is indicated with number two in Figure 5.4. Producing one million tons of green steel requires approximately 4.4 TWh of energy. Given that Tata Steel IJmuiden currently produces 7 million tons of steel annually, this would translate to a total energy demand of around 31 TWh (McKinsey & Company, 2020). To facilitate this energy transition, Tata Steel has sold a portion of its land to TenneT for the construction of an electricity transformation station, under the condition that Tata Steel receives priority access to the electricity before any other users. Since the alternating current supplied by TenneT operates at 380 kV, while Tata Steel requires 150 kV, the company will also need to construct its own transformation station to adjust the voltage accordingly (Tata Steel Nederland, 2023). The electricity consumption is around 25 kWh per ton Direct Reduced Iron (DRI) (Energiron, 2024). One EAF will use 300 MW electricity, which is equal to the current electricity demand of Tata Steel. Therefore the electricity demand will increase significantly (Tata Steel, 2025c). This change in demand for electricity is shown in Figure E.3.

5.4. Construction and spatial planning

Since the DRP-EAF and all other related factories have to built while the current operations continue, there is a lack of space on the Tata Steel sight for construction. To reduce the amount of space needed. modular building will be used. Modules will be constructed outside of the plant and will be transported to the building site when finished. These modules will arrive on ships, a new transporting system in the plant will bring the modules to the right place as shown in Figure E.4. This transporting system has to be completely electrical driven since it passes a Natura 2000 area (Interview 8). The route takes a detour because of obstruction by pipelines of the current installations. Roads and rails need to be adjusted on the plant since the modules are very large and they cannot pass everywhere (Tata Steel, 2025c). Modular building is also chosen to limit the amount of extra people needed on sight during the construction. To reduce the construction activities on the site and reduce the pressure on the logistics. It reduces the local NOx emissions on site and shortens the construction phase on site. The DRP will for example be delivered as one piece which is 15 x 15 x 40 meters. This will be placed in to a tower which is built in modules as well. Modules of 15 to 27 meters high as displayed in Figure E.5. Figure E.6 shows how the modules will be transported over site (Tata Steel, 2025a).

A mobile concrete batching plant will be temporary placed on the factory site. One hundred thousand cubic meters of concrete will be needed for construction, which would equal 10.000 concrete mixers. This would cause a lot of disturbance on sight and surrounding areas when this would be transported to the plant. Therefore Tata Steel decided to produce the concrete on sight with this mobile concrete batching plant (Tata Steel, 2025d).

The EAF's must be installed close to the steel plant, as they are involved in steel production. Additionally, the EAF's need to be located within a maximum distance of 250 meters from the DRP. Before construction can take place, some destruction or relocation needs to be done as well. There currently is a large Oxy gasholder facility close to the steel factory. This gasholder facility needs to be constructed elsewhere on site and destructed at its current place since the EAF needs to be placed close to the steel factory (Tata Steel, 2022).

> *"This is an Oxy gas holder facility. We are going to relocate it, or rather rebuild it. It is 46 meters tall and currently situated next to the steel factory. It's in the way because the EAF will be placed there. Therefore, it first needs to be built elsewhere. Once the old one can be taken out of operation, it can be demolished, and then construction can start there again. It's like a building block system."* (Interview 9)

5.5. Permitting procedures

Before the construction phase can start, Tata Steel needs to apply for new permits concerning construction and destruction, a change environmental activities and the activities concerning the environmental act. The output of the basic engineering phase will be used to apply for new permits and Environmental Impact Assessment (EIA). During this application phase, the detail engineering will take place. The time in which these permits will be granted will determine the timeline of the implementation of the new product process. The construction can start after the permits have come into effect. There are permits needed for the construction of the new factories as well as for the relocation of current processes. This relocation will be necessary to create space for the construction (Tata Steel Nederland & FNV, 2021). There are three types of regulations that need to be considered for all activities: construction-related permits, permits for environmentally impactful activities, and regulations under the environmental framework, such as those related to nitrogen deposition, emissions, and nature conservation. For the construction related activities there is a building environment regulation, this includes demolition permits that will be needed for demolition of buildings before and after construction of the new factory.

> *"First, you must apply for a demolition permit because you will be demolishing more than twenty-five cubic meters. This requirement is outlined in the Building Environmental Regulations."* (Interview 5)

The building environmental regulations also specify the documents that must be submitted as part of the application, including demolition plans, material flow documentation, and information about the responsible party for material disposal. In addition to demolition activities, construction work requires a building permit. This permit consists of two components: the technical construction activity and the spatial construction activity. While these permits can be applied for simultaneously, they address different aspects of the project. The Building Environmental Regulations (BER) also detail what documentation is required and when a permit obligation applies. For example, if construction exceeds 5 meters in height, a building permit is mandatory. For the spatial component, the project must be assessed to determine whether it complies with the applicable environmental plan. If it conforms, no permit is required. However, if the project deviates from the environmental plan, an application must be submitted for either an in-plan or out-of-plan environmental activity, as defined in the Activities Environmental Regulations (AER) (Omgevingsloket, n.d.). The environmental component of the project involves changes to environmentally impactful activities. Examples of these changes include modifications to emissions, additional storage tanks, or new installations. These activities also fall under the AER and may require permits. If the company is classified as a complex company, for instance due to exceeding certain thresholds, an extended procedure automatically applies unless it can be demonstrated that there are no significant environmental impacts.

> *The activities that will be undertaken are likely to change from what is currently being done, although the core activity, steel production, will remain the same. However, emissions into the air will be different, and additional storage tanks or gas tanks may be required. These are all*

environmentally impactful activities, which are regulated under the AER. A permit must also be obtained for these activities. (Interview 5)

The application for an environmental permit requires a comprehensive set of documents, including air quality studies, noise analysis, nitrogen calculations for both construction and operational phases, energy use assessments, waste stream evaluations, wastewater management plans, documentation on the use of substances of very high concern and evidence of the application of best available techniques. Soil protection and soil quality must also be taken into account during the environmental permit process. The project must also address nature-related aspects, particularly nitrogen deposition on Natura 2000 areas and the possible presence of protected species. A flora and fauna quick scan may be required, particularly during demolition or construction activities, such as for detecting the presence of bats. For nitrogen deposition on Natura 2000 areas, a Natura 2000 activity permit must be obtained, which was previously regulated under the Nature Conservation Act. Whether spatial permits are required depends on the applicable environmental plan. For instance, permits are necessary if a new oven exceeds the current allowable height or if the built-up area percentage is exceeded. The project involves constructing a new facility before demolishing the old one, which will temporarily increase the use of the site. It is critical to verify whether this increased usage remains within the limits outlined in the environmental plan. (Interview 5)

5.6. Costs of green steel production

The transition to green steel production at Tata Steel involves both significant Capital Expenditure (CAPEX) and increased Operational Expenditure (OPEX). The CAPEX required for the construction of the first DRP installation and accompanying EAF's is estimated to exceed one billion euros (Tata Steel Nederland & FNV, 2021). Besides that the application for new permits for the new production process is also a costly procedure (Elderkamp, 2023). Beyond these upfront investments, OPEX will also rise. Producing steel through hydrogen-based DRP processes is considerably more expensive than using conventional blast furnaces or natural gas-based production methods (Tata Steel Nederland & FNV, 2021).

In addition, shifting economic conditions around carbon pricing are reshaping cost structures. Under the European Emission Trading System (ETS), the steel sector has historically received free emission allowances to protect its global competitiveness. However, by 2034, these free allocations will be fully phased out. At the same time, the availability of emission rights will be reduced, increasing their market price. This will make the OPEX of traditional, carbon-intensive steel production higher, thereby reinforcing the financial case for low-carbon alternatives (Elderkamp, 2023). The ETS will increase the cost of gray steel production in the future. As a result, the price difference between green steel and gray steel will decrease compared to today's prices.

However, green steel will still remain more expensive than steel produced through the current processes, which means the market must be willing to accept higher prices. If the BF close, their gasses can no longer be used for heating purposes on-site, this results in to the need for purchasing more external energy which will increase costs for Tata Steel. Besides that, the valuable BF slag is not produced anymore in the new process, therefore the revenues for selling this slag will be missed (Tata Steel Nederland & FNV, 2021). However, the Original Equipment Manufacturer (OEM) mentions the capturing and selling of CO_2 as an additional source of revenue:

"Energiron is the only technology that offers an additional revenue source beyond the DRI product. CO_2 capture and sale to off-takers is a lucrative business, providing millions of dollars in annual income to the DR plant operator." (Energiron, 2021)

According to interviewee 1, the costs of producing steel will change which will affect the position to compete. The locations where the plants are built were favorable when coal was needed. However it may not be a favorable location to produce steel by the use of electricity and hydrogen and therefore prices may rise:

"The way we currently produce steel in Europe, using coal and iron ore, is going to change. That also means that the cost of producing steel will change accordingly. This will have an impact

on competitiveness, because the locations that were ideal for blast furnace production may not necessarily be the best locations for producing with a DRI plant. What matters now is having efficient logistics for the supply of coal and iron ore at low cost. But going forward, what will be important is access to cheap natural gas or cheap hydrogen, and, as a result, cheap electricity. [...] So location becomes quite important, because the conditions for keeping costs low will simply change due to the energy transition." (Interview 1)

5.7. Tailored agreements

To support Tata Steel IJmuiden's transition toward green steel production, the Dutch government is negotiating tailored agreements with the company. These agreements aim to facilitate critical aspects of the transition, such as access to hydrogen and green electricity, permitting processes, and high investment costs, while safeguarding Tata Steel's economic and regional role (Interview 3). The primary objectives of these tailored agreements are threefold: to achieve measurable improvements in public health, accelerate sustainability efforts, and reduce nitrogen emissions in the IJmuiden region (Directoraat-generaal Bedrijfsleven & Innovatie, 2025). These priorities reflect growing societal and political pressure to align industrial operations with environmental and health standards. A central element of the tailored agreements is financial support. The feasibility of Tata Steel's Green Steel project depends heavily on government backing. As one interviewee explained:

"There hasn't been a final investment decision yet, otherwise, they definitely would have announced it. What they have announced is that they've started basic engineering [...] As far as I know, that investment decision is closely tied to the tailored agreements, because those ultimately determine how much government support will be available. So the shareholder naturally wants to understand that part of the financial picture before making a decision. So I think it's not just about the project or the engineering itself, but also everything surrounding it, especially the customized agreements." (Interview 1)

In addition to direct financial aid, the agreements are designed to remove infrastructural and regulatory barriers. They include commitments to improve access to critical infrastructure such as an upgraded electricity grid, hydrogen and CO_2 pipelines, and storage facilities. These are prerequisites for enabling large-scale industrial de-carbonization (Tata Steel, 2022). Importantly, tailored agreements are structured as conditional support packages. Funding is released in phases, with subsidies linked to the company's performance and progress on agreed sustainability targets. This performance-based approach ensures that public resources are used effectively and aligned with national climate and health goals (Interview 3). Beyond financial and infrastructural support, tailored agreements also play a strategic role in setting long-term conditions for Tata Steel's operations in the Netherlands. They address the dual challenge of reducing CO_2 emissions and improving environmental quality for local communities. In doing so, they seek to create a balanced framework in which industrial competitiveness and sustainability can coexist.

"These tailor-made agreements are really about one central question: what conditions can we create to enable you to make your operations more sustainable? You have to imagine that sustainability efforts by a company happen on their own little patch within a larger patchwork. If you see the Dutch industry as one big patchwork of interlinked chains of activities, then each company operates on its own patch. So they can only make changes on their own site. But the real challenge is that the government, through its policies and frameworks, has to ensure coherence across the entire patchwork. And how does it do that? By creating the right enabling conditions." (Interview 3)

In summary, the tailored agreements are not merely financial instruments but comprehensive frameworks that coordinate infrastructure, regulation, and performance standards. They are instrumental in aligning Tata Steel's strategic transformation with the broader goals of national environmental policy and industrial innovation.

5.8. Labor

The transition from a fossil fuel-based production process with BFs to a hydrogen-based production process with EAF, asks for different expertise and knowledge within the firm and its employees.

According to FNV, n.d., the new production method is less labor intensive and less employees will be needed. However, according to interviewee 8, more people will be needed than initially thought:

> *"What we see in practice is that the supplier of the DRI installation actually delivers a very basic level of automation, far from the level we, as the user, would want. [...] As a result, we initially thought we could operate the installation with 130 to 140 people in continuous shifts. But now we're saying it really has to be around 180. We simply need more people in the field."* (Interview 8)

As stated by the citation above, the type of labor changes as well for the operator. More manual operational adjustments are required in the new process. This will require training to be able to handle the new production process.

> *"Operators will need retraining to learn how the new plant operates. In the years leading up to the new plant becoming operational, many operators will need to visit existing plants to observe and understand how such a plant functions. You'll get a manual, but this is far more complex than a television manual, which you don't really need. [...] That's not how it works with a plant like this; it requires more study and training beforehand."* (Interview 1)

According to interviewee 9, the first visit to an already existing DRP plant have already occurred to learn from it:

> *"Last year, we visited a steelplant in the US. A similar installation that operates already for 10 years, it is delivered by the same supplier. [...] So while it's relatively new for us in Europe, in Egypt, Saudi Arabia, Mexico, and America, such installations already exist. So we went there."* (Interview 9)

The changes within the factory take mostly place in the upstream production process, in this part 1800 people are working. In the coal and gas factory and the sinter factory work currently 550 people. The expectation is that the same amount of people will be needed in the shaft furnaces as in the BFs. However, the coal and gas and sinter factories will entirely shut down. The main challenge will lie in the required knowledge, employees will need to be re-educated (Tata Steel Nederland & FNV, 2021).

5.9. Safety considerations

Transitioning to a de-carbonized production process introduces new safety risks and challenges. This section explores the specific safety considerations related to the DRP and hydrogen use, focusing on the safety and environmental risks in 5.9.1. After which Section 5.9.2, discusses the mixing hydrogen and gas with its risks and challenges. Next the measures that need to be taken to reduce possible human errors are discussed in 5.9.3 and the required safety distances will be discussed in 5.9.4.

5.9.1. Safety and environmental risks

Switching from natural gas to hydrogen in the DRP eliminates the risk of producing carbon monoxide, which is toxic to humans. However, hydrogen introduces heightened explosion risks due to its high combustion speed and lower ignition energy. While hydrogen ignition may occur earlier, potentially reducing the impact, its physical and chemical properties necessitate new safety precautions. Unlike natural gas, which is odorized to facilitate detection, hydrogen is odorless, making leaks harder to identify and making visual monitoring during combustion or accidents more challenging (Gersen & DNV, 2023; Rijpkema et al., 2022).

> *"Hydrogen is harder to detect, as it's also colorless and odorless. That means you have to set high standards for the design of your systems. You need to start thinking about whether it gets cold and whether it could potentially affect your materials. So, you'll need to conduct tests for that."* (Interview 2)

Besides the odorless and colourless properties, there are other physical and chemical properties introduce unique risks compared to natural gas. Its broad flammability range (4% to 75% by volume in air) and extremely low ignition energy (0.020 mJ) make it far more prone to accidental ignition than natural gas, which has a narrower flammability range (5.3% to 15%) and higher ignition energy requirements (0.29 mJ). Hydrogen also disperses rapidly due to its low molecular weight, this reduces the risk of ground-level gas clouds (Interview 2). Hydrogen combustion also generates higher temperatures than natural gas, this can potentially cause damage on the equipment and increase the NOx emissions. This necessities measures to reduce these emissions since they are a sensitive environmental issue in the Netherlands. (Gersen & DNV, 2023). As one interviewee explained:

> *"The technical risks are manageable. What is harder to prevent is the high temperature of combustion, the temperature of hydrogen compared to natural gas. This leads to higher NOx emissions, which is a sensitive issue in the Netherlands. You need to be aware that you are burning at a different temperature than natural gas."* (Interview 6)

The material compatibility of pipelines and equipment also plays a critical role in hydrogen safety, as hydrogen can diffuse into materials and cause embrittlement, leading to potential leaks or equipment failure. Furthermore,

> *"That means you need to stay up to date with the latest developments. [...] You need to monitor your system closely. You should try to minimize the amount of piping. Welded joints can increase the risk of leakage. [...] A flange is a potential leak point, not just for gas, but also for hydrogen."* (Interview 2)

Additionally, the DRP reactor operates under high pressure (8 bar), posing risks such as equipment failure and leakage. Hydrogen's small molecular size increases the likelihood of leaks, which can lead to explosions. One interviewee emphasized the importance of mitigating these risks:

> *"The reactor is a device that operates under pressure, specifically 8 bar. It is a pressure vessel, and something can always go wrong with a pressure vessel. For example, connections can break. There are people working around the installation, such as field operators. So, if something breaks while someone is nearby, things can go very wrong. An explosion is the most significant example of what could go wrong, especially because the installation operates on hydrogen. Hydrogen is a small molecule that can easily leak."* (Interview 8)

For employees, additional risks include burns from hot components and entrapment near rotating machinery. However, these are typical industrial hazards that can be managed with appropriate measures, such as separating people from machines and implementing strict monitoring systems:

> *"For the staff, there are also risks such as hot components, which can lead to burns. In addition, there is the danger of entrapment. For example, someone could get trapped near a sieve or a rotating device. Of course, measures are taken to prevent this, such as separating people and machines. This is also monitored. So yes, these are the normal industrial hazards that we already face in the current operations."* (Interview 8)

Despite these risks, one interviewee pointed out that safety risks are inherent to all fuels and can be managed effectively, just as they are for natural gas:

> *"You more often hear in the news about boilers exploding than any other fuel, as far as I know, and we have a boiler with natural gas in every house."* (Interview 6)

5.9.2. Mixing hydrogen and gas

Increasing the hydrogen use in the DRP introduces several engineering and safety challenges, especially when blending it with natural gas. While these gases can be safely mixed, doing so requires technical adaptations to ensure reliable and efficient operations. Currently, in many existing plants, more than half of the reduction process is already performed by hydrogen (Gersen & DNV, 2023).

> *"Mixing gases doesn't pose any additional risks. We're already used to mixing various gases. There are mixing stations all over the site. We already have several stations where we currently mix different gases."* (Interview 8)

While the reactor vessel can already handle mixed gases, modifications are required to the surrounding systems, including pipelines and mixing infrastructure.

> *"The reactor vessel is fully capable of using both gases mixed together. But everything around it needs to be adjusted, including where you mix the hydrogen. The natural gas and hydrogen pipelines have to be installed, and you need to ensure they are mixed correctly. This has safety implications, requiring additional measures to meet safety standards."* (Interview 1)

One of the core adaptations concerns the combustion process. Hydrogen burns at a higher temperature than natural gas, producing more radiant energy, up to 25% more, which changes how heat is distributed. Moreover, hydrogen combustion generates water vapor instead of CO_2, affecting flue gas composition and heat transfer. While CO_2 is more effective at radiating heat, the higher flame temperature of hydrogen compensates for this.

> *"All the properties of the reaction depend on the temperature. These will also change if you use a different fuel, as you'll reach a different temperature."* (Interview 6)

These temperature changes also influence reaction behavior in the furnace. As hydrogen is blended in, the air-to-fuel ratio must be carefully managed due to hydrogen's lower calorific value. This demands advanced burner control systems capable of adjusting to fluctuating fuel compositions (Gersen & DNV, 2023).

> *"You need to re-engineer your balance of plants [...] to handle gases and all combinations of gases, you will need to engineer for multiple scenarios. But it is certainly possible."* (Interview 1)

Beyond the core systems, hydrogen use impacts the infrastructure, cooling water, gas pipelines, monitoring equipment, and raises additional material and safety concerns. One critical consideration is the Wobbe Index, which determines the interchangeability of fuels in burners:

$$\text{Wobbe Index} = \frac{\text{Calorific Value}}{\sqrt{\text{Relative Density}}}$$

The Wobbe index for natural gas is 53.47, compared to 48.35 for hydrogen. Because of hydrogen's lower value, a greater volume is required to achieve the same energy output. This may necessitate larger piping and system upgrades. Operating outside the Wobbe index range can lead to combustion instability: too high can cause incomplete combustion and CO formation; too low can cause flame lifting and safety risks. Blending hydrogen also introduces the risk of hydrogen embrittlement, which weakens certain materials under pressure. Proper material selection, engineering for multiple scenarios, and regular inspections are critical to avoid failure (Zachariahwolff et al., 2006).

5.9.3. Reducing human error

Human error remains a key safety concern when working with multiple gases or in new production processes. Effective training and clear system design are essential to ensure workers understand the differences between natural gas and hydrogen and can operate safely.

> *"If you have both feedstocks and you don't want them to mix, make sure that cross-contamination is ruled out by simply making the connections different. Different in color, different in shape, different in diameter, then mixing will at least not be possible."* (Interview 2)

Training is critical to build awareness and confidence among employees:

> *"You need to make people very aware of the differences between natural gas and hydrogen, so that you can educate and train them on how to work safely with hydrogen. That knowledge and experience can be shared at that moment. That is the greatest protection for your employees."* (Interview 2)

To prevent accidental gas mix-ups, plant design should include clearly differentiated connections, using unique colors, shapes, and sizes, so incorrect fittings are physically impossible.

> *"There are rules for which colors we should assign to pipes, for example, for hydrogen, nitrogen, and other gases. This also applies to the connections, so that everything is clearly identifiable and cannot be mixed up. For instance, when you visit the energy company, you see an entire panel with various connections specifically designated for different gases. In this way, it is ensured that everything remains safe and organized."* (Interview 8)

During the transition phase, when both hydrogen and natural gas systems are active, operational errors can be reduced by assigning staff to a single plant:

> *"If you use two materials that are both necessary for your process but have different properties, and you use them simultaneously, you must ensure that operators from plant A never work in plant B. If you put people in a situation where they have to work with A today and B tomorrow, there is a chance that something might go wrong."* (Interview 2)

5.9.4. Safety distances

Safety distances play a key role in the planning and deployment of hydrogen systems, helping to maintain external safety and minimize the risks linked to possible incidents. Hydrogen systems consist of various components, such as electrolysers, low-pressure storage (up to 30 bar for on-site generation), high-pressure storage (up to 60 bar for purchased hydrogen), piping networks, refueling stations, and mobile tube trailers for transport. Each component introduces specific risks that must be addressed during the design phase. A key element in safety assessments is the 10^{-6} risk contour, which defines the area where the annual probability of a fatal incident due to hydrogen activities is one in a million. This contour serves as a regulatory benchmark for land-use planning and facility siting, requiring that individual risk contours from all components be integrated into the overall site design to ensure compliance and protect surrounding areas.

Hydrogen storage poses significant safety concerns, particularly the risk of explosion and pressure waves. For example, the failure of a high-pressure storage system containing 5,000 kg of hydrogen at 30 bar could produce an overpressure of 1 bar within 50 meters, capable of severe structural damage. At 200 meters, the overpressure may still reach 0.14 bar, and at 665 meters, it could measure 0.03 bar, which is sufficient to cause light structural damage. The radius of impact depends on factors such as storage pressure, hydrogen volume, and system configuration, emphasizing the importance of carefully considering these parameters in infrastructure planning. Due to the unique physical properties of hydrogen, such as low ignition energy, high diffusivity, and wide flammability range, its systems produce more intense effects during failure compared to natural gas systems. This necessitates special attention to spatial planning and containment measures during the design process. Early integration of safety distances is essential, combining quantitative risk assessments, adherence to safety regulations, and practical layout strategies to minimize risks. By addressing these factors, hydrogen systems can be designed to protect both personnel and the surrounding environment effectively. (Interview 2)

5.10. Operations and maintenance

Effective O&M are vital to the success of industrial transitions, especially those involving new technologies. Equipment failures can cause significant direct losses through unplanned downtime and repair costs, as well as indirect consequences such as reduced output, environmental harm, and reputation damage. For a company like Tata Steel, a single failure could disrupt production, compromise environmental safety, and erode stakeholder trust, ultimately threatening the success of the green transition. This section starts in 5.10.1 by outlining general O&M practices. Section 5.10.2 addresses the specific changes required on maintenance for hydrogen-based systems. Section 5.10.3 introduces smart maintenance practices, and Section 5.10.4 connects O&M to the contextual transition elements.

5.10.1. Operations and maintenance practices

Industrial O&M relies on structured strategies that balance cost, asset performance, and risk. Proactive approaches help avoid failures and their cascading effects on safety, compliance, and public perception. Maintenance activities follow the Plan-Do-Check-Act (PDCA) cycle, beginning with strategy development based on asset criticality and failure modes. High-criticality assets require preventive measures, while less essential components may follow a run-to-failure model. Another key element is the availability of materials during maintenance. Inadequate access to spare parts can delay repairs and increase downtime. Spare parts management, guided by OEM recommendations and tools like Failure Mode, Effects, and Criticality Analysis (FMECA), is crucial to avoid delays and minimize downtime (The Global Forum on Maintenance and Asset Management, 2021).

Failure Mode Effect Critical Analysis (FMECA)
FMECA is a risk analysis tool widely used across industries to anticipate potential failures and improve the availability of installations. By identifying failure modes and assessing their impact, FMECA helps ensure systems are operational when needed, ultimately enhancing reliability and minimizing downtime (Kiran, 2022). As described in an interview:

> *Failure mode means, I have this pump. Where can it break down? [...] A failure mechanism could be that the seal has broken. Then you look at how critical this is for the environment, for the person, or for the installation. You do this with an FMECA study, so you basically look at where it can fail, what is acceptable and what is not acceptable. Based on the FMECA, you can say, okay, this means we need to regularly inspect it for leaks. And for example, that means we test once per quarter to check if it still functions."* (Interview 9)

By evaluating the likelihood and severity of failures, FMECA informs preventive actions, such as regular inspections or design changes, to avoid operational disruptions. It enables designing robust systems that can handle potential failures and remain available when needed. Its structured approach makes it a valuable tool for improving reliability, availability, and safety in industrial operations (Kiran, 2022).

Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE)
Another study used to create the maintenance plan is RAMSHE. This study is a systematic approach used to evaluate and optimize the performance, reliability, and sustainability of industrial systems by focusing on six key dimensions. It expands the typical RAM focus to include Safety, Health, and Environment. As explained in Interview 9:

> *"In projects, you use RAMSHE studies. [..]. This means you look closely at the subject, for example by zooming in on a 3D model of the installation parts. What happens if there is a serious failure somewhere? [...] Reliability and availability are numbers you can influence in the design. [...] A study like this is basically the foundation to check if the design is solid enough to guarantee, for example, 8000 hours of operation. This is also done for safety, health, and the environment."* (Interview 9)

Reliability is the likelihood that a system will perform its function without failure over a given time, often measured by Mean Time Between Failures (MTBF). Availability refers to the chance an installation is operational when needed, which can be improved through redundancies like extra pumps. Maintainability concerns how quickly and easily a system can be repaired, with a focus on restoring operations within a set time. For Tata Steel, the RAMSHE framework also includes Safety, Health, and Environment, emphasizing designs that minimize environmental impact, ensure safe operations, and protect workers and the community (Kumar et al., 2024).

Hazard and Operability Study (HAZOP)
Alongside RAMSHE, HAZOP is used to inform maintenance practices. This structured method identifies potential hazards and operational issues by analyzing deviations from intended design conditions. As a core part of Preliminary Hazard Analysis (PHA), it supports safe system design and operation. Using tools like Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID), each system component is reviewed under both normal and abnormal conditions. Risks are assessed by severity and likelihood, guiding the implementation of safety measures (Dunjó et al., 2009). For instance, a HAZOP study evaluates whether maintenance or replacement can be safely performed during operation:

> *"We need to replace it, so this is something you must be able to do during operation. The other three will continue producing. And then they made sure, using so-called HAZOP studies, that the operations were safe. For example, what do we do? You need to replace it. Okay, what do we do? Loosen valves, tighten valves, bolts. Can this be done safely? Then you already know you need two valves and venting in between to ensure no gas can escape or come into contact with the people."* (Interview 9)

5.10.2. Maintenance change due to the use of hydrogen

Hydrogen introduces new O&M challenges. Due to its small molecular size and high diffusivity, it poses greater leakage risks than natural gas. Hydrogen pipelines must be regularly inspected, and maintenance protocols must include safe isolation, depressurization, purging with nitrogen, and post-maintenance revalidation (Gersen & DNV, 2023; Wolff et al., 2023). Hydrogen's flammability and combustion characteristics require adjusted flame detection systems and operator training. Its high flame speed can cause acoustic issues, while its high flow velocity can introduce mechanical stress. Burners must operate within defined parameters to mitigate vibrations and erosion. Turbine meters are preferred over ultrasonic ones due to their reliability with hydrogen, and regular calibration is essential (Gersen & DNV, 2023).

5.10.3. Smart Maintenance

Tata Steel applies smart maintenance to optimize processes and enhance reliability through predictive and preventive strategies. Real-time monitoring, such as tracking motor hours and vibrations in rolling mills, allows early detection of failures, minimizing downtime. The Asset Management & Diagnostic Center analyzes system data to assess wear and its impact on product quality (Tata Steel, n.d.).

Predictive maintenance uses ultrasonic sensors to detect early-stage wear. As degradation progresses, vibration and oil signals trigger preventive action. Once wear becomes audible or causes looseness, damage is often already severe. Continuous monitoring improves maintenance planning and production reliability. Smart maintenance combines predictive analytics, condition monitoring, Internet of Things (IoT), automation, and asset management. Sensors and data analytics predict issues, IoT devices collect real-time data, and automated systems streamline responses. Asset management tracks performance and extends equipment life.

Key benefits include reduced costs, fewer failures, and greater efficiency and sustainability. Implementation begins with digitalizing equipment data using IoT sensors. AI-driven analysis creates predictive models that guide timely maintenance. Clear goals, infrastructure development, pilot testing, staff training, and phased roll-out are essential for success. Ongoing optimization and knowledge sharing further enhance system performance (Smart Industry, n.d.).

5.10.4. Relation O&M to the contextual factors

O&M both influences and is influenced by several key aspects of the hydrogen-based green steel production system which are previously discussed in this chapter. Clarifying these relationships helps identify where O&M should be actively involved or adapt to external requirements. The interaction, with its direction, of all aspects and O&M are displayed in Figure 5.5.

Figure 5.5: Visual representation of the interactions between O&M and the other interrelated factors. The arrows illustrate the direction of the interaction.

- **Environmental and social pressure (5.1):**
O&M is central to managing emissions and pollutants through proper monitoring, timely replacement of filters, and maintenance of abatement systems. Good O&M ensures continuous compliance with environmental standards which reduces social pressure. However, O&M is also influenced by the environmental and social pressure, due to these pressures Tata Steel needs to make sure maintenance prevents operational failure.

- **Hydrogen (5.2):**
The properties of hydrogen, such as high flammability, small molecule size, and high diffusivity, directly influence O&M procedures. Maintenance must address hydrogen-specific hazards with enhanced detection, safe material selection, and operator training (The Global Forum on Maintenance and Asset Management, 2021).

- **Green electricity (5.3):**
The intermittent nature of renewable electricity affects system operations and the scheduling of maintenance. O&M must adjust to fluctuations in power availability and ensure energy efficiency under variable supply conditions.

- **Construction (5.4):**
Early O&M involvement in the design and construction phases can improve maintainability and reduce future operational risks. Conversely, the construction phase determines how accessible and safe systems will be for ongoing maintenance.

- **Permits (5.5):**
Operating the new facilities requires updated environmental and safety permits, which are closely tied to O&M performance. Regulatory compliance depends on documented, verifiable maintenance procedures and operational reliability. Maintenance plans must align with permit conditions, and readiness for audits is essential throughout the asset lifecycle (The Global Forum on Maintenance and Asset Management, 2021).

- **Costs of green steel (5.6):**
Efficient maintenance reduces downtime and enhances energy efficiency, contributing to lower production costs and improved cost competitiveness of green steel.

- **Tailored agreements (5.7):**
  Performance in O&M affects the ability to meet environmental and health objectives tied to phased agreements. O&M practices determine whether operational conditions align with agreed benchmarks, impacting support continuation. The tailored agreements set boundaries for O&M in which they need to comply to (Directoraat-generaal Bedrijfsleven & Innovatie, 2025; Tata Steel, 2022).

- **Labor (5.8):**
  O&M depends on the availability of skilled workers and adequate training, particularly for hydrogen-related safety. At the same time, O&M practices determine the degree of automation or physical labor needed and therefore the amount of workforce (The Global Forum on Maintenance and Asset Management, 2021).

- **Safety (5.9):**
  Safety requirements shape how O&M is performed, from work procedures to required competencies. In turn, well-executed O&M ensures that safety systems function as intended, reducing the likelihood of incidents (The Global Forum on Maintenance and Asset Management, 2021).

This interconnectedness highlights that successful de-carbonization hinges on more than technical feasibility, it requires a robust, responsive, and well-integrated O&M function that can anticipate and adapt to changing conditions. However, as these interdependencies grow more complex, so too do the uncertainties surrounding the transition. The following section explores these uncertainties and contradictions in greater depth, examining how they challenge assumptions about hydrogen technology, project timelines, and the overall implementation trajectory.

5.11. Uncertainties and contradictions

The transition to hydrogen-based steelmaking at Tata Steel is surrounded by a range of technological, logistical, economic, and social uncertainties. These uncertainties not only affect the feasibility of the transition but also shape the pace and structure of its implementation. A central technological question concerns the use of 100% hydrogen in the DRI process. While technology providers such as Tenova and Danieli claim that their Energiron plant is capable of running on 100% hydrogen without major modifications (Pauluzzi et al., 2021), interviewees presented contrasting views. One expert stated:

> *"The DRI installation cannot operate entirely on 100% hydrogen without any carbon. A small amount of carbon is necessary to keep the metallurgical process running."* (Interview 8)

Another interviewee emphasized that, in theory, it is possible, but practical applications remain rare:

> *"There are not many DRI installations that actually operate on 100% hydrogen yet. It presents an additional challenge because you are not adding carbon to the iron, but you need carbon to produce steel [...] So if carbon is not added during the DRI process, it must be added during melting or in the steelmaking plant."* (Interview 1)

The CO_2 emissions of the DRI plant are also uncertain, as they depend on the ratio of natural gas to hydrogen utilized in the production process. According to Tata Steel, this is still being researched, and no final technology has been chosen for CO_2 capture or transport. Questions remain about whether captured carbon would be stored on-site, in pressurized tanks, or cooled and transported by ship. These options are all under consideration, but "*nothing has been decided yet*" (Interview 8).

The hydrogen supply itself presents another significant challenge. Tata Steel does not plan to produce all needed hydrogen on-site. Instead, the assumption is that hydrogen will be purchased externally. However, such reliance on the network introduces supply risks and uncertainties. Unlike natural gas, where continuous delivery through the grid is standard and storage is often unnecessary, green hydrogen is subject to fluctuations. As one expert put it:

> *"Very theoretically, if you receive twenty-four-seven delivery from the backbone, you wouldn't need local storage. In practice, however, you always need some local storage, for example, during*

maintenance periods. [. . .] And national or European storage capacity is insufficient. So you're inevitably dealing with curtailment. Whether or not curtailment actually occurs depends on the measures we take to prevent it. Knowing that, according to current projections, curtailment is expected to occur regardless, this means you'll need more storage capacity and greater flexibility, both on the production side and the consumption side." (Interview 6)

To mitigate this uncertainty, Tata Steel is installing equipment that can operate fully on natural gas, ensuring production can continue even when hydrogen availability is limited or prices are volatile. Furthermore, Tata Steel's projected hydrogen needs have changed multiple times during infrastructure planning, making it difficult to accurately design the hydrogen backbone network, leaving many uncertainties (Interview 7). This level of variability is not unique to Tata Steel, but reflects broader uncertainty within the industry as many companies have yet to commit to a definitive de-carbonization path (Interview 7). Economic factors add further unpredictability. The hydrogen market is still in its early stages, and price forecasts remain speculative:

"There is a bandwidth you need to take into account in terms of costs for hydrogen [...] Unfortunately, that's the reality. Sometimes, you have to take those risks and see what happens." (Interview 7)

Another interviewee remarked:

"No one can say with certainty exactly what will happen to prices, because it is market-driven. [...] Then everything has to come from renewables, and if the energy demand remains intact, and the supply will be what it will be, then, as far as I can see, this means that energy prices will rise." (Interview 1)

This could lead to relocation of energy-intensive industries, potentially lowering demand, but such effects are difficult to predict.

The social dimension presents contradictions as well. While Tata Steel has committed, through a social plan with trade unions, to prevent job losses due to the green transition by using natural attrition, this stands in tension with more recent developments. However, this commitment contrasts with the announcement of 1,600 layoffs, creating significant uncertainty and concern among the workforce (NOS, 2025b).

Finally, there is the fundamental uncertainty around the availability of green hydrogen and electricity itself. As Tata Steel a representative acknowledged:

"We need an awful lot of green energy, green electricity, green hydrogen, and we don't have it yet. But by taking this step now, we think we can help drive the hydrogen market and ensure its acceleration" (Gasunie, n.d.).

This statement underscores the reality that, despite not yet having secured the necessary energy supply, the company is choosing to take a calculated leap, hoping that by committing to demand, it will stimulate the growth of the supply side. As one interviewee aptly summarized:

"If you want to make your operations more sustainable or decarbonize by 2030, you need to start making concrete plans now. [...] Because the situation in the future is still so uncertain and difficult to predict, it is also very challenging at this stage to design the system around it." (Interview 7)

An important contradiction that was found is the level of automation in the operations. According to the OEM, the new installations are foreseen of highly automated systems:

"Energiron plants are controlled by a highly automated system providing level 2 automation, requiring minimal human intervention and providing high plant availability and reliability" (Energiron, 2021)

However according to interviewee 8, Tata Steel finds this automation very limited and much more manual intervention is needed than in the current production process:

> *"We had hoped: we are going to build the factory of the future. So we thought we would implement a highly advanced automated system, like what we are already accustomed to at Tata Steel. Here, we have factories that are already highly automated. But what we are seeing in practice is that the supplier of the DRI installation is actually providing a very basic level of automation, nowhere near the level we, as users, would like. [...] The operator will have to do more, for example, continuously adjust the temperature. He or she will have to monitor trends and deviations much more closely. Where deviations were normally corrected automatically, this will now have to be adjusted manually."*

5.12. Conclusion

This chapter addressed the second sub-question of this research: *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"* The analysis demonstrated that Tata Steel's transition toward net-zero steel production is not merely a technological substitution, such as replacing BF-Basic Oxygen Furnace (BOF) systems with DRP-EAF technology, but a multidimensional transformation that is profoundly shaped by meso and macro contextual factors. These include environmental and social pressure, energy infrastructure of hydrogen and green electricity, spatial constraints during construction, permitting procedures, economic viability, institutional support through tailored agreements, labor capabilities and safety considerations.

A key insight from this chapter is that the successful implementation of green steel technologies hinges on the coordinated availability of green hydrogen and renewable electricity, both in terms of supply and cost. Hydrogen emerges as a central pillar of Tata Steel's de-carbonization strategy, but its effectiveness is conditioned by the development of a national hydrogen backbone, import arrangements, storage facilities, and clarity on purity and price. Similarly, sufficient access to green electricity is vital, not only to power the plant but also to produce hydrogen itself, placing additional demands on grid infrastructure and long-term energy planning. The chapter also revealed that spatial and environmental constraints, such as those related to Natura 2000 regulations and limited plant area, pose substantial challenges to constructing new infrastructure. These constraints require modular and adaptive construction strategies that minimize environmental disruption while accommodating the scale and complexity of the transition. From an economic perspective, the cost gap between conventional and green steel remains a barrier to implementation, even with the increasing stringency of the EU ETS. In this context, tailored agreements with the government become crucial, not only for de-risking capital investments but also for aligning permitting, infrastructure development, and environmental accountability. These agreements act as a systemic enabler, transforming fragmented dependencies into coordinated action.

The analysis further underscored the importance of labor and organizational change. Shifts in automation levels, operational control, and safety protocols necessitate significant retraining and reconfiguration of the workforce. This includes developing new competencies in hydrogen safety, manual monitoring, and preventive maintenance. Safety considerations also emerge as a non-negotiable requirement. The flammability and volatility of hydrogen demand new protocols, sensors, operator roles, and physical design changes that meet higher safety thresholds. These risks are compounded by the potential for human error and the need for culture change within operations. Moreover, the chapter emphasized that permitting procedures introduce time-sensitive and technically complex hurdles. These include environmental impact assessments, air quality modeling, nitrogen deposition studies, and compliance with both local and EU-level legislation. The pace of the transition will be partially dictated by the efficiency of these regulatory processes.

Lastly, the role of O&M is not peripheral, but central to ensuring the long-term sustainability and reliability of green steelmaking. As technological systems grow more complex and interdependent, smart maintenance strategies, supported by predictive analytics and integrated planning, are essential for delivering on both environmental performance and economic efficiency. Among these, the greatest uncertainties lie in the supply and use of hydrogen, which is foundational to the transition. Issues such as the availability and pricing remain unresolved. In particular, the feasibility of operating on 100% hydrogen remains uncertain due to current technological limitations. Tata Steel's fallback strategy to install dual-compatible systems that can also run on natural gas illustrates the need for flexibility in response to these uncertainties. A second area of tension involves automation. On one hand, the shift to new systems like DRI-EAF offers opportunities for increased digitalization and predictive maintenance. On the other hand, the installations as provided by the OEM greater manual control and operator awareness. This contradiction introduces organizational challenges around labor, training, and procedural design, impacting the daily functioning of O&M.

Crucially, the interrelated macro factors analyzed in this chapter do not only shape Tata Steel's macro level strategic direction, they also directly influence the micro-level practice of O&M. As outlined in Section 5.10.4 and illustrated in Figure 5.5, O&M is both a dependent and active agent within the transformation system.

In conclusion, Tata Steel's strategic transition toward net-zero steel production is shaped by an intricate network of interrelated factors. These include:

1. Evironmental and social pressure
2. Hydrogen availability and uncertainty around full hydrogen operation
3. Green electricity supply
4. Environmental and special constraints during construction
5. Environmental and permitting requirements
6. High capital and operational costs
7. Government support through tailored agreements
8. Labor transitions and layoffs
9. Safety risks associated with hydrogen systems
10. Robust and adaptive O&M practices

These macro- and meso- factors not only influence strategic feasibility but also fundamentally reshape the daily praxis of O&M at the micro plant level. Therefore, the feasibility and implementation of this transformation will depend on the coordinated alignment of these external conditions with internal capabilities, particularly O&M, which acts as both an enabler and a safeguard within the broader system. Only through a systems-level approach that explicitly connects macro and meso constraints with micro operational realities can the transition to green steelmaking at Tata Steel be successfully realized.

6 Operations and maintenance in the future state

This chapter addresses the third sub-question of this research: *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"* This chapter investigates how strategy is enacted through the concrete, situated activities by practitioners responsible for Operations and Maintenance (O&M) practices within Tata Steel's green steel transformation. Rather than treating strategy as a top-down blueprint, this chapter emphasizes the micro-level practices, roles, and interactions that shape how the net-zero ambition is realized on the ground.

In the context of Tata Steel's future hydrogen-based steel production, O&M becomes a critical strategic practice. It is not merely a technical function aimed at ensuring the Reliability, Availability, and Maintainability (RAM) of equipment, but also a key enabler of Safety, Health, and Environmental (SHE) performance in a fundamentally altered production environment. The shift to technologies such as the Direct Reduction Plant (DRP)-Electric Arc Furnace (EAF) and the use of hydrogen as an alternative fuel introduces novel risks and uncertainties, particularly those associated with hydrogen's volatility and its implications for equipment integrity, system design, and operator safety. As a result, O&M must evolve to include new routines, tools, competencies, and collaborative relationships.

This chapter maps the constellation of stakeholders as practitioners involved in enacting O&M as a strategic practice. These include internal actors such as process owners, control and field operators, installation managers, and Tata Steel's hydrogen committee, as well as external practitioners such as Original Equipment Manufacturer (OEM)s, specialized maintenance firms, regulators, the local community, and emergency response teams. Their contributions span across multiple phases of O&M, from concept development and planning to proactive/reactive maintenance, operations, and feedback loops. These roles are analyzed not just in terms of functional responsibility, but as sites of practical strategizing and negotiation in the unfolding transition. Drawing on stakeholder theory (Freeman, 1984) and insights from interview data (see Appendix E), the chapter foregrounds how the practitioners' routines and decisions actively shape the strategic direction of Tata Steel's decarbonization. It highlights the interplay between operational reliability and broader institutional, safety, and environmental objectives, showing that O&M is not peripheral, but central to the transformation.

The structure of this chapter is as follows: Section 6.1 outlines the core phases of maintenance activity. Section 6.2 situates operations within this maintenance practice and praxis. Section 6.3 examines the distributed roles of stakeholders as strategic practitioners throughout the phases of O&M. Finally, Section 6.4 synthesizes these insights to answer the sub-question.

6.1. Phases of maintenance

Based on the literature, as discussed in Chapter 2, a basis for a framework considering all different phases of maintenance were considered. Planning of maintenance, proactive and reactive maintenance were included as phases for maintenance. However, from the interviews it was clear that the maintenance concept phase and feedback phase are very important to consider as well:

> *"This is the step before you actually start planning. This is the design of your maintenance concept, and that concept says something about failure mechanisms, like frequency, what we need to do, especially the what and the how. [...] So, essentially, it's like creating the maintenance manual for your car."* (Interview 9)

These practitioner insights emphasized that effective maintenance requires attention not only to execution but also to the upfront conceptual development of maintenance strategies and the structured evaluation of tasks afterward.

> *"Besides your preventive and reactive maintenance, you also have a feedback phase. We always say: evaluate your task. [...] If you don't turn that into actions, you'll make the same mistake next time. Plan-Do-Check-Act (PDCA): plan, do, check, act."* (Interview 9)

The foundation of Tata Steel's maintenance strategy lies in its maintenance concept, which focuses on creating structured guidelines and processes to ensure the reliability and longevity of installations. By combining traditional approaches with modern technologies, the concept enhances performance while addressing critical components, identifying failure mechanisms, and meeting legal requirements. This comprehensive framework prioritizes systems that are essential to production and environmental goals, ensuring installations are equipped to operate efficiently and safely. Based on the identified failure mechanisms, the maintenance plan can be defined.

> *"What are the actual causes of why that thing breaks down? We're trying to zoom in on those failure mechanisms so that we can perform very specific maintenance aimed at preventing those problems."* (Interview 8)

Building on the maintenance concept, maintenance planning systematically translates guidelines into actionable schedules and procedures. This phase ensures maintenance processes are executed effectively, with clear timelines designed to minimize downtime and disruptions. Maintenance planning coordinates tasks across interconnected systems, such as the DRP, EAF, and steel plant, enabling smooth operations even in complex production environments. Through precise scheduling and resource allocation, downtime is minimized, ensuring operational continuity. The maintenance plan is entered into the Systems, Applications, and Products (SAP) system (SAP, n.d.).

> *"SAP is nothing more than a digital planning board. So it tells you, today you need to do this, and that's this order. That's a digital order, and then you look and see all kinds of tasks listed. [...] Company X does that together with Company Y, we do this ourselves, production does that, and eventually, I have to inspect it, give approval, and hand it over again to production, and they will put it back into operation. All those kinds of things also need to be recorded."* (Interview 9)

Proactive maintenance, and specifically preventive maintenance is emphasized as a key strategy to maintain high availability and reduce costly unplanned downtime. By proactively addressing potential issues, preventive measures focus on ensuring components operate reliably over extended periods. This phase leverages advanced monitoring tools, such as sensors, to perform condition-based maintenance to prevent failures. More details regarding the use of sensors and data for preventive maintenance can be found in Section 5.10. Proactive maintenance can also be time-based and determined by law obligations. Proactive maintenance plays a vital role in sustaining production efficiency and mitigating risks associated with equipment wear and tear.

> *"We choose to perform as much preventive maintenance as possible. That means we plan maintenance in advance. [...] We focus on Condition-Based Monitoring and Condition-Based Maintenance."* (Interview 8)

Despite the emphasis on preventive strategies, reactive maintenance, or corrective maintenance, is employed to address unexpected failures and unplanned issues that arise during operations. This phase minimizes the impact of disruptions by focusing on rapid detection and resolution of faults. Reactive maintenance ensures that critical systems are restored quickly, maintaining production efficiency and reducing downtime. Standardized procedures and safety protocols are implemented to handle emergencies effectively, including those involving hazardous systems.

> *"Corrective maintenance is a choice; it should be a choice."* (Interview 9)

The feedback loop is integral to Tata Steel's maintenance strategy, serving as a critical mechanism for continuous improvement. This phase evaluates maintenance tasks, identifies gaps, and refines processes to enhance operational efficiency. Root-cause analysis techniques, such as the 5 Whys (Andersen & Fagerhaug, 2006), are used to understand failures and implement corrective actions. By integrating the PDCA cycle, the feedback loop ensures maintenance strategies evolve in response to real-world challenges, driving long-term reliability and performance. All the phases described are displayed in Figure 6.1.

> *"We will have trained people, and they need to be familiar with troubleshooting, but also with finding the root cause. So, root-cause analysis is very important to us. Why did something break? If you ask 'why' five times, you'll get to the root cause."* (Interview 9)

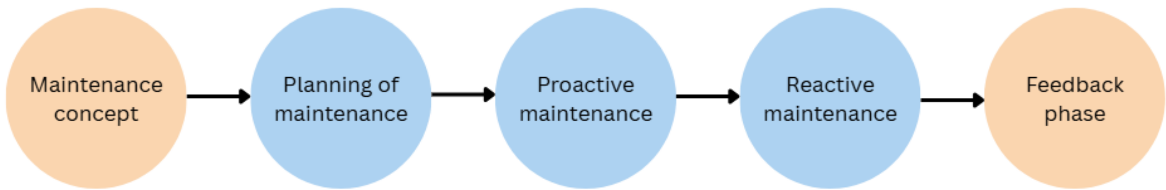

Figure 6.1: Visual representation of the different phases in maintenance. The phases based on literature are colored in blue, the phases based on the interviews are colored in orange.

6.2. Operations

The operation of installations is closely tied to maintenance strategies, which are designed to ensure efficient, reliable, and continuous production by optimizing reliability, availability, and maintainability, while also upholding rigorous standards for safety, health, and environmental protection. These integrated Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE) considerations form the foundation for minimizing downtime and supporting sustainable, long-term operational performance. Operations represent the real-time environment in which both proactive and reactive maintenance are enacted, emphasizing the dynamic interplay between these functions. Operators play a pivotal role in monitoring and managing production processes, responding to deviations, and maintaining overall system performance. Maintenance, in turn, provides the foundation for continuous operations. Proactive maintenance practices, such as preventive and predictive maintenance, are instrumental in keeping installations in optimal condition. By identifying and addressing potential issues through regular inspections, monitoring, and scheduled interventions, maintenance minimizes disruptions and ensures continuous, and efficient operations. For instance, preventive measures can significantly reduce the likelihood of equipment failures that might otherwise halt production, safeguarding operational continuity and reliability.

> *"This installation aims to keep running continuously for as long as possible, because otherwise you have energy loss. You have to slowly heat it back up at 50 degrees per hour when it cools down, before you can start producing again. So that means every malfunction can immediately cause production loss, but also that you need some time to heat it back up before you can put it back into operation."* (Interview 9)

Operational demands directly influence maintenance priorities and schedules. High-output installations, such as the DRP and EAF in steel manufacturing, operate under substantial stress due to continuous production cycles. This constant operation generates wear and tear on critical components, such as pumps, filters, and conveyors, necessitating regular maintenance to sustain performance. Maintenance schedules are carefully tailored to align with operational requirements, ensuring critical systems are serviced without compromising production timelines. A good example of this interdependence is seen in the relationship between the DRP and the EAF in a steel plant. The DRP produces hot Direct Reduced Iron (DRI), which is directly used in the EAF for steel production, as is further detailed in Chapter 4. If the DRP undergoes scheduled maintenance, the EAF may lose its supply of hot DRI, leading to production disruptions. To mitigate this, cold DRI buffers are maintained to ensure the EAF can continue operating during DRP downtime. This example highlights the importance of synchronized downtime planning and the interdependent nature of such systems.

> *"You're also part of a chain of production factories. We supply to the EAF, which internally supplies the steel plant, and then to the casting machine. That makes the slabs, and those slabs go to the hot strip mill or the direct sheet plant. [...] So you're part of that entire chain, which means that if we come to a standstill for three days, the EAF can keep running for a while. That's because we produce hot DRI but can also produce cold DRI. By that time, we make sure the buffers with cold DRI are full so that we might just be able to manage."* (Interview 9)

These interconnected systems demand precise coordination of maintenance and operational activities. Maintenance schedules are often aligned with operational stops, ensuring that critical tasks, such as annual inspections or quarterly inspections, are completed without adversely affecting production output. This synchronization minimizes downtime and ensures that both O&M can function seamlessly. It is also possible that the EAF needs to stop its operations for reactive maintenance for example. Instead of shutting down the operations of the DRP as well, it can produce cold DRI to not loose operational capacity.

> *"But suppose the EAF team says, "Oh, we can't continue," then you need to be able to stop production immediately. In that case, it would be a waste to completely halt production, so instead, we switch to producing cold DRI."* (Interview 9)

Operators act as a critical link between O&M. Field operators perform essential tasks such as manual inspections, lubrication, and sampling to monitor equipment health, while control room operators oversee automated systems and respond to deviations. Their real-time observations and reports provide invaluable data for maintenance teams, enabling timely interventions and adjustments. In less automated installations, such as the new DRP systems, operators are increasingly required to perform manual interventions, such as adjusting temperatures, valves, and flow feeders. This shift further underscores their role in bridging the gap between operations and maintenance.

> *"They perform various tasks needed to keep the installation running, such as small maintenance jobs, lubricating valves, and checking valve positions. Field operators are essentially the ears, eyes, and nose of the installation in the field."* (Interview 8)

Maintenance strategies also play a key role in ensuring safety within industrial operations. Regular inspections, adherence to safety protocols, and compliance with legal requirements prevent hazardous conditions and protect personnel, equipment, and the environment. This relationship between maintenance and safety ensures that operations proceed without compromising health, safety, or environmental standards.

Within the maintenance framework as displayed in Figure 6.1, operations can be understood as a distinct phase situated between proactive and reactive maintenance. It is during operations that proactive maintenance strategies are executed and their effectiveness tested. When unforeseen issues occur despite these efforts, reactive maintenance is initiated to restore functionality. In this sense, operations serve as the dynamic environment where system performance unfolds in real-time, both benefiting from proactive maintenance and triggering reactive responses when necessary. This placement highlights the pivotal role of operations as the interface through which maintenance strategies evolve as shown in Figure 6.2.

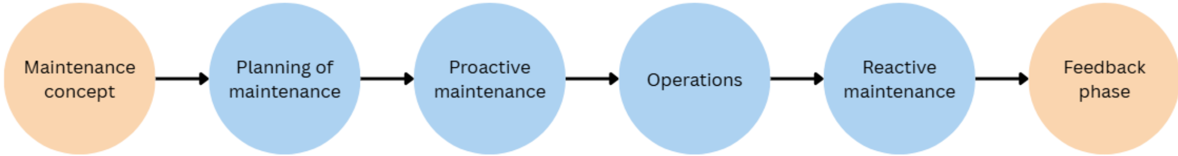

Figure 6.2: Visual representation of the different phases in O&M. The phases based on literature are colored in blue, the phases based on the interviews are colored in orange.

6.3. Roles and contributions of stakeholders in Operations & Maintenance

The operational and maintenance phases involve a diverse range of stakeholders as practitioners, each contributing to various phases including the concept, planning, proactive maintenance, operations, reactive maintenance, and feedback phases. This section outlines the roles and responsibilities of stakeholders including the process owner, field operator, control operator, installation manager, hydrogen committee, OEM, maintenance firms, regulatory bodies, emergency teams, and the local community. A comprehensive overview of this chapter is displayed in Table 6.1.

Each section of this chapter illustrates the involvement of stakeholders across the different phases of the system lifecycle, as depicted in Figure 6.2. In the figure, arrows from stakeholders to specific phases indicate that the stakeholder plays an active role or exerts influence in that phase. Conversely, arrows pointing from a phase to a stakeholder signify that the stakeholder is affected or impacted by the activities within that phase.

6.3.1. Process owner

The process owner plays a central role across all maintenance phases as shown in Figure 6.3. During the concept phase, the process owner designs the maintenance strategy using information provided by the Original Equipment Manufacturer and existing maintenance experience. This strategy identifies critical units and maintenance-intensive components, focusing on failure mechanisms and leveraging analytical studies such as RAMSHE, Hazard and Operability Study (HAZOP), and Failure Mode, Effects, and Criticality Analysis (FMECA). These studies were described in more detail in Chapter 5. The maintenance plan is integrated into SAP, a widely used enterprise resource planning system that helps streamline maintenance processes, track schedules, and manage resources efficiently, while replacement strategies and responsibilities are clearly defined. In the planning phase, the process owner ensures maintenance tasks are aligned with operational goals, compliant with legal requirements, and coordinated efficiently. Proactive maintenance tasks are overseen with an emphasis on preventing equipment failure, particularly for critical installations. The process owner ensures safety measures, clear procedures, and comprehensive documentation, including yearly and quarterly production stops for preventive maintenance. During operations, the process owner manages day-to-day functionality, ensuring safety, reliability, and compliance while training the workforce, publishing annual reports, and preparing production stops. In the reactive maintenance phase, the process owner responds to unplanned equipment failures, restores functionality promptly, documents activities, and addresses root causes to prevent recurrences. Finally, during the feedback phase, the process owner analyzes maintenance performance, incidents, and outcomes to refine strategies, sharing findings globally within Tata Steel to improve metrics like mean time between failures and mean time to repair.

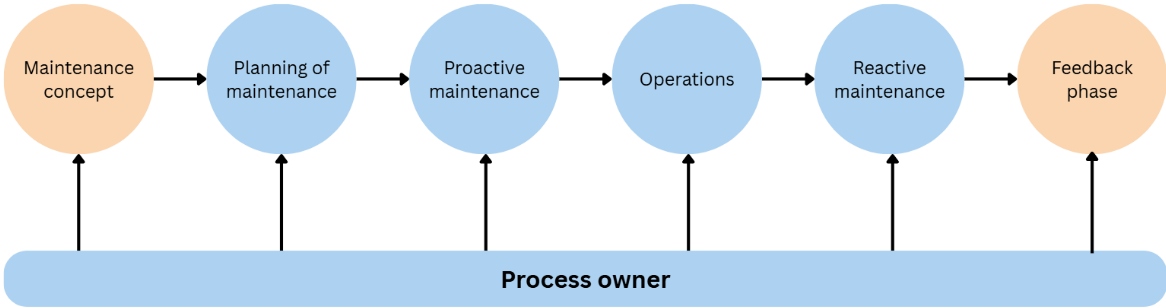

Figure 6.3: Visual representation of the influence of the process owner in the different phases in O&M. The process owner has an influence on all stages of maintenance and the operation.

6.3.2. Field operator

The field operator serves as the link between real-world operational conditions and maintenance strategies. They have a role in all phases of O&M as shown in Figure 6.4. In the concept phase, the field operator provides data, observations, and feedback to shape the maintenance concept and identify components that require frequent maintenance. Proactive maintenance involves monitoring equipment to prevent failures and ensuring compliance with safety regulations. During operations, the field operator conducts minor maintenance tasks such as lubrication, steel sampling, and executing SAP-generated tasks to maintain high production availability. In reactive maintenance, the field operator acts as the first responder to equipment failures, addressing issues promptly to minimize downtime, while performing cleanup and hazard mitigation under managerial direction. In the feedback phase, the field operator documents completed activities, recurring issues, and observations to identify root causes and improve future maintenance efforts.

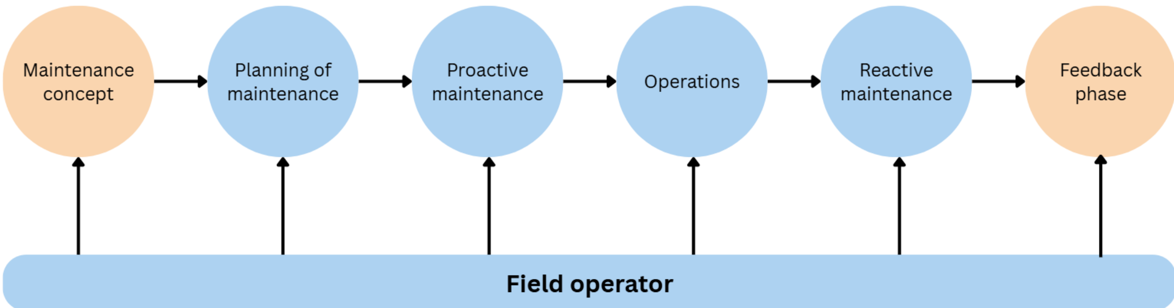

Figure 6.4: Visual representation of the influence of the field operator in the different phases in O&M. The field operator has an influence on all stages of maintenance and the operation.

6.3.3. Control operator

The control operator is crucial for monitoring and managing systems across all phases as shown in Figure 6.5. During the concept phase, the control operator provides operational feedback to optimize maintenance plans based on real-world conditions. Proactive maintenance tasks involve ensuring systems are shut down and prepared for maintenance during scheduled stops. The control operator is affected by this downtime since the operational work is paused. In the operations phase, the control operator monitors equipment using advanced sensors such as vibration detectors, pressure drop measurements, and temperature sensors, identifying issues early. Due to limited automation, control operators actively oversee processes, requiring constant vigilance and quick decision-making. Reactive maintenance involves documenting alarm codes, reporting them to the manager, and shutting down production if required for safety. During emergencies, the control operator coordinates with field operators and responders to mitigate risks. In the feedback phase, the control operator provides insights into recurring issues, identifies root causes, and documents observations for future improvements.

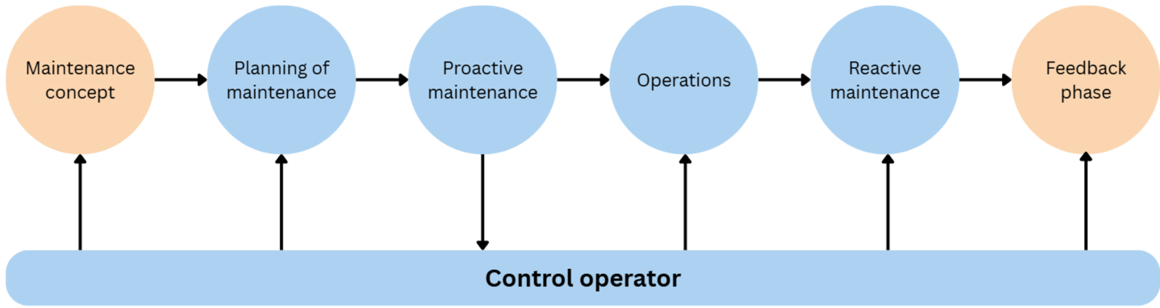

Figure 6.5: Visual representation of the influence of the control operator in the different phases in O&M. The control operator has an influence on almost all stages of maintenance and the operation. They are influenced by the proactive maintenance phase since their work stops during that time.

6.3.4. Installation manager

The installation manager ensures the coordination and compliance of all O&M activities. During the concept and planning phases, the manager allocates resources such as spare parts, workforce, and schedules, ensuring legally mandated activities are executed on time. Proactive maintenance involves supervising execution, ensuring adherence to plans, compliance with safety protocols, and approving systems for restart after maintenance. In operations, the manager monitors plant efficiency, responds to alarms, and ensures smooth functionality. Reactive maintenance involves directing emergency responses, analyzing alarm codes, and coordinating actions, ensuring incidents are documented and reported to regulatory bodies. During the feedback phase, the manager analyzes trends and adjusts strategies to improve reliability and operational efficiency, overseeing post-incident documentation for lessons learned and preventive measures. This influence on all stages of operation and maintenance is shown in Figure 6.6.

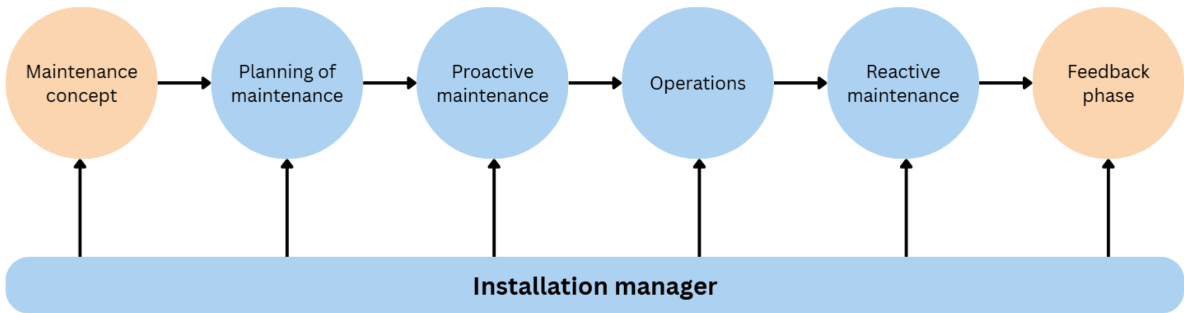

Figure 6.6: Visual representation of the influence of the installation manager in the different phases in O&M. The installation manager has an influence on all stages of maintenance and the operation.

6.3.5. Tata steels maintenance organization

The maintenance organization at Tata Steel is actively involved across all phases of the maintenance process, as shown in Figure 6.7, ensuring reliability, safety, and continuity in production. In the concept phase, the head of maintenance contributes practical experience to help shape effective maintenance strategies early on. During planning, the team prepares detailed schedules and resource plans for major interventions, such as the three-week DRP stop, including sourcing parts and organizing manpower.

Proactive maintenance for the maintenance organization is guided by a structured plan that outlines necessary tools, materials, and timing to avoid unplanned downtime. During operation, a 24/7 service team monitors performance and handles faults in real time, ensuring quick recovery. If failures occur, reactive maintenance is carried out swiftly to minimize production losses, often with limited resources but using the same technical methods as planned maintenance. Finally, all maintenance actions are documented, feeding back into the system to improve future planning and execution.

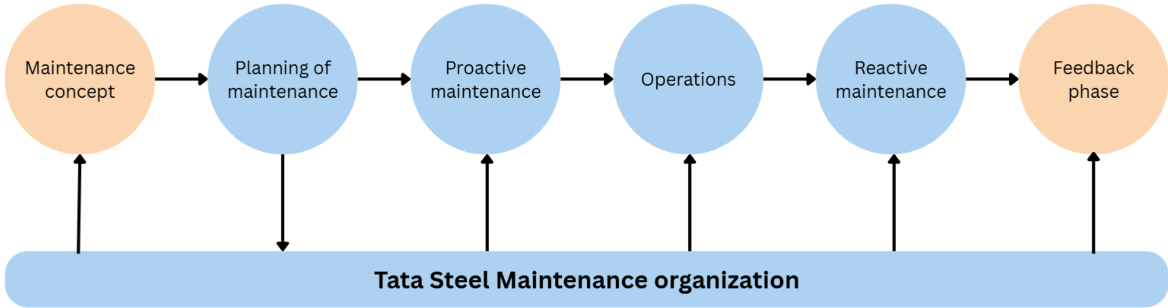

Figure 6.7: Visual representation of the influence of Tata Steels maintenance organization in the different phases in O&M. They are involved during all stages of maintenance and the operation.

6.3.6. Hydrogen committee

The Hydrogen Committee plays a vital role in ensuring safe and efficient practices as Tata Steel transitions to hydrogen-based production. Established to address the unique safety challenges posed by hydrogen, the committee provides guidance on how hydrogen affects critical materials such as valves and seals. During the concept phase, it develops safety guidelines grounded in current legislation and continuously updates them as new research, technological developments, or regulations emerge. The committee's advice is actively applied during both operations and emergency responses involving hydrogen systems, helping to maintain high safety standards throughout the plant's lifecycle. The committee's role across these stages is illustrated in Figure 6.8.

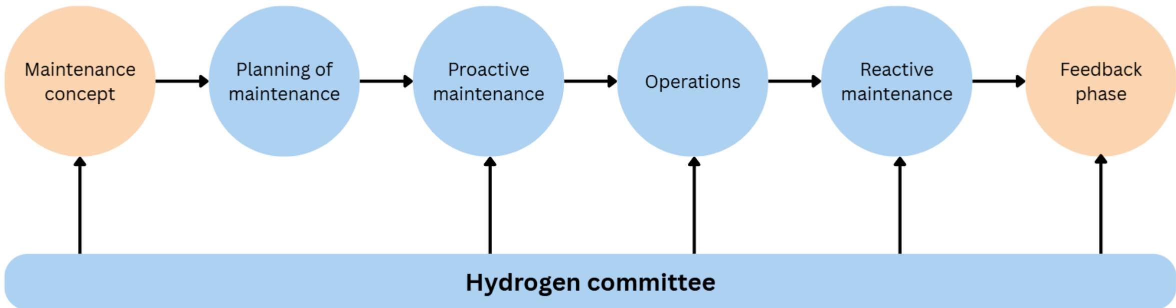

Figure 6.8: Visual representation of the influence of the hydrogen committee in the different phases in O&M. They are only not involved in the planning of the maintenance.

6.3.7. Original Equipment Manufacturer

The OEM plays a key role during the early stages of maintenance planning, as illustrated in Figure 6.9. In the concept phase, the OEM provides maintenance manuals and recommendations that form the foundation of the maintenance strategy. They also offer feedback on established plans and estimate annual maintenance needs, including the hours required for both planned and unplanned maintenance and during the equipment start-up. However, beyond this initial phase, the OEM is not involved in proactive or reactive maintenance activities or daily operations. Despite this, their early input remains essential for shaping the overall maintenance approach.

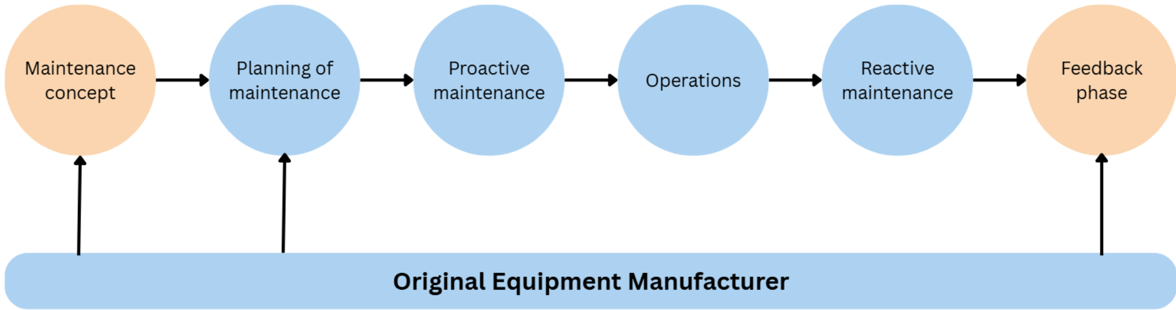

Figure 6.9: Visual representation of the influence of the Original Equipment Manufacturer in the different phases in O&M. The OEM has an influence during the concept, planning and feedback phases.

6.3.8. Firms

Maintenance firms are primarily responsible for executing outsourced physical maintenance tasks at the plant. Their involvement begins during the concept phase, where they contribute valuable practical insights and provide feedback on maintenance plans, helping to ensure that proposed strategies are feasible and effective. These firms play a critical role in preparing for both annual and quarterly operational stops, during which they carry out a range of proactive and reactive maintenance activities. Through their hands-on experience, maintenance firms help optimize maintenance costs while supporting improved equipment reliability and long-term performance. Although they are actively engaged in maintenance activities during planned shutdowns and unplanned interventions, their involvement does not extend into routine daily operations. The scope and timing of their participation across the different phases are illustrated in Figure 6.10.

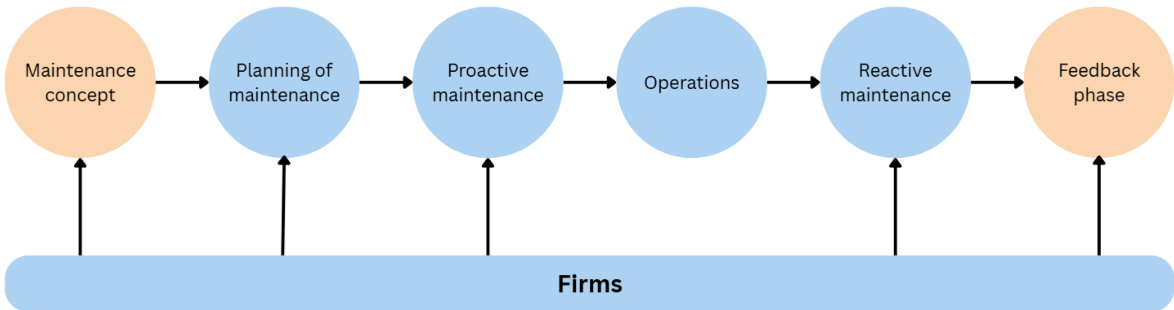

Figure 6.10: Visual representation of the influence of the firms in all different phases in O&M.

6.3.9. Regulatory bodies

Regulatory bodies play a critical role in ensuring that all aspects of plant operation comply with applicable laws and regulations throughout every phase, as illustrated in Figure 6.11 (Directoraat-generaal Bedrijfsleven & Innovatie, 2025). They establish the legal framework governing maintenance concepts, including setting mandatory inspection frequencies, safety standards, and environmental requirements. Maintenance plans are regularly monitored by these authorities to verify compliance, while operational data is scrutinized to ensure that emissions and other environmental impacts remain within legally defined limits. Regulatory oversight extends beyond routine checks; incidents must be reported promptly, often within strict deadlines, such as a 15-minute notification window for emergency situations. In the event of serious incidents, such as major environmental releases or explosions, additional regulatory bodies including Rijkswaterstaat and labor inspection authorities are engaged to oversee investigations and enforce corrective actions. Through these measures, regulatory bodies uphold safety, environmental protection, and worker welfare, ensuring that de-carbonization and maintenance efforts align with broader societal and legal expectations.

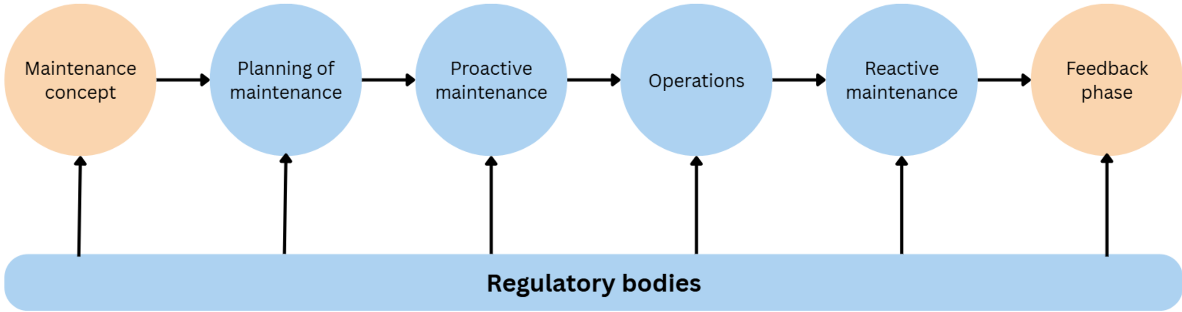

Figure 6.11: Visual representation of the influence of the regulatory bodies during all different phases in O&M.

6.3.10. Emergency team

The emergency team consists of internal firefighters, regional firefighters, and both local and central crisis teams, each playing a vital role in responding to incidents. Internal firefighters, who have in-depth knowledge of the plant's installations and associated hazards, are the first responders to big on-site emergencies, enabling quick and effective action. When incidents surpass the capacity or expertise of the internal team, regional firefighters are summoned to provide additional support and specialized skills. For large-scale emergencies, local and central crisis teams take charge of coordinating response efforts, ensuring that established protocols and communication channels are rigorously followed to manage the situation safely and efficiently. The emergency team's involvement is confined to the reactive maintenance phase, focusing on managing and mitigating incidents as they occur. Their role across this phase is illustrated in Figure 6.12.

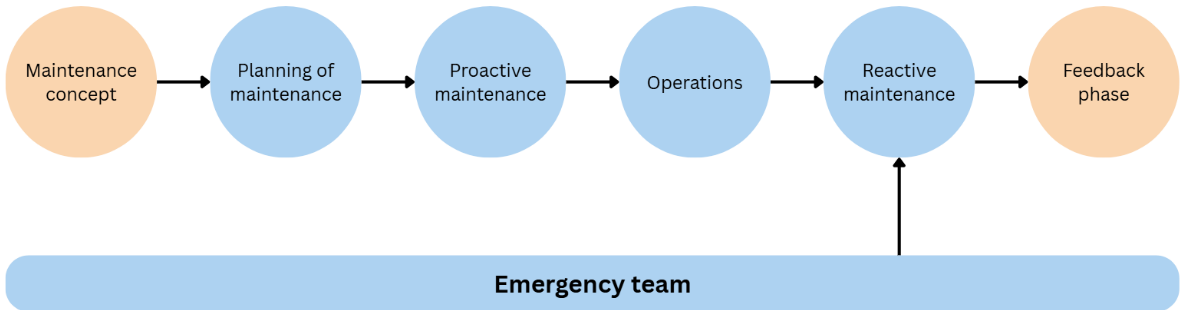

Figure 6.12: Visual representation of the influence of the emergency team during the reactive maintenance phase.

6.3.11. Local community

Finally, the local community plays an indirect role during the concept and planning phases, primarily as recipients of information about operational activities during participation evenings, as mandated by the Environment and Planning Act. The transition to new processes eliminates significant sources of pollution like coal piles and coking plants, reducing emissions of dust, Nitrogen Oxides (NOx), and Polycyclic Aromatic Hydrocarbons (PAH)'s, which benefits the local environment. However, emissions like dioxins may slightly increase, and dust emissions will persist due to activities such as iron pallet transport, slag processing, and pellet coating. An annual report detailing the operational impact is published for public access. During emergencies, such as when gas is flared to release pressure, Carbon dioxide (CO_2), dust, and noise emissions are immediately reported to authorities to minimize damage. The impact of the operations and reactive maintenance on the local community is displayed in Figure 6.13.

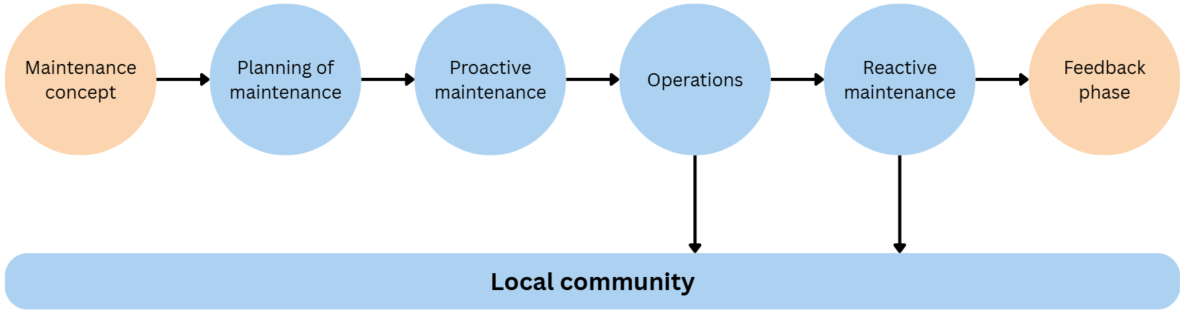

Figure 6.13: Visual representation of the influence of the operations and reactive maintenance on the local community.

6.3.12. Clients

Clients are primarily impacted during the operational phase, as illustrated in Figure 6.14. One significant concern is the potential reduction in automation within the production process, which may lead to increased variability in steel quality. This variability can result in less consistent product characteristics compared to current standards, potentially affecting clients' manufacturing processes and final product performance. As clients often rely on predictable and high-quality steel inputs, fluctuations in material properties could require adjustments in their own operations, quality control measures, or supply chain planning. Understanding and managing this variability will be crucial to maintaining strong client relationships and meeting market expectations throughout the transition to new production methods.

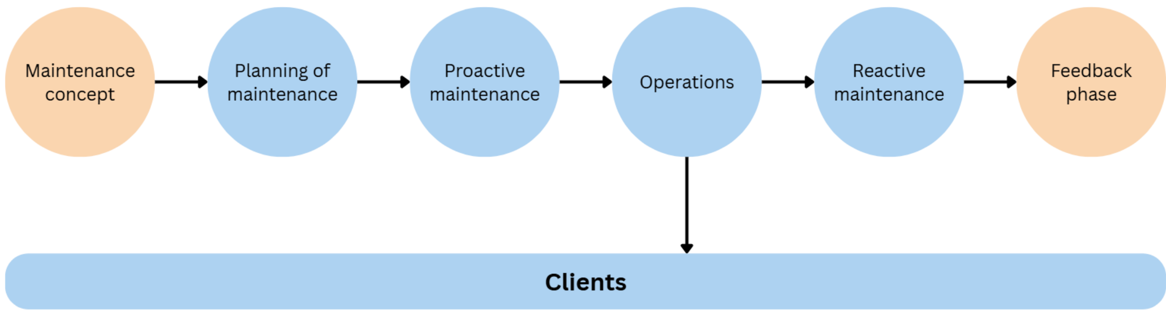

Figure 6.14: Visual representation of the influence of the operation on the client.

6.4. Conclusion

This chapter addressed the question: *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"* The findings demonstrate that O&M are not merely supporting functions, but constitute a strategic backbone in Tata Steel's de-carbonization journey. In the future green steel plant, O&M ensures the Reliability, Availability, and Maintainability of critical systems, while also safeguarding Safety, Health, and Environmental standards. These RAMSHE principles are not abstract goals, they are concretely enacted through day-to-day practices, routines, and decisions by a diverse set of stakeholders. As such, O&M is best understood as a dynamic and distributed practice of strategizing that underpins the continuous operation and long-term sustainability of the plant.

With the transition to DRP-EAF technology and hydrogen-based reduction, the role of O&M evolves significantly. Maintenance is mainly proactive, knowledge-driven, and adaptive to new risks, especially those related to hydrogen's volatility. Smart maintenance strategies, including condition-based and predictive maintenance, supported by IoT technologies and sensor networks, enable early fault detection and intervention. These strategies not only reduce downtime but also ensure regulatory compliance and long-term equipment integrity. Importantly, the chapter highlighted that O&M begins well before the first piece of equipment is installed. The concept development phase, where failure mechanisms, frequencies, and intervention strategies are first defined, is critical to establishing a resilient and efficient maintenance foundation. Likewise, the feedback phase is indispensable for continuously refining operations, aligning with the principle of continuous improvement. These phases, often under emphasized in literature, emerged from practitioner insights as essential components of strategic O&M.

Operations are tightly interwoven with maintenance. In the future plant, operators will be essential in the less automated systems such as the DRP. Their real-time observations, manual interventions, and close coordination with maintenance teams anchor the reliability and responsiveness of the production process. Hydrogen's introduction amplifies the strategic relevance of O&M. It brings novel safety concerns and demands new protocols for equipment handling, storage, and leak prevention. The hydrogen committee will be vital in updating guidelines and safety standards. Here, O&M functions not only as a technical necessity but as an institutional mechanism for translating safety norms into practice.

Stakeholders are central actors in this process. From field operators and installation managers to external maintenance firms, regulatory bodies, and the local community, each plays a role in shaping and executing the O&M strategy. Their collaboration is essential in bridging technical goals with regulatory, social, and environmental expectations. The interdependence of these actors reinforces that O&M is not organized in isolation but through distributed and ongoing negotiation.

In conclusion, stakeholders organize and strategize O&M in Tata Steel's de-carbonized production process through a distributed, proactive, and collaborative approach. O&M is not simply a set of operational tasks; it is a strategic infrastructure that enables the company's de-carbonization. Stakeholders, from field operators and installation managers to external partners and regulatory bodies, contribute through distinct roles across the different phases, from concept development to feedback. Their involvement ensures that RAMSHE principles are integrated into daily routines, risk mitigation strategies, and long-term planning. The organization of O&M reflects a dynamic interplay of tools, practices, and cross-functional coordination, making it the practical enactment of the de-carbonization strategy at the micro plant level. This chapter has mapped how O&M is envisioned to function in the future hydrogen-based DRP-EAF steel production system. The following chapter builds on these insights to explore the concrete transitions, learning processes, and capacity-building efforts necessary to realize this sustainable future. The next chapter builds on these insights to identify the concrete changes, learning processes, and capacity-building efforts required to move from today's state to the sustainable future described here.

Table 6.1: An overview of all stakeholders involved in the future O&M, along with their responsibilities and activities during the phases of maintenance and operations. Information in italics was derived from the interviews, while the remaining details were explicitly stated in the interviews.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Process owner	Responsible for developing the maintenance strategy and collecting the information needed.	Coordinate maintenance activities to align with operational goals through a detailed plan that minimizes risk, optimizes downtime, and ensures compliance.	Coordination of maintenance and ensuring safe execution of all activities by creating a safe workspace and providing clear instructions.	Managing day-to-day functioning of equipment. It is responsible for operational control, safety, reliability, environmental compliance, and cost management.	Manage unplanned maintenance tasks for equipment or systems that fail unexpectedly and coordinate the maintenance teams.	Identifies the root-cause of an incident and improves the maintenance plans accordingly.
Field operator	Provide relevant data and experience from the field to feed into the system and ensure its alignment with real-world conditions.	Provides relevant data and experience from the field for the maintenance plan.	Performs preventive maintenance obligated by law that needs to be executed that day and cannot be postponed.	Executes tasks such as checking of installations, lubricating, and sampling steel.	Solve unexpected maintenance; they are sent by the manager.	*Provides insights and observations, identifying the root-cause of an incident.*
Control operator	Provide relevant data and experience from the field to feed into the system and ensure its alignment with real-world conditions.	Provides relevant data and experience from the field for the maintenance plan.	There is once a year a three-week operation stop and three times a three-day stop for maintenance.	Monitoring tasks and conditions to prevent production interruption. Guards the process and acts actively when the system deviates.	Responsible for analyzing alarm codes in the system, bringing the system back to a safe state in case of emergency. Coordinates the field operator for maintenance.	*Provides insights and observations, identifying the root-cause of an incident.*

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Installation manager	Receives and utilizes the maintenance information for planning and execution (reserve parts, activities, time, men count).	Responsible for overseeing maintenance activities.	Responsible for overseeing maintenance activities and ensuring the system is utilized effectively. Approves for operation again after maintenance.	Sees the alarm code reported by the operator that something is off and checks the maintenance schedule.	Receives alarm notifications, reviews unexpected maintenance for insights, and oversees emergency responses, escalating to factory or site management depending on the severity.	Monitors reactive maintenance trends to adjust the maintenance plan and creates a red line report after major incidents, detailing the cause, impact, and preventive actions.
Tata Steel maintenance organization	Experience and knowledge of the maintenance team is used for the maintenance concept. The head of maintenance is included to share experiences.	Preparing maintenance before the 3-week stop of the DRP, and the maintenance on the EAF and pallet factory.	There is a preventive maintenance plan for the maintenance organization, including where to buy or test materials needed for maintenance, required resources, manpower, time, tools, warehouse items, and article numbers.	24/7 service team addresses faults and restores the installation as quickly as possible. This occurs during operation.	Fewer people and less quality materials might be used in reactive maintenance. Methods of installation and removal are the same as during preventive maintenance. Repairs are done as quickly as possible so operation can resume, minimizing TTR.	*Documents the performed maintenance.*
Hydrogen committee	The committee stays up-to-date on developments in the hydrogen field. It researches the impact of hydrogen on valves and seals.	The committee stays up-to-date on developments in the hydrogen field. It researches the impact of hydrogen on valves and seals.	*Due to the research on the impact of hydrogen on materials, preventive maintenance can better be estimated.*	*The committee provides operational insights on working with hydrogen.*	*Due to the research on the impact of hydrogen, emergency responses can be adjusted.*	If there are changes regarding rules and laws of hydrogen, the committee provides this information for adjustment of the plan.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
OEM	Provides instructions for maintenance of the equipment and decides on the brands for the equipment and therefore maintenance needs.	Provides feedback on the maintenance plan.	The OEM indicated the number of hours for planned and unplanned maintenance.	The OEM is only involved in the operation when the equipment is handed over to the process owner at the start of production.	The OEM indicated the number of hours for planned and unplanned maintenance.	OEM and firms get the chance to give feedback on maintenance plans once they are ready.
Firms	The knowledge and experiences with maintenance of firms are used in the maintenance concept.	Provides feedback on the maintenance plan.	Performs the proactive maintenance.	*Perform maintenance during the operational downtime periods.*	*Performs non-emergency-related reactive maintenance.*	The knowledge and experience of maintenance firms have an essential role in optimizing costs and long-term performance.
Regulatory bodies	Laws of the regulatory bodies are used to construct the maintenance concept.	The environmental service monitors the plans and tests if they comply with the law and the rules of the hydrogen committee, if they stay within the environmental boundaries, and if working conditions are safe.	Legally obligated maintenance by the regulatory bodies determines the preventive maintenance based on time.	The environmental service receives operational data regarding the environmental measures every year. They check the operational safety and environmental impact of the operations.	The environmental service checks the safety. In case of an emergency, the incident needs to be reported to the environmental service within 15 minutes.	Checks whether the maintenance has happened within the requirements of the law.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Emergency team	-	-	-	-	In case of an emergency, the internal firefighters and crisis team can come into action. They take over and instruct the operators.	-
Local community	-	-	-	Emissions of dust, NOx, and PAH's will decrease, reducing the harm to the local community. Emissions of dioxins will increase, and some dust will remain.	During incidents where the installation needs to release pressure, gas is flared, which can cause CO_2 emissions, dust, and noise, which can harm the local community.	-
Clients	-	-	-	Due to less automation of the operations, steel quality may be less consistent than it currently is.	-	-

7 Required changes in operations and maintenance

This chapter aims to address the fourth sub-question of this research: *"What changes in operations & maintenance are required to support Tata Steel's de-carbonization transition?"* It explores how Tata Steel's shift from coal-based to hydrogen-based steelmaking is being operationalized through changes in everyday Operations and Maintenance (O&M) practices. Rather than treating the transition as a top-down roll-out, the chapter adopts a micro-level view of how strategy is enacted through the actions, decisions, and interactions of those directly involved in O&M. Section 7.1 outlines the current O&M setup within the traditional blast furnace system. Section 7.2 then compares these to the future requirements of a hydrogen-based Direct Reduction Plant (DRP)-Electric Arc Furnace (EAF) system, identifying critical changes such as new maintenance strategies for hydrogen safety, the introduction of predictive monitoring tools, and stronger integration between operational and safety functions.

It also highlights how roles and responsibilities evolve, operators, managers, external firms, and regulators all contribute to shaping and sustaining this transformation. These shifts are not only technical but organizational, affecting how work is coordinated, risks are managed, and strategy is practiced on the ground. Finally, Section 7.3 synthesizes these insights to show how reconfigured O&M practices support the de-carbonization strategy and ensure that new systems operate safely, reliably, and sustainably.

7.1. Current Operations & Maintenance

Table 7.1 outlines the current responsibilities of key stakeholders across the maintenance lifecycle, mainly based on interviews 8 & 9: concept, planning, proactive tasks, operation, reactive tasks, and feedback loops as outlined in Chapter 6. Stakeholders include process owners, field and control operators, managers, Tata Steel's maintenance teams, external firms, regulatory bodies, utility providers, clients, and specialized committees such as the Oxygen Committee. Utility providers are key stakeholders in the current production process due to their role in supporting circular energy use. Specifically, gases emitted from the Blast Furnace (BF)s are utilized by utility providers for electricity generation, contributing to the site's overall energy efficiency. However, as BFs are phased out in the transition to green steel production, these by-product gases will no longer be available. Consequently, the role of utility providers is limited to the current O&M context and does not extend into the future state. Additionally, the existing steelmaking process relies heavily on oxygen, particularly in the Basic Oxygen Furnace (BOF), as outlined in Chapter 2. To manage the safe handling of oxygen in daily operations, an oxygen committee is currently in place to provide safety guidelines and oversight. Furthermore, there is currently no significant involvement from Original Equipment Manufacturer (OEM)'s in the day-to-day maintenance of existing installations. Most equipment was procured decades ago, with OEM's only participating during the initial installation and start-up phases.

Table 7.1: An overview of the current roles of each stakeholder within O&M. Information in italics was derived from the interviews, while the remaining details were stated in the interviews.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Process owner	Manages the maintenance system (Systems, Applications, and Products (SAP)) to organize, monitor, and execute maintenance activities efficiently.	Coordinates downtime of interconnected systems, such as the BF and steel factory, and ensures maintenance plans prioritize safety and environmental compliance.	Uses condition-based and time-based maintenance with advanced monitoring. Big data and Artificial Intelligence (AI) are used to optimize maintenance cycles and detect trends.	Relies on process data and automation for production control. Constantly measures environmental parameters and publishes performance annually. Coordinates buffer downstream production by producing extra steel before planned maintenance stops.	Manages unplanned maintenance tasks for equipment or systems that fail unexpectedly and coordinates the maintenance teams.	Uses incident data for root-cause analysis. Shares insights across global Tata Steel locations to drive continuous improvement.
Field operator	*Provides field data for system input and monitoring.*	*The field operators are being scheduled for operational and maintenance tasks.*	Executes automated maintenance tasks from SAP. Conducts on-the-ground checks (lubrication, sampling, inspections) to keep systems running.	Acts on instructions from the control room. Operates machinery and monitors for abnormalities.	Responds to emergencies (e.g., loss of containment) and may need to halt operations to stop hazardous spread. Is contacted to assess injury situations.	Provides practical feedback after incidents to improve procedures and prevent recurrence.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Control operator	*Provides field data for system input and monitoring.*	Control operators are scheduled as part of the five-shift system. These operators are assigned to continuously monitor and operate the installations around the clock.	Uses sensor data to monitor conditions like pressure drops, vibrations, and temperature. Detects early signs of equipment wear.	Supervises processes via control panels. Observes system behaviour and trusts automation to self-correct most issues. Operators are assigned to specific system areas.	Logs alarms and notifies managers. In emergencies, follows safety protocols: shuts down the system, confirms safe conditions, alerts response teams, and initiates containment. Environmental services must be informed within 15 minutes of major incidents.	Identifies root causes post-incident. Shares alarm codes and operational disruptions for further analysis.
Manager	Uses maintenance information to oversee planning, execution, and resources.	Oversees the planning of maintenance tasks using data on parts, timelines, personnel, and other resources.	Ensures the maintenance system operates effectively. Uses SAP data for insight into asset condition and proactive maintenance.	Manages escalations and coordination during operations. Provides support and approval where needed.	Receives alarm codes from control operators. Reviews incident reports and initiates emergency protocols. Decides if emergency services or crisis teams are needed. May escalate to site or factory management.	Analyzes trends from reactive maintenance. After major incidents, completes a "Red Line" report detailing cause, impact, and preventive actions.
Tata Steel's maintenance organization	Provides hands-on operational insights for system improvements.	Shares practical knowledge and experience to support maintenance teams and planning.	Performs proactive maintenance.	*Supports continuous operations through maintenance activities.*	Performs reactive maintenance.	Provides feedback on maintenance activities.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Oxygen committee	Develops and enforces safe working practices related to oxygen.	Stays informed on developments in the oxygen field, including new safety practices, regulations, and material behaviour. This knowledge helps inform maintenance planning.	*Conducts research on the impact of oxygen, allowing better estimation of preventive maintenance needs.*	*Provides operational guidelines and insights for working safely with oxygen installations and systems.*	*Updates emergency response protocols based on findings from oxygen-related research to improve preparedness and response effectiveness.*	Advises when laws or regulations change regarding oxygen, ensuring maintenance plans are updated to comply with new standards.
Firms	Execute maintenance tasks on Tata Steel's behalf.	Their services are included in the maintenance plan.	Perform both condition-based and time-based maintenance on components like conveyors, screening systems, and abrasive-exposed equipment.	*Supports continuous operations through maintenance activities.*	*Steps in to handle urgent or unplanned repairs when internal teams require external support.*	Shares insights from field experience for service improvement.
Regulatory bodies	Laws define the maintenance concept.	Can audit maintenance plans at any time for legal and regulatory compliance.	Monitor Tata Steel's compliance with environmental boundaries and safety standards. Time-based maintenance is legally mandated.	Receive environmental data annually for review.	Must be notified of major environmental incidents within 15 minutes. For large-scale incidents, Rijkswaterstaat may become involved.	*Conducts audits and inspections. May update regulations based on incident findings.*
Local community	-	-	-	-	-	Can view Tata Steel's published environmental performance reports.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Utility providers	Coordinate energy production with Tata Steel's maintenance schedule.	Align their maintenance schedules with Tata Steel's planned downtime (e.g., BF outages).	-	-	-	-
Clients	Expect high-quality, consistent steel products.	-	Rely on Tata Steel's automated systems for consistent quality control.	-	-	-

7.2. Required changes for the de-carbonization transition

Based on the current and future state of O&M, and additional information obtained from interview 8 and 9, an overview of the needed changes is presented in Table 7.2. First, major changes are discussed below.

7.2.1. From fossil-based to hydrogen-based production

The environmental transition introduces entirely new installations, such as the DRP reactor, which replaces the carbon-intensive BF process. These installations include a wide array of components such as compressors, heaters, filters, and piping systems, many of which are unfamiliar or used differently in current operations. More than 40,000 new units will need to be integrated into Tata Steel's SAP system for maintenance tracking and scheduling. Each of these units must be registered with relevant technical data, failure modes, and criticality levels. Although many components, such as pumps and filters, are already familiar to Tata Steel's maintenance teams, the way they function within the new hydrogen-based environment adds a new layer of complexity.

> *"What is important for the new installations is that we are going to set up the SAP system completely from scratch. For those new installations, this means that we need to enter 40,000 new items into SAP. Each item is a component of the installation."* (Interview 8)

In particular, the DRP system operates under significantly different conditions, including high pressure (up to 8 bar) and extreme temperatures (up to 1100°C). These environmental factors demand more robust materials, specialized training, and heightened safety procedures. Furthermore, the DRP reactor is housed in a vertical tower reaching heights of up to 150 meters, which introduces additional safety challenges for maintenance personnel who will be required to perform inspections and repairs at height.

7.2.2. Operational downtime and planning of maintenance

One of the most fundamental operational changes involves the scheduling of maintenance downtime. Whereas the BF process required an annual four-day stop, the DRP-EAF system necessitates a three-week full-stop once per year, supplemented by three quarterly three-day stops. These extended and more frequent downtimes demand detailed hour-by-hour planning and a complete rethinking of the maintenance calendar. The scheduling must also account for the production and storage of cold Direct Reduced Iron (DRI) prior to these stops to ensure that downstream steel production in the EAF can continue uninterrupted. But it also includes considering how many extra people will be on-sight during operational downtime for maintenance, where will all these people walk or park. This level of planning complexity requires increased collaboration among various stakeholder groups, including production planners, control room operators, and the maintenance organization.

> *"For the DRI installation, a four-week shutdown is required once a year. However, this shutdown must coincide with the shutdown of the EAF. Additionally, it must also align with the shutdown of the pellet plant, which supplies feedstock to the DRI installation."* (Interview 8)

Coordinating these annual shutdowns across interconnected installations not only requires precise technical alignment, but also introduces complex logistical challenges related to workforce mobilization, site access, and safety management during periods of intense activity.

> *"At another DRP plant, they had around 1,000 people working extra during an annual shutdown. [...] So then you're dealing with the question of how many people will be on a site like this? They all arrive in cars or vans and have to go through the gate, which makes the logistics quite a challenge as well."* (Interview 9)

7.2.3. Changing roles and responsibilities for stakeholders

The transition to a hydrogen-based production process significantly affects the roles and responsibilities of all key stakeholders in O&M. Process owners, who manage the SAP system and define maintenance strategies, must now oversee the integration of thousands of new components into the system and ensure that failure modes and operational dependencies are fully mapped out. They also bear the responsibility of identifying the most critical systems, particularly within the DRP, and ensuring that the most critical units are prioritized within the maintenance concept. Field and control operators face a considerable shift in how they interact with the production system. In the current BF-BOF-based process, automation minimizes the need for manual intervention. In contrast, the DRP-EAF setup is characterized by significantly lower levels of automation, requiring operators to take on more active roles in managing and correcting process deviations. This shift necessitates a new training regime, including visits to facilities already operating DRI technology, to prepare operators for the hands-on responsibilities they will soon get.

> *"We thought we would implement a highly advanced automated system, like what we are already accustomed to at Tata Steel. [...] But what we are seeing in practice is that the supplier of the DRI installation is actually providing a very basic level of automation, nowhere near the level we, as users, would like. [...] The operator will have to do more, for example, continuously adjust the temperature. He or she will have to monitor trends and deviations much more closely. Where deviations were normally corrected automatically, this will now have to be adjusted manually."* (Interview 8)

The role of the manager evolves as well, with greater emphasis placed on emergency coordination, downtime management, and incident reporting. New responsibilities include overseeing the preparation and storage of cold DRI prior to planned maintenance stops and ensuring that lessons learned from reactive maintenance are fed back into proactive planning. The Tata Steel maintenance organization must prepare itself to handle a range of new components, some of which require different tools, spare parts, or even safety procedures due to their operation under high pressure and temperature. Staff must become qualified to perform these new tasks, and this may require new contractual arrangements with external maintenance firms. Moreover, feedback loops must be established to ensure that field-level maintenance experiences are systematically fed back into the planning and design processes. A new hydrogen committee must also be established to stay abreast of evolving regulations and best practices related to hydrogen safety. This committee will be responsible for defining guidelines for hydrogen safety zones, emergency protocols, and ensuring that all O&M activities comply with current and future legal frameworks.

> *"Now that we are transitioning to steel production based on hydrogen, we decided we need a hydrogen committee. [...] This committee focuses on monitoring legislation related to hydrogen, keeping track of developments in that field, but also on the practical application and use of hydrogen. For example, they investigate how hydrogen affects valves, seals, and other components."* (Interview 8)

7.2.4. Integration of environmental and safety considerations

In addition to technical challenges, the new installations require an integrated approach to environmental and safety concerns. For example, the Carbon dioxide (CO_2)-capture system is a critical part of the DRP installation. If CO_2 is not removed from the chemical reaction, the entire iron production process will halt. As such, CO_2 extraction, cleaning, and reuse or storage systems must be maintained with the highest priority. These systems must be included in the same maintenance planning frameworks as the core iron production equipment. Other environmental challenges include the need for improved dust control systems, such as filters and extraction units for conveyor belts, and water treatment installations to manage process water. These elements, while auxiliary to the production process, are essential to Tata Steel's environmental compliance and must be included in both preventive and reactive maintenance.

> *"We need to remove the CO_2 from our gas, because otherwise the reaction will stop fairly quickly. CO_2 takes its place, and you can't reduce sufficiently, so the CO_2 installation is extremely important. There could be a small part of the installation in place that ensures that if the CO_2 capture isn't working, you can only produce in a very limited way and will have to stop fairly quickly."* (Interview 9)

7.2.5. System integration

The successful implementation of the new maintenance strategy depends on effective integration with Tata Steel's current IT infrastructure, the SAP maintenance management system. Components must be tagged and categorized using standardized codes to facilitate easy identification and scheduling. The integration process involves not only technical data entry but also the configuration of workflows that accommodate the unique maintenance demands of the DRP and EAF systems. Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE) studies will be required to assess the availability of critical units and determine whether redundant units are needed to ensure a baseline of 8000 operational hours per year, leaving 31 days for maintenance. These studies will also inform the selection of equipment and suppliers during the procurement phase, which is executed in collaboration with the Engineering, Procurement and Construction Management (EPCM) company and the OEM.

7.2.6. Legal compliance and community engagement

The environmental transition also introduces new legal and community obligations. Regulatory bodies will impose new emission limits, hydrogen safety requirements, and permit conditions. Tata Steel must ensure that all maintenance activities comply with these updated frameworks. Participation evenings with the local community must be organized to explain the environmental implications of the new installations and to maintain public trust. Clients will also need to adapt to potential fluctuations in steel quality due to the increased involvement of human operators in the production process. Tata Steel must therefore establish clear communication channels and feedback loops to address client concerns and continuously improve product consistency.

> *"The operator of one shift may perform better than the operator of another shift. This can lead to greater differences in product quality and production volume between shifts. Whereas, with a fully automated system, everyone works toward the same optimal operating point."* (Interview 8)

Effective O&M will determine the long-term success of the DRP-EAF route. By updating systems, retraining teams, and redesigning workflows with a proactive and safety-centric mindset, Tata Steel can realize its environmental ambitions while maintaining operational excellence.

Table 7.2: An overview of the change needed in O&M for each stakeholder. Information in italics was derived from the interviews, while the remaining details were explicitly stated in the interviews.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Process owner	Add 40,000 new articles into SAP and develop conversion tools. Include resonant system strategies, failure mechanisms, and system familiarity in design.	The downtime for resonant systems needs hour-to-hour coordination. Cold DRI must be prepped before DRP maintenance. Include sensors in the plan.	Critical A installations must be identified. No major change in hydrogen handling, but scale increases. Define new workspace safety requirements for contractors.	Order sensors for monitoring. Operators shift from passive to active roles. Train 180 operators instead of 140 due to lower automation. Dust and water treatment measures needed.	Critical D installations must be mapped. Failure consequences must be clear before using reactive strategy.	Critical installation failures need predefinition. Maintenance info must be complete and accurate to reduce risk.
Field operator	Identify relevant data and experience from the field to feed into the new maintenance approach. Learn DRP-EAF-specific risks and tasks (e.g., hydrogen areas).	*Need to work in a new maintenance plan.*	*Learn how to perform the new maintenance activities.*	Support inter-site operations with consistent monitoring of the new system. The teamwork of control room operator and field operator becomes more important.	-	Share knowledge and experience on similar installation units.
Control operator	*Identify relevant data and experience from the field to feed into the new maintenance approach. Learn DRP-EAF-specific risks and tasks (e.g., hydrogen areas).*	*Need to work in a new maintenance plan.*	Has more operational downtime due to the increase in downtime needed for the maintenance on the DRP compared to the BF.	The teamwork of control room operator and field operator becomes more important. The control room operator needs to actively restore the process when something is off.	React faster due to less automation and unfamiliar equipment. Learn new response protocols and alarm prioritization for the new process.	Share knowledge and experience on similar installation units.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Manager	Identify known technologies and manufacturers to guide OEM choices.	*Identify existing operational knowledge for planning the maintenance strategies.*	Coordinate the increased downtime periods for maintenance on the DRP.	Coordinate extra production of cold DRI before the planned downtime of the DRP.	Coordinate the increased downtime periods for maintenance on the DRP.	Ensure red-line reviews and Root Cause Analysis (RCA) post-incidents.
Tata Steel's maintenance organization	Identify experience with similar installations; recommend trusted suppliers.	Build spare parts inventory for the new process and hydrogen-sensitive components.	*Become qualified to perform maintenance for the new equipment.*	*Prepare for new operational downtime periods.*	*Become qualified to perform maintenance for the new equipment.*	*Create field-to-planning learning feedback loops.*
Hydrogen committee	Experts define hydrogen safety rules, conduct Research and Development (R&D), and create uniform working protocols. Validate safety zones and hydrogen usage.	*Laws regarding working with hydrogen in equipment and mandated maintenance need to be identified by the committee.*	*Construct emergency procedures for hydrogen leakage during operation.*	*Review and refine hydrogen-related escalation protocols.*	-	Update safety strategies based on incidents and global practices.
OEM	Receive list of preferred manufacturers from Tata. Collaborate with EPCM on equipment selection.	Need to provide feedback on the maintenance plans.	*Recommend predictive schedules based on wear data of other factories.*	Sensors (vibration, pressure, temp.) to be installed in equipment.	*Support early-stage troubleshooting and critical part failures.*	*Incorporate field feedback into new versions of equipment.*
Firms	Need to be informed on changing work.	Need to provide feedback on the maintenance plans.	Prepare for the changed work in maintenance.	Prepare for the changed operational downtime periods.	Prepare for the changed work in maintenance.	Provide feedback during first maintenance performances.
Regulatory bodies	Laws regarding safety and environment for hydrogen systems need to be identified.	Review hydrogen zone plans and validate safety criteria.	Laws for preventive maintenance for the new equipment need to be complied with.	New permits need to be provided for the changed operations and environmental impact. Inspect emissions and procedural adherence for new installations.	*Enforce post-incident evaluation protocols.*	Check whether operations stay within the new permitted boundaries.

Stakeholder	Concept	Planning	Proactive	Operation	Reactive	Feedback
Local community	Participation evenings for the local community should be organized, required by law. Presentations should inform about the new operations and allow questions.	-	-	Measures must be taken to collect the dust: filter systems, belt covers, extraction systems, and water treatment to decrease the impact on the local community.	-	-
Utility providers	-	-	-	-	-	-
Clients	-	*Communicate changes in delivery timelines due to new downtime periods from DRP-EAF startup.*	Needs to be able to handle small differences in steel quality.	-	-	*Provide feedback on steel quality to influence process tweaks.*

7.3. Conclusion

This chapter addressed the question: *"What changes in operations & maintenance are required to support Tata Steel's de-carbonization transition?"* Framing O&M as a strategic practice, this chapter examined how the shift from traditional BF-based steelmaking to a hydrogen-based DRP-EAF configuration demands not only technological adaptation, but also a reconfiguration of everyday work, routines, and practitioner interactions. The environmental transition is not implemented solely through top-down planning; it is enacted through changes in how operators, engineers, managers, and external partners collectively perform O&M on the ground. This involves rethinking maintenance strategies, safety procedures, stakeholder coordination, and the competencies needed to navigate a more complex and uncertain technological environment.

7.3.1. Changing activities and processes

In the future DRP-EAF configuration, operational tasks will shift from primarily monitoring automated systems to active manual control of key process parameters. This requires a more hands-on approach from operators. This change in operational demands necessitates a comprehensive training regime, including site visits to reference plants already operating with DRI technology. Maintenance schedules will shift significantly, moving from a single annual maintenance stop to a more fragmented structure consisting of one full three-week shutdown and three additional three-day stops. Additionally, the physical characteristics of the new installations, high pressures, extreme temperatures, and tall structures, necessitate advanced safety measures, specialized equipment, and strict procedural training, particularly for working at heights and with hydrogen.

7.3.2. Evolving external stakeholder roles

As the BFs are decommissioned, utility providers who currently repurpose furnace gases for electricity generation will no longer play a role. This shift illustrates how the stakeholder network is evolving. At the same time, the involvement of OEM will increase in the first phases of the transition, particularly during the design, planning, and start-up of future installations. Furthermore, Tata Steel may need to enter new contractual arrangements with external maintenance providers who can deliver the highly specialized services now required. At the same time, regulatory bodies will impose new environmental and safety requirements. Compliance with these standards will require integrated efforts across legal, technical, and community relations functions.

7.3.3. Changing internal roles

Besides the changing in the external stakeholder network, the roles within the organization will also change. Control room operators will transition from passive supervision to active engagement with process variables, requiring upskilling and reskilling. Maintenance personnel will need new qualifications for working in high-risk environments involving hydrogen, pressure, high temperatures and elevation. Maintenance in these conditions introduces new safety risks, requiring specialized training, height safety protocols, and more robust protective equipment. A new hydrogen committee has to be established to define safety guidelines, oversee emergency procedures, and ensure legal compliance as hydrogen becomes central to operations.

7.3.4. Challenges and uncertainties

The changes needed for O&M in the shift towards a green steel production plant imposes some challenges and uncertainties. The future production setup requires the integration of approximately 40,000 new equipment articles into Tata Steel's SAP system. Each component must be documented with detailed technical data, failure modes, and criticality levels. This represents a major administrative and technical challenge for asset management and maintenance planning. The DRP operates with significantly lower levels of automation compared to the current BF-BOF setup. Operators must take on a more hands-on role, actively intervening in process deviations. This shift not only increases cognitive and physical workload but also heightens the risk of operational errors and variability in product quality. Increased human intervention in the DRP-EAF process may result in inconsistent steel quality across different shifts. This variability can affect customer satisfaction and may necessitate more robust quality control and communication processes with clients. The new maintenance regime includes a full shutdown of approximately three weeks annually, in addition to quarterly three-day stops. These periods require a much larger workforce on-site, leading to potential bottlenecks related to logistics, site access, parking, and safety coordination. Hydrogen introduces unique risks related to flammability and leakage. Currently, there is limited organizational experience with hydrogen on such a scale, requiring the establishment of a dedicated Hydrogen Committee to develop and monitor safety protocols, zoning policies, and emergency procedures. In the current system, by-product gases from the BFs are utilized by utility providers for electricity generation. With the phase-out of BFs, this circular energy benefit will disappear, which reduces the site's integrated energy efficiency.

Besides these challenges, there are also some uncertainties regarding the changes that are needed. Initially, the DRP-EAF configuration was expected to be highly automated. However, supplier constraints and design realities have led to a lower-than-anticipated automation level. It remains unclear whether future technological updates will improve this situation. Legal frameworks and best practices for hydrogen safety are still developing. The Hydrogen Committee must remain adaptive, but the long-term regulatory landscape remains a moving target. In all the new installations, their operational behavior and maintenance needs are not yet fully known in the specific plant of Tata Steel. The transition may require specialized skills that existing staff do not possess. It is unclear to what extent tasks will be handled internally versus being outsourced, and new contractual arrangements may be necessary. Tata Steel's success in navigating this transition depends on its ability to anticipate these changes not as discrete technical updates, but as part of an interconnected system that requires systemic coordination, adaptive capacity, and organizational learning.

8 Discussion

This thesis has explored how Tata Steel IJmuiden, one of the Netherlands' largest energy-intensive industrial sites, is navigating its transition toward de-carbonization in practice, with particular emphasis on the implications for Operations and Maintenance (O&M). Conducted as a narrative case study, the research applied a Strategy as Practice (SasP) theoretical framework to examine how strategic de-carbonization initiatives are enacted and adapted within the daily realities of industrial operations. The study followed the principles of the Standards for Reporting Qualitative Research (Standards for Reporting Qualitative Research (SRQR)) as outlined by O'Brien et al. (2014), ensuring transparency, rigor, and reflexivity throughout the research process.

The analysis was structured across multiple levels of abstraction as visualized in Figure 8.1. Chapter 2 established the theoretical foundation by introducing the macro level de-carbonization strategies in energy intensive industries and the steel industry in specific, and pracitces of O&M. It also introduced the theoretical framework of SasP through which this research has been analyzed. Finally it discussed the knowledge gap addressed and the scientific contribution of this research. Chapter 3 provided the methodological backbone of the study, outlining the research design, the literature review and interviews, as well as the synthesis of expert knowledge integration and measures taken to ensure validity and reliability. It concluded with a discussion of the used tools and software during the research.

The empirical case study commenced in Chapter 4, which presented Tata Steel's macro level de-carbonization strategy as the foundation for the remaining chapters. This chapter situated the transition in a real-world industrial context, highlighting both the strategic intent and the complexity of implementing such large-scale change. Chapter 5 examined a range of interrelated meso- and macro-contextual factors, such as infrastructure constraints, regulatory frameworks, cost structures, green electricity and hydrogen supply, and safety risks, that impact the feasibility of the de-carbonization strategy. These contextual elements also influence the implementation of O&M at the micro plant level. This chapter thus served as a bridge between meso- / macro-level contextual factors and micro level practices.

Chapter 6 focused on the micro plant level, analyzing how practitioners on the plant floor engage with the transition. It highlighted the concrete actions by stakeholders as practitioners and the new routines, revealing how strategy is translated into practical action. This chapter is crucial in showing how the de-carbonization transition is not just designed at the top but enacted through day-to-day operations. Chapter 7 analyzed the operational strategy from a micro-level perspective by comparing the current and future O&M. It revealed the structural and procedural changes needed for the successful implementation of the de-carbonization transition. This included the redesign of routines, new responsibilities, coordination mechanisms, lower automation, and shifts in system integration and plant logic.

The thesis provided a multi-level and integrative perspective, progressing from strategy formulation and external context to operational enactment. Importantly, this structure loops back to the macro level in this discussion chapter. The transition process was analyzed through a SasP lens, allowing the research to examine how strategy is enacted at the micro plant level in practice. The Tata Steel IJmuiden case served to contextualize the framework, grounding them in a real-world setting. The discussion chapter performs a de-contextualization by reframing the findings from the case to inform broader insights on industrial de-carbonization. In doing so, the analysis draws micro-level actions into macro-level considerations and outlines what can be done more generally across energy-intensive industries. This recursive logic sets the stage for answering the main research question in Chapter 9: *"How can large energy-intensive industries transition towards de-carbonization in practice?"*

To this end, the discussion begins in Section 8.1 by linking the case study findings to the theoretical de-carbonization strategies introduced in Chapter 2, along with their implications for operations management across strategies. It then explores how these strategies interact in Section 8.2, acknowledging that firms often pursue hybrid approaches rather than single trajectories. Section 8.3 outlines the key barriers to implementation as experienced in the case, and finally Section 8.4 addresses contradictions and uncertainties encountered during the research process.

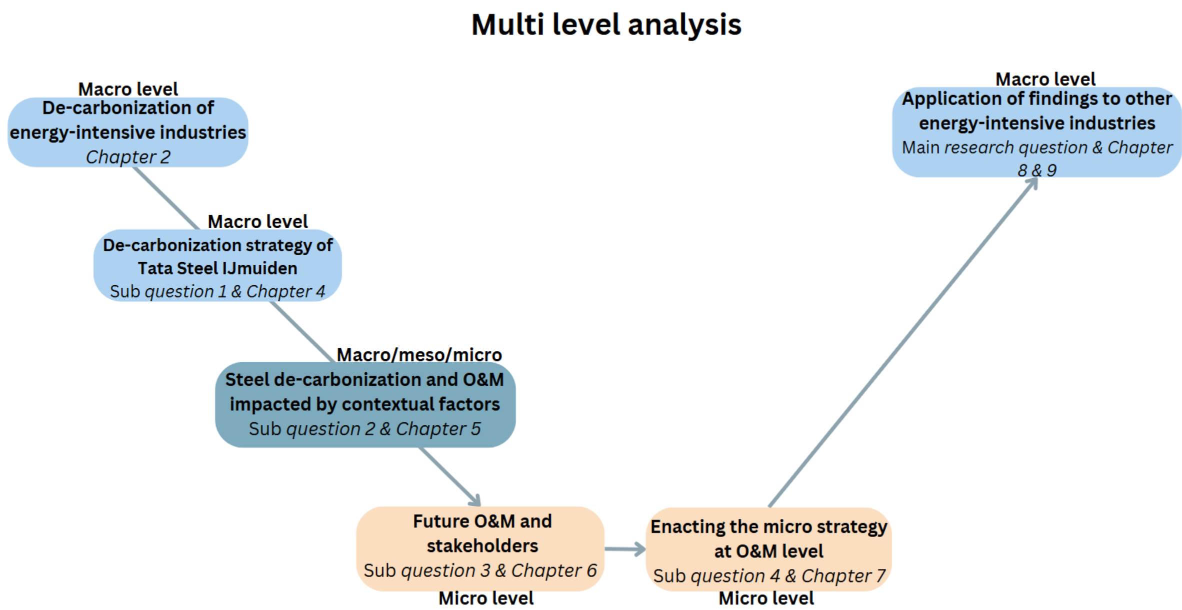

Figure 8.1: Visualization of the multi levels analyzed throughout the thesis with the dedicated chapters indicated.

8.1. De-carbonization strategies in energy-intensive industries

This section provides a comprehensive overview of the macro level de-carbonization strategies. As identified in the literature review (Chapter 2), a broad spectrum of macro-level de-carbonization strategies exists, including energy efficiency improvements, Carbon Capture Utilization and Storage (CCUS), hydrogen integration, electrification, fuel switching, heat recovery, digitalization, circularity, recycling and reuse, and technological substitution.

Tata Steel's transformation embodies many of these strategies. However, they consider three main de-carbonization strategies: The increase of recycled materials, the use of alternative fuels and finally CCUS. To enable these strategies, old technologies have to be substituted. Following this fundamental technology shift, further improvements in energy efficiency are necessary through the effective integration of new equipment within existing factory systems. This integration will be supported by advances in automation and digitalization, with embedded sensors enabling real-time monitoring and control to optimize operational performance. The detailed examination of these de-carbonization strategies below, illustrates not only how they manifest in Tata Steel's transition but also provides insights applicable to other industries pursuing similar de-carbonization strategies. The practical realities of the implementation of these strategies highlight critical nuances and interdependencies, especially regarding their impact on plant-level O&M activities. The interconnectedness and practical challenges of implementing combined strategies emphasize the critical role of O&M in enabling and sustaining this transition. The expanded O&M implications of these strategies and their applicability across sectors are summarized in Table 8.1.

8.1.1. Energy efficiency and heat recovery

Energy efficiency, including heat recovery, is the most commonly cited de-carbonization strategy across sectors such as cement, chemicals, pulp and paper, food and beverage, glass, and steel. Tata Steel has historically optimized energy efficiency, particularly through waste heat recovery and reuse of blast furnace gases to generate electricity. However, the shift to hydrogen-based steelmaking leads to the loss of these legacy heat recovery systems, resulting in a temporary decline in overall plant efficiency during the transition. One key innovation in the new process is the installation of a HYTEMP tower between the Direct Reduction Plant (DRP) and Electric Arc Furnace (EAF), designed to maintain the Direct Reduced Iron (DRI) at a high temperature and reduce the energy input needed during melting. Although the HYTEMP claims minimal maintenance needs, this reflects a broader trend: the adoption of fundamentally new technologies can render previously optimized energy systems obsolete, necessitating re-optimization efforts.

Operationally, achieving and maintaining energy efficiency requires continuous monitoring and fine-tuning of processes, which can increase wear on critical equipment due to higher utilization rates. This intensifies the need for proactive maintenance and condition-based monitoring to avoid unexpected failures. Furthermore, operations must be optimized not only within individual departments but also through enhanced cross-department collaboration to ensure system-wide efficiency gains. In tightly integrated systems, maintaining process synchrony emerges as a significant operational challenge, demanding strong coordination across functions (see Table 8.1, Energy Efficiency).

8.1.2. Carbon Capture, Utilization, and Storage

CCUS is a widely recognized de-carbonization strategy used in sectors such as cement, chemicals, glass, pulp and paper, food and beverage, steel, and oil refining. Tata Steel plans to deploy CCUS alongside its hydrogen transition, partly due to uncertainties about achieving high-quality steel with 100% hydrogen-based DRI. This underscores that CCUS remains essential in the near term for net-zero ambitions. However, CCUS cannot function as a stand-alone strategy when emissions include other harmful pollutants, such as those from coal-based processes.

From an O&M perspective, CCUS introduces entirely new systems with critical components that require specialized maintenance. Frequent inspection of pressurized and chemical processing units is necessary to ensure safety and reliability. Additionally, emissions monitoring systems must be regularly calibrated to maintain accuracy and regulatory compliance. The integration of CCUS also demands complex coordination of plant shutdowns to accommodate maintenance and repairs without disrupting overall production. These operational challenges illustrate that CCUS adoption requires not only technical capabilities but also robust O&M planning and cross-department collaboration.

8.1.3. Hydrogen

Hydrogen as a clean fuel is increasingly considered in industries requiring high temperatures, such as chemicals, ceramics, and glass, and as a reduction agent in steel production. While it offers a zero-carbon pathway, integrating hydrogen presents notable safety and O&M challenges. The strategic transition from coal to hydrogen in steel production highlights operational risks related to hydrogen's properties: its small molecular size causes high leakage potential, flammability, and low ignition energy. To address these risks, Tata Steel plans to establish a Hydrogen Committee tasked with tracking hydrogen developments, regulations, and safety protocols.

High safety risks associated with hydrogen require specialized training for operators and maintenance staff. Moreover, hydrogen embrittlement demands regular material inspections to prevent premature equipment failure. The implementation of hydrogen-specific emergency protocols is critical to manage potential leaks or explosions effectively. These proactive measures at Tata Steel provide valuable lessons for other sectors adopting hydrogen, emphasizing the need for tailored O&M strategies, rigorous safety management, and continuous regulatory oversight.

8.1.4. Electrification

Electrification, applied in sectors such as cement, chemicals, pulp and paper, glass, iron and steel, and ceramics, alters both energy inputs and maintenance strategies. At Tata Steel, the EAF represents a core shift from fossil-based melting to electricity-based operations. This shift demands large volumes of renewable electricity, an availability challenge particularly in the Netherlands. For O&M, electrification means the focus shifts from mechanical to electrical systems, requiring new skill sets among personnel to manage high-voltage equipment safely. Fault detection increasingly relies on digital and predictive technologies, enabling earlier intervention and reducing downtime. Additionally, thermal management becomes critical to prevent overheating in electrical components. Industries planning similar transitions must prepare their workforce for these changes and ensure resilience in their electrical infrastructure, especially as system downtime increasingly results from grid or control system failures rather than mechanical breakdowns.

8.1.5. Fuel switching

Fuel switching is another strategy seen in cement, paper and pulp, food and beverage, and glass industries. Tata Steel's transition from coal to hydrogen is one such example, but the literature also mentions options such as biofuels and ammonia. While offering emission reductions, new fuels often introduce unique chemical and physical properties that affect operational safety and maintenance needs. Operators must be retrained to understand the specific risks associated with new fuels. Existing equipment may require retrofitting or even replacement to handle different fuel characteristics safely. Additionally, residue and emissions profiles change, necessitating updated monitoring and maintenance practices. Regulatory compliance and safety standards may also require revisions to accommodate new fuel types. Other industries must similarly assess how different fuels interact with legacy equipment and safety systems, adapting their O&M programs accordingly.

8.1.6. Digitalization and automation

Though less frequently mentioned in literature, digitalization is an emerging de-carbonization enabler for steel, cement, and chemicals. Tata Steel's new installations will be equipped with advanced sensors and digital monitoring systems. This shift entails more maintenance on sensors and digital systems, requiring new skills and approaches. Digitalization enables predictive maintenance and automation, improving plant efficiency and reducing unplanned downtime. However, it also introduces new challenges, such as the need for strong cybersecurity measures and coordinated Information Technology and Operational Technology management. Staff must develop digital skill sets to operate and maintain these systems effectively. As seen in Tata's case, automation for new technologies must be redeveloped when replacing legacy systems. For other industries adopting Industry 4.0 principles, this reinforces the importance of investing in digital literacy and cyber-resilient maintenance strategies.

8.1.7. Recycling and reuse

Recycling is broadly applied in cement, chemicals, paper, ceramics, and plays a significant role in steel as well. Tata Steel intends to incorporate up to 40% recycled steel in its production as part of their de-carbonization strategy. However, the quality degradation limits this percentage when producing high-grade steel. This constraint applies similarly to other sectors where material properties are critical, such as glass or high-performance ceramics. Recycling strategies require additional systems for sorting and processing, as well as maintenance for filtration and purification systems. The quality variation of recycled inputs may affect O&Mroutines, necessitating adjustments to maintenance and operational procedures. Traceability systems become essential to ensure quality assurance throughout the recycling process. Although the impact of recycling on O&M was not fully captured in this research, especially for systems like wastewater treatment (linked to circularity), which were out of scope, the broader insight is that recycling introduces new operational demands and maintenance complexities.

8.1.8. Substitution of old technologies

Substituting outdated technologies is rarely emphasized as a primary de-carbonization strategy for steel in the literature, yet it is central to Tata Steel's transition to enable other strategies and widely applied in industries like paper, oil refining, and ceramics. At Tata Steel, replacing the Blast Furnace (BF)-Basic Oxygen Furnace (BOF) route with the DRP-EAF represents a transformative overhaul, enabling hydrogen as a reductant, electrification for melting, and integration of CCUS. This foundational shift makes advanced de-carbonization pathways feasible. Such substitution goes beyond equipment replacement, it reconfigures entire systems. Energy efficiency must be re-integrated, digitalization rebuilt, and new O&M programs developed. These include identifying critical components, adapting to new operating conditions, and redesigning maintenance routines. Reduced automation in less mature systems may require more operator involvement, necessitating training and new skillsets. Similar patterns can be seen in industries phasing out kilns, boilers, or reactors. Rather than a standalone strategy, substitution acts as a structural enabler for hydrogen integration, electrification, and CCUS. It reshapes supply chains, operational practices, safety protocols, and digital infrastructure, while triggering the reinvention of heat recovery, emissions control, and automation systems. Substitution also facilitates the sequencing of strategies, allowing shifts from fossil fuels to hydrogen or electrified systems. These one-directional, transformative changes demand long-term commitment and vision, making substitution a cornerstone of industrial transformation rather than an isolated de-carbonization measure and it is therefore not included in the table below.

Table 8.1: Implications for O&M per de-carbonization strategy and relevant industries

Strategy	Implications for O&M	Industries
Energy efficiency	• Operations need to be optimized to gain efficiency. • Requires continuous monitoring and fine-tuning. • May increase wear on critical equipment due to higher utilization. • Cross-department collaboration becomes more vital.	Chemical, cement and lime, pulp and paper, food and beverage, glass, iron and steel
CCUS	• Introduces new systems with critical components. • Requires frequent inspection of pressurized and chemical units. • Emissions monitoring systems need calibration. • Complex coordination of shutdowns.	Chemical, cement and lime, pulp and paper, food and beverage, glass, iron and steel, oil
Hydrogen	• High safety risks require specialized training. • Hydrogen embrittlement demands material inspections. • Need for hydrogen-specific emergency protocols. • A hydrogen committee may help track developments and regulations.	Chemical, glass, iron and steel, ceramics

Strategy	Implications for O&M	Industries
Electrification	• O&M focus shifts from mechanical to electrical. • High-voltage systems require skilled personnel. • Fault detection becomes more digital and predictive.	Chemical, cement and lime, pulp and paper, iron and steel, ceramics
Fuel switching	• Operators must be retrained for new fuels and risks. • Existing equipment may need retrofitting or replacement. • Residue and emissions characteristics change. • Regulatory compliance and safety updates may be required.	Cement and lime, pulp and paper, food and beverage, iron and steel, glass
Digitalization	• More maintenance on sensors and digital systems. • Enables predictive maintenance and automation. • Requires cybersecurity and IT/OT coordination. • Staff must develop digital skill sets.	Chemical, cement and lime, iron and steel
Recycling	• Additional systems needed for sorting and processing. • Maintenance needed for filtration and purification systems. • Quality variation of recycled inputs may affect O&M routines. • Traceability systems are key for quality assurance.	Chemical, cement and lime, pulp and paper, iron and steel, ceramics, glass

In summary, Tata Steel's de-carbonization journey highlights the complex nature of transitioning energy-intensive industries towards sustainability. The adoption of hydrogen, electrification, CCUS, recycling, and digitalization requires not only technological innovation but also significant shifts in O&M practices. Critical O&M implications include the need for enhanced cross-departmental coordination to maintain process synchrony, proactive and condition-based maintenance to manage increased equipment wear, specialized safety training to handle hydrogen risks, and new skill sets for managing advanced electrical and digital systems. Additionally, the integration of CCUS demands careful maintenance of chemical and pressurized units, alongside coordinated shutdowns to minimize production disruptions. Substituting legacy technologies, to enable other strategies, further necessitates reconfiguring maintenance routines, developing new digital literacy, and implementing cyber-resilient systems. These operational challenges emphasize that de-carbonization is a layered transformation where effective O&M is essential to ensure system reliability, safety, and efficiency.

The lessons learned from Tata Steel's transition provide valuable insights for other industries, underscoring that successful de-carbonization depends on aligning technological advances with robust and adaptive operational management strategies. While this section provides a useful snapshot of individual challenges and requirements, the practical implementation of these strategies unfolds as a layered, staged transition rather than isolated interventions as will be discussed in the next subsection.

8.1.9. A Layered, staged transition in practice

Tata Steel's approach reflects a layered and staged transformation, which can serve as a reference for other industries:

1. **Foundational transition:** Replace legacy production technology BF-BOF with DRP-EAF to enable other de-carbonization strategies.
2. **Initial de-carbonization:** Use natural gas in the DRP and increase recycling input.
3. **Deep de-carbonization:** Transition to hydrogen, add CCUS to cover residual emissions.
4. **Digital integration:** Gradually re-automate by implementing digital tools for process monitoring, predictive maintenance, and safety.
5. **Efficiency re-optimization:** Once the new system stabilizes, redesign energy efficiency strategies.

Each stage builds upon the previous one, and success depends on aligning technical readiness with organizational capabilities and maintenance maturity. For instance, hydrogen integration and CCUS require new skill sets, materials expertise, and control systems, while digitalization demands reliable data infrastructure and cybersecurity awareness. Therefore even the "future state" of the Tata Steel plant will be a process in which automation and optimization will occur just as that has been done for over 100 year for the current production plant. The sequencing and interaction of these de-carbonization strategies deeply shape O&M functions:

1. Early stages focus on up-skilling for new equipment and fuels, managing transition risks, and maintaining system reliability during major process changes.
2. Middle stages introduce new systems (CCUS, hydrogen increase) that require specialized monitoring and maintenance.
3. Later stages emphasize data-driven optimization and re-integration of efficiency measures, where O&M plays a proactive and strategic role.

This phased and layered de-carbonization highlights that O&M is not a static support function but a dynamic part of strategy enactment. As technologies and processes evolve, maintenance routines, competencies, and organizational roles must co-evolve. De-carbonization in practice is not a one-time event but a dynamic, multi-step process of technological substitution, system layering, and operational adaptation. Tata Steel's trajectory illustrates how strategies must be carefully combined and sequenced, with each stage requiring different forms of support from O&M. As a result, it is crucial to evaluate how different de-carbonization strategies interact with each other, as their interplay can significantly influence operational complexity and maintenance demands.

8.2. Interaction between de-carbonization strategies

Therefore this section discusses how different de-carbonization strategies can be combined or interact. The following matrix (Table 8.2) outlines how different de-carbonization strategies can interact with one another in industrial contexts. It highlights the need to consider not just the individual effect of each strategy, but also the relational dynamics between them. This section will first describe how the interaction table has been developed, after which the type of interactions based on theory will be explain and lastly the interaction table itself will be displayed and the main findings will be described.

8.2.1. Interaction table development

The de-carbonization strategy interaction table presented in Section 8.2.3 emerged through an integrative research process combining literature insights, interview findings, and reflective input from an academic supervisor, as described in Section 3.4. This approach enabled the incorporation of tacit expert knowledge and theoretical framing into the analytical structure of the study (Marshall, 2019).

The idea to explicitly structure the interactions between de-carbonization strategies in tabular form was encouraged by Prof. Dr. Roland J. Ortt during a supervisory discussion. This suggestion was not arbitrary, but directly grounded in his broader academic work on system innovation. In particular, Ortt and Smits, 2006 argue that innovation occurs within a complex, multi-level system where trends interact. They highlight that the combined effects of these trends are more important than treating them in isolation. Further support for this interaction-oriented approach comes from Ortt's later work (Ortt & Kamp, 2022), which suggests for future research to look at interactions over time, rather than focusing solely on static elements of technological innovation systems.

These insights directly informed the development of the interaction table. It suggests the relevance of analyzing de-carbonization strategies as dynamic, interacting elements rather than stand-alone solutions. Thus, the inclusion of the interaction table in the discussion was a theoretically grounded step that reflected both the academic literature and expert supervisory insight. It provides a structured way to explore the multi-strategy interplay necessary for deep de-carbonization.

8.2.2. Type of interactions

To assess the interaction relationships among de-carbonization strategies, this study adopts interaction patterns grounded in innovation, policy, and systems literature. The five interaction categories: complementary, sequential, substitutive, contradictory, and independent, help explain how strategies can support, conflict with, or remain neutral to one another. These definitions were applied during the analysis and are supported by empirical and theoretical work.

Complementarity refers to a *positive* relationship between activities or strategies. In innovation policy literature, complementarity is present when "the marginal returns to one variable increase with the level of another," or when "the factors act together and reinforce each other" (Mohnen & Röller, 2005). In practice, this means that combining two strategies can lead to greater emissions reductions than when each is applied in isolation. Jaureguy et al., 2023 also define complementarity as cases where the joint effect of two factors is greater than the sum of their individual effects.

Sequential interactions are generally *positive*, but *conditionally*, as their effectiveness depends on proper ordering or timing. Schwerhoff, 2022 describes this in terms of "policy sequencing," where preliminary steps pave the way for more advanced interventions. This reflects real-world dynamics in which certain de-carbonization strategies depend on pre-existing strategies to function effectively.

Substitution indicates a *negative* relationship, where one strategy decreases the utility or relevance of another, either by fulfilling the same role or through unintended crowding-out effects Roper et al., 2024. In that case one strategy has a negative impact on the other. Similarly, Jaureguy et al., 2023 define substitutive effects as those where the presence of one factor diminishes the effectiveness of another.

Contradictory interactions represent a *negative* relationship where one strategy not only reduces the value of another but may actively hinder its effectiveness. T. Kim et al., 2018 identify contradiction as occurring "where either or both effects are reduced or negated."

Independent strategies exhibit *neutral* relationships according to T. Kim et al., 2018, they neither enhance nor hinder one another. As Roper et al., 2024 describe, the effect of two independent strategies is simply the sum of their separate effects, without synergy or conflict. Recognizing independence is important for identifying parallel implementation pathways in policy or innovation planning.

This classification enables a structured and theory-informed interpretation of how de-carbonization strategies interact in practice. It supports strategic planning by clarifying where synergies can be maximized, where sequencing is necessary, and where potential conflicts or redundancies may arise. Based on this theoretical foundation, definitions of these interactions were established and used in the interaction analysis:

- **Complementary:** Strategies that reinforce or enhance each other *positively* when implemented with the other.
- **Sequential:** Strategies that must be staged in a particular order to be have a *positive* effect.

- **Contradictory:** Strategies that may interfere with each other's effectiveness *negatively*, where one strategy reduces or negates the impact of another due to conflicting mechanisms, assumptions, or unintended side effects.
- **Substitutive:** Strategies that fulfill similar functions or goals, where the implementation of one reduces the necessity or added value of the other, potentially crowding out its impact *negatively*.
- **Independent:** Strategies that do not interact with or depend on each other and can be implemented separately in a *neutral* way.

This typology provides a practical lens for analyzing strategic interactions, enabling a more integrated and adaptive approach to planning de-carbonization pathways in complex industrial settings.

8.2.3. Interaction table

The interaction between the different de-carbonization strategies was grounded on this theoretical foundation. The main insights were based on the findings during the case study on Tata Steel IJmuiden. While the matrix maps the core de-carbonization strategies, the substitution of old technologies functions more as a structural enabler than a discrete de-carbonization strategy. It provides the necessary infrastructure and system change that enables other strategies, such as hydrogen integration or electrification, to be realized. For this reason, substitution of old technologies is not included in the interaction matrix, which focuses instead on the interaction between de-carbonization strategies themselves.

The matrix (Table 8.2) with the interactions among de-carbonization strategies illustrates that industrial transformations depend on understanding the multifaceted interactions between technological pathways. Several key insights emerge:

- **Complementarity:** Complementarity is a *positive* and frequent interaction among de-carbonization strategies, where the implementation of one approach enhances the effectiveness or amplifies the benefits of another. For instance, electrification can increase the efficiency and utility of hydrogen or other clean fuels, while fuel switching, digitalization, and recycling can strengthen the impact of energy efficiency measures. These synergies enable deeper emissions reductions when strategies are combined, compared to implementing them in isolation. Notably, digitalization was identified as universally complementary, as it consistently reinforces the effectiveness of all other strategies.
- **Sequential relationships:** Sequential relationships highlight the importance of timing and order to have a *positive* effect. Fuel switching, for instance, may need to precede hydrogen adoption to ensure system readiness and maintain overall efficiency. This staging requires careful planning and integration to avoid disruptions and maximize cumulative gains.
- **Substitutive interactions:** Substitutive interactions occur when one strategy can replace another, such as electrification substituting fuel switching or hydrogen serving as an alternative fuel source, which can be the case the other way around as well. These substitutions strategies interact in a *negative* way and emphasize the need for context-specific choices tailored to industry characteristics and resource availability.
- **Contradictory interactions:** Contradictions highlight potential trade-offs and barriers between de-carbonization strategies. Some approaches may complicate or undermine the effectiveness of others in a *negative* interaction. For example, the widespread adoption of hydrogen could significantly reduce Carbon dioxide (CO_2) emissions, thereby decreasing the necessity for carbon capture and storage (CCUS) and potentially undermining its relevance as a de-carbonization strategy. While digitalization itself is complementary to all other de-carbonization strategies, it is subject to contradictory effects from those same strategies: as more measures are implemented, they collectively increase the digital complexity of the system. This added complexity can lead to integration challenges, reduced optimization, and a higher risk of inefficiencies or systemic failures.

- **Independent strategies:** No de-carbonizations are completely independent from others, thus have a mutual *neutral* relationship. While the CCUS strategy has barely to none impact on the electrification strategy, the CCUS is influenced when electrification on site takes place. So no complete independent combinations occur.

The analysis of interactions between de-carbonization strategies reveals that industrial transformation cannot proceed through isolated or linear actions. Insights from both theory and the Tata Steel case demonstrate the importance of managing multiple strategies in parallel: leveraging synergies, carefully sequencing interventions, and addressing inherent trade-offs. The typology of interactions, complementary, sequential, substitutive, contradictory, and independent, provides a useful lens to understand how these strategies relate and influence one another.

Among these, digitalization emerges as a foundational enabler, offering the tools for optimization, monitoring, and adaptability across all strategies. However, its growing complexity necessitates integrated oversight to prevent misalignment and contradictions.

While the substitution of old technologies is not a de-carbonization strategy in itself, it plays a critical enabling role by reshaping the technical, operational, and digital foundations of industrial systems. Substitution allows for the integration of other strategies, such as hydrogen use, electrification, and CCUS, by replacing legacy infrastructure that is incompatible with low-carbon technologies. As such, the substitution of old technologies can mark a pivotal step in the transition and will be explored in greater depth in the following section.

8.2.4. Interaction with substitution of old technologies

A critical aspect of de-carbonization strategies is their potential to substitute or render obsolete existing technologies, requiring a comprehensive transformation beyond simply changing inputs. Fuel switching exemplifies this dynamic, where adopting alternative fuels, such as moving from coal or oil to biofuels or hydrogen, often necessitates significant modifications or complete replacement of combustion equipment, boilers, burners, or entire process units. This substitution effect cascades through industrial systems, influencing energy efficiency measures, process control, and even waste handling. Such technology substitution creates both challenges and opportunities. On the one hand, retrofitting or replacing legacy systems entails substantial Capital Expenditure (CAPEX), operational disruption, and technical uncertainty. On the other hand, it can unlock step-changes in efficiency, emissions reduction, and system flexibility not achievable through incremental improvements. For example, switching to hydrogen may require new materials resistant to embrittlement, specialized safety systems, and advanced digital controls to manage the novel fuel dynamics, thus linking substitution closely to digitalization. Moreover, substitution interactions emphasize the sequential and conditional nature of de-carbonization pathways. Some strategies can only succeed after replacing outdated technologies, while others become unnecessary or less effective once new systems are in place. This underlines the importance of holistic planning to avoid stranded assets and ensure smooth transitions. Replacing old technologies might be necessary due to the switch in fuels, such as hydrogen, or electrification. This might include CCUS. This replacement causes a need for digitalization and energy efficiency. All of which can be complemented by recycling.

Understanding the layered and interacting nature of de-carbonization strategies, and their role in substituting legacy technologies, also highlights the complexity of industrial transformation. These multifaceted changes are not only technical but deeply embedded in economic, organizational, behavioral, and institutional contexts. As such, the following section examines the key barriers that industries like Tata Steel face in implementing de-carbonization, ranging from financial constraints and workforce capabilities to infrastructural and market challenges. Addressing these barriers is crucial to realizing the potential of the strategies outlined above and ensuring a sustainable, resilient transition.

Table 8.2: The effects of de-carbonization strategies on top on the other strategies positioned on the left. The neutral interactions are displayed in black, the positive interactions in green and the negative interactions in red.

Influencing→ / Affected↓	**Energy Efficiency**	**CCUS**	**Hydrogen**	**Electrification**	**Fuel Switching**	**Digitalization**	**Recycling & Reuse**
Energy Efficiency	—	Contradictory: May increase complexity and energy demand; installation may disrupt optimized setups	Complementary or contradictory: Hydrogen may enhance or conflict energy efficiency, depending on system integration	Complementary: Electrification may enhance energy efficiency	Complementary or contradictory: Fuel changes may unlock new efficiencies or disrupt setups	Complementary: Energy efficiency might increase due to optimized energy savings when digitalized	Complementary: Recycled inputs may allow process optimization
CCUS	Contradictory: Higher efficiency reduces the need for CCUS	—	Contradictory **or** substitutive: The use of hydrogen reduces CO_2 emissions, making CCUS less necessary or not needed at all	Complementary **or** contradictory: Electrification can reduce CCUS emissions and it can reduce CO_2 emissions as well, making CCUS less needed	Complementary **or** contradictory: A different fuel may enhance or decrease the Carbon Capture (CC) potential and need	Complementary: CCUS Functions better with digital support to optimize capture	Contradictory: Contaminants in reused materials may hinder CC
Hydrogen	Complementary: Higher efficiency reduces the amount of hydrogen needed, making it a better solution	Complementary: Can be used to capture residual CO_2	—	Complementary **or** substitutive: Electricity can supplement or substitute hydrogen	Sequential: Fuel switching may be a step before hydrogen adoption	Complementary: Hydrogen systems function better with digital control and safety infrastructure	Contradictory: Some recycled inputs may not be hydrogen-compatible
Electrification	Substitutive: Higher energy efficiency reduces the demand of electricity	**Independent**: CCUS has minimal impact on electrification itself	Substitutive **or** complementary: Hydrogen can replace or work alongside electricity in some processes	—	Substitutive **or** complementary: Fuels can replace or complement electricity in some processes	Complementary: Electrification requires digitalization for automation and optimal functioning	Contradictory: Some recycled materials may not tolerate electrified processes

Influencing→ / Affected↓	Energy Efficiency	CCUS	Hydrogen	Electrification	Fuel Switching	Digitalization	Recycling & Reuse
Fuel Switching	**Sequential**: Efficiency must be re-optimized post-switching fuels	**Complementary**: CCUS can be paired with fuel switching to address remaining emissions	**Substitutive**: Hydrogen replaces the need for other fuels	**Complementary or substitutive**: Can replace need for alternative fuels or complements it	—	**Complementary**: Fuel can benefit from digitalization to manage new fuel dynamics	**Contradictory**: Recycled inputs may not be compatible with all fuels
Digitalization	**Contradictory**: Energy efficiency increases the complexity for digitalization requirements	**Contradictory**: CCUS needs digital support to optimize capture which increases digital complexity	**Contradictory**: Hydrogen requires digital control increases]ing digital complexity	**Contradictory**: Electrification needs digitalization for automation which increases digital complexity	**Contradictory**: Fuel switch needs digitalization to manage new fuel dynamics increasing digital complexity	—	**Contradictory**: Digitalization for sorting and tracing increases complexity
Recycling & Reuse	**Complementary**: Enables low-energy processing of reused materials	**Complementary**: Can reduce emissions from recycling activities	**Contradictory**: Some recycled materials degrade in hydrogen environments	**Independent**: Electrification has a minimal impact on recycling	**Contradictory**: Reused inputs may not be fuel-compatible	**Complementary**: Digitalization can enable traceability and sorting for recycling	—

8.3. Barriers to de-carbonization

The shift to hydrogen-based steelmaking at Tata Steel is hindered by a diverse set of barriers, many of which are consistent with those observed across energy-intensive industries such as cement, chemicals, pulp and paper, iron and steel, food and beverage, glass, ceramics, and oil refining. These obstacles span economic, organizational, behavioral, technological, infrastructural, institutional, regulatory, training, and business dimensions, reflecting the intricate challenges of decarbonizing a complex sector.

- **Economic and financial barriers** dominate the discourse, highlighting high upfront capital costs, unpredictable hydrogen prices, and unclear returns in an emerging market. Tata Steel faces additional financial uncertainty due to fluctuating energy prices and unresolved investments in infrastructure like CC and hydrogen supply chains. The tailored agreements can play a significant role in overcoming this barrier.
- **Organizational and managerial barriers** arise from managing workforce transitions and operational realities. For Tata Steel, tensions exist between commitments to avoid layoffs and recent job reductions, undermining workforce trust and complicating change management. Additionally, discrepancies between supplier claims of automation and the necessity for more manual operator intervention increase management complexity and training demands.
- **Behavioral resistance** stems from workforce concerns about job security and unfamiliar operational processes, requiring targeted engagement and reskilling to support acceptance and effective transition.
- **Technological barriers** include uncertainties around the metallurgical feasibility of operating the DRP on 100% hydrogen. While equipment suppliers advocate compatibility, experts highlight the need for minimal carbon inputs to maintain process stability. Furthermore, unresolved carbon management strategies and the undefined configuration of Carbon Capture and Storage (CCS) complicate technology adoption.
- **Infrastructural constraints** reflect barriers for Tata Steel linked to hydrogen supply reliability and the intermittent nature of renewable energy sources. Tata Steel's reliance on external hydrogen procurement, coupled with an underdeveloped hydrogen transport and storage network, challenges consistent operations and long-term infrastructure planning.
- **Institutional and regulatory challenges** include unclear policy frameworks and insufficient incentives for hydrogen adoption, contributing to strategic uncertainties in the transition.
- **Training and capacity barriers**, though less emphasized in industry literature for steel, emerge as significant in Tata Steel's context due to new operational demands and the divergence between expected and actual automation levels.
- **Market and business model barriers** concern fluctuating demand influenced by energy prices and the nascent hydrogen market, complicating long-term strategic planning and investment decisions.

An additional barrier that did not prominently emerge in the existing literature but proved to be significant during the analysis is the challenge of constructing new technologies and facilities. In particular, this was highlighted as a key concern in the Dutch context, where limited physical space and strict environmental regulations constrain the development of large-scale industrial infrastructure. These spatial and regulatory limitations complicate the implementation of essential de-carbonization technologies, which require both substantial land use and environmental permits. As such, this barrier adds a critical layer to the broader set of challenges identified in the transition, offering a more grounded understanding of the practical limitations faced by Tata Steel and similar industries. Together, these barriers provide a comprehensive view of the hurdles encountered in the transition, setting the stage for examining the more nuanced contradictions and uncertainties that arise in operational and strategic planning.

8.4. Contradictions and uncertainty

During the course of this thesis, a number of specific contradictions and uncertainties, technological, logistical, economic, and social, related to Tata Steel's move toward hydrogen-based steelmaking have been identified through interviews and detailed analysis. While the barriers outlined above were primarily drawn from the literature review and reflect common challenges across energy-intensive industries, the following section focuses on the unique, context-specific uncertainties and contradictions that shape the feasibility, pace, and trajectory of Tata Steel's transformation.

8.4.1. Technological ambiguity in hydrogen use

A core area of uncertainty lies in the technological viability of using 100% hydrogen in the DRI process. While Original Equipment Manufacturer (OEM)'s such as Tenova and Danieli claim that their Energiron DRI technology is compatible with full hydrogen operation without significant retrofitting, expert interviews indicate that metallurgical constraints complicate this claim. Stakeholders diverge in their assessments: while some assert that a minimal carbon input is essential to maintain process stability, others acknowledge the theoretical possibility of hydrogen-only operation but point to its rarity in practice. This suggests a disconnect between supplier claims and operational reality, which complicates both planning and training for future operations.

Further uncertainties stem from carbon management strategies. While Tata Steel aims for carbon neutrality, the exact configuration of CCS systems remains undefined. The choice between on-site storage, transportation via ship, or pipeline infrastructure is still under evaluation, as confirmed by multiple stakeholders. This lack of clarity hinders long-term investment decisions and integration planning.

8.4.2. Infrastructural and supply chain risks

The hydrogen supply chain itself presents a significant logistical risk. Tata Steel has indicated that it will depend primarily on external hydrogen procurement rather than producing hydrogen on-site. This approach introduces supply reliability issues, especially given the fluctuating nature of green hydrogen production, which is dependent on intermittent renewable energy sources. Unlike natural gas, where continuous delivery via grid infrastructure is taken for granted, hydrogen supply will require buffer storage and real-time monitoring systems to ensure operational continuity. This infrastructural uncertainty is compounded by evolving and frequently changing hydrogen demand estimates, which complicate efforts to develop a coherent hydrogen backbone network. The lack of an industry-wide consensus on hydrogen needs reflects a broader indecisiveness within the steel sector, where few actors have committed to a definitive de-carbonization road map.

8.4.3. Economic volatility in the hydrogen market

Economic uncertainty is another defining feature of this transition. The hydrogen market remains immature, and price forecasts are speculative at best. Interviewed stakeholders underscored the financial risk involved in betting on green hydrogen, with cost variability driven by supply-demand mismatches and regulatory volatility. The potential relocation of energy-intensive industries in response to rising energy prices could alter future demand profiles in ways that are difficult to anticipate. These economic dynamics create planning challenges not only for Tata Steel but also for infrastructure developers and policymakers who must balance market incentives, regulatory support, and long-term investment risk.

8.4.4. Social and organizational contradictions

The social dimension of Tata Steel's transition introduces further complexity. Although the company initially committed, through agreements with trade unions, to avoid layoffs by relying on natural attrition, recent announcements of 1,600 job reductions have created significant uncertainty among the workforce. This contradiction undermines employee trust and complicates internal change management efforts, particularly in the context of operational retraining and workforce reallocation. Compounding this are discrepancies in expectations around automation. While promotional materials from the OEM suggest high levels of operational automation in the DRI plant, boasting Level 2 control systems with minimal human intervention, Tata Steel's internal assessments reveal a different picture. Due to limitations in the delivered systems, operators will need to engage in manual process adjustments far more frequently than anticipated. This unexpected operational burden increases the need for intensive training and real-time process oversight.

8.4.5. Strategic uncertainty and forward commitment

Perhaps the most fundamental uncertainty is tied to resource availability. Tata Steel's transformation is predicated on the future availability of large quantities of green electricity and hydrogen, resources that are not yet sufficiently developed or secured. Despite this, the company has chosen to move forward with its transformation strategy, under the belief that demand-side commitment will catalyze supply-side investment. While this strategy is bold, it introduces a calculated risk into the company's long-term sustainability pathway. As one expert put it, "If you want to decarbonize by 2030, you need to make your plans concrete now. But because the future is so hard to predict, it's very difficult to design the system around it" (Interview 7).

8.4.6. Hydrogen as the core uncertainty

What becomes evident from these findings is that the vast majority of uncertainties, technological, logistical, economic, and social, are fundamentally tied to the availability, affordability, and reliability of hydrogen. Whether it concerns the feasibility of using 100% hydrogen in the DRI process, the dependence on an external and intermittent supply chain, or the volatile and speculative nature of hydrogen pricing, hydrogen consistently emerges as the central variable shaping Tata Steel's transition. This interdependence significantly increases the likelihood of delays, especially if a stable hydrogen infrastructure is not realized in time. For this reason, the accelerated development and roll out of green hydrogen capacity in the Netherlands and across Europe is not just important, it is essential. Without it, energy-intensive industries like steelmaking may be forced to postpone de-carbonization plans or, in a worst-case scenario, relocate to regions with more favorable conditions.

8.4.7. Reflection on systemic uncertainty and implications for O&M

To reflect on these findings, hydrogen emerged as the most significant uncertainty in this analysis. In my view, beyond the direct findings of this research, industries must prepare proactively for this uncertainty. Tata Steel's strategy, for example, to initially use natural gas and switch to hydrogen only once it becomes available, is a pragmatic way to reduce dependency. Relying fully on hydrogen before the supply chain is secure poses a major risk: plans could collapse midway, after substantial investments have already been made. At the same time, governments must take decisive action to establish a reliable hydrogen supply in time. Doing so would significantly reduce the risks currently faced by industry and increase the likelihood that companies will commit to hydrogen-based strategies. Public investment and strong coordination in infrastructure development, pricing frameworks, and regulatory clarity are essential to support this transition. Only then can industries move forward with greater confidence and reduced exposure to volatility.

From my perspective, companies should not only acknowledge such uncertainties but also monitor and adapt to them actively. Hydrogen prices, for instance, remain highly unpredictable due to the immaturity of the market and its susceptibility to geopolitical, technological, and regulatory shifts. Tracking price trends and maintaining technological flexibility, such as the ability to switch to alternative fuels like natural gas, can help mitigate these risks. In this context, having a functional CCUS system is crucial. It enables companies to stay on track with their de-carbonization goals, even if temporary reliance on fossil-based fuels becomes necessary. Another layer of uncertainty comes from global geopolitical tensions and international trade policy. Events such as conflicts, resource nationalism, or political instability in key regions can disrupt hydrogen supply chains or increase prices for energy and raw materials. Likewise, changes in steel import tariffs can directly affect business competitiveness, especially for companies like Tata Steel that operate across borders. While companies cannot control such macro-level dynamics, they should stay alert by continuously monitoring international developments and engaging with policymakers through industry associations. Early awareness can allow firms to adapt procurement, production, or pricing strategies in time. Though influence is limited, transparency, dialogue, and resilience planning can reduce exposure.

Uncertainty is an inherent challenge: although the future cannot be predicted, decisions must be made today. This creates a DRP-EAF setup which introduces unknowns around product quality. The lower degree of automation, compared to the current configuration, could affect output quality, though to what extent, and for how long, remains uncertain. In my opinion, the best course of action is to make clear agreements with the OEM regarding the re-automation possibilities and timelines, while preparing in advance for a phase requiring greater manual intervention and communicating potential temporary change in steel quality in time to clients.

Finally, it is important to acknowledge the broader presence of known unknowns, uncertainties that surfaced during this research, such as potential geopolitical disruptions, evolving climate policies, or unforeseen technological setbacks. More importantly, I believe unknown unknowns will inevitably arise as the hydrogen transition progresses. This reinforces the need for adaptive planning, institutional resilience, and a flexible approach to managing the complex and unpredictable landscape of industrial de-carbonization.

9
Conclusion

This thesis investigated how large energy-intensive plants can de-carbonize in practice. This was done by a case study on Tata Steel IJmuiden with a particular emphasis on the evolving role of Operations and Maintenance (O&M) as practice. Using the case of Tata Steel's de-carbonization strategy, the research demonstrates that O&M is not merely a technical or support function, but a strategic enabler of environmental transition strategy. It focused on the micro level of plant operations, O&M practices and how they play a crucial role in translating and implementing macro-level de-carbonization strategies. The central research question guiding this thesis was:

"How can large energy-intensive industries transition towards de-carbonization in practice?"

Before answering the main research question in Section 9.2, the conclusions on the sub-questions, as provided in the concerning sections are shortly repeated in Section 9.1. After answering the main research question, Section 9.3 reflects on the methodological aspects of the interviews and data quality as well as on the research process and positionality of the researcher. Section 9.4 discusses the contribution of this research to science as well as to practice. The limitations of this research are addressed in Section 9.5, and the thesis concludes with practical recommendations to de-carbonizing energy-intensive industries and avenues for future research in Section 9.6.

9.1. Conclusions to sub research questions

In Chapter 4, the first sub-question guiding this research was explored:

Sub question 1: *"What does the de-carbonization strategy of the Tata Steel plant in IJmuiden entail?"*

Tata Steel's macro de-carbonization strategy hinges on the phased substitution of old technologies, to enable other strategies, such as the use of alternative fuels and Carbon Capture Utilization and Storage (CCUS). Increasing recycling is the third de-carbonization strategy adopted by Tata Steel. The substitution of technologies includes the replacement of the traditional Blast Furnace (BF)-system, by a Direct Reduction Plant (DRP)-Electric Arc Furnace (EAF) setup. In the first phase, scheduled in 2030, the construction of the first DRP and EAF will enable the shutdown of BF 7 and Coke and Gas Plant 2, resulting in a Carbon dioxide (CO_2) reduction of 5 million tonnes per year. In the second phase, after 2032, a second DRP and EAF will replace BF 6, the sinter plant, and Coke and Gas Plant 1, achieving an additional 3.8 million tonnes in annual emissions cuts. The use of hot and cold Direct Reduced Iron (DRI), gradual hydrogen integration, and Carbon Capture and Storage (CCS) technologies are central to this strategy.

In Chapter 5, the second sub-question guiding this research was explored:

Sub question 2: *"What contextual factors influence Tata Steel's de-carbonization strategy, and how do they shape the feasibility and implementation of this transformation?"*

This chapter showed that Tata Steel's de-carbonization transition is not simply a technological replacement, but a strategic transformation shaped by an interconnected set of social and environmental, infrastructural, spatial, regulatory, economic, and organizational factors. These meso- and macro-level dynamics, such as hydrogen availability, permitting constraints, and capital intensity, do not remain external; they directly shape the routines, priorities, and decisions at the micro operational level.

Importantly, O&M is not just influenced by these factors, but also plays a shaping role. O&M practices determine how reliably hydrogen systems can be run, how safety risks are managed, and how spatial and environmental limitations are handled through adaptive maintenance and modular scheduling. In this way, O&M is both a recipient of strategic pressure and a key enabler of its realization. Through the daily work of practitioners, adapting to energy uncertainties, redesigning protocols, managing new risks, strategy is continuously enacted and redefined. Thus, Tata Steel's green transition hinges not only on high-level planning, but on the alignment between systemic conditions and local O&M capabilities, where strategy is lived and practiced at the micro plant level.

In Chapter 6, the third sub-question guiding this research was explored:

Sub question 3: *"How do stakeholders organize and strategize Operations & Maintenance in Tata Steel's de-carbonized production process?"*

Stakeholders organize and strategize O&M in Tata Steel's de-carbonized production process as a coordinated, technology-enabled, and stakeholder-driven system. O&M form the backbone for ensuring reliability, safety, environmental compliance, and continuous production. O&M is organized around Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE) principles, which are essential for sustaining de-carbonized operations. Maintenance focuses on critical systems like the DRP, EAF and Carbon Capture (CC) by employing preventive and predictive strategies supported by advanced sensor and Internet of Things (IoT) technologies. Time- and condition-based maintenance ensure optimal equipment performance and legal safety compliance, with ongoing feedback loops enabling continuous improvement. Stakeholders play integral roles in this strategy in which O&M are closely integrated. Operators actively monitor and manually intervene in less automated systems, providing real-time data to maintenance teams for timely action. The handling of hydrogen introduces specific safety challenges, requiring specialized protocols managed by a hydrogen committee and aligned maintenance strategies to prevent leaks and explosions. O&M also supports environmental objectives by minimizing emissions and optimizing resource use through smart maintenance. The organization of O&M reflects a complex and distributed collaboration among actors including process owners, field operators, installation managers, external maintenance firms, regulators, and the local community. Their involvement spans all lifecycle phases, from early concept development to continuous feedback, demonstrating that O&M is both a technical function and a strategic practice that connects tools, routines and stakeholders in support of Tata Steel's green transformation.

In Chapter 7, the fourth and last sub-question guiding this research was explored:

Sub question 4: *"What changes in operations & maintenance are required to support Tata Steels environmental transition?"*

Tata Steel's environmental and de-carbonization transition from BF-based to hydrogen-driven DRP-EAF steel production requires comprehensive changes in O&M at the micro plant level, across activities, roles, and stakeholder networks. Operationally, there is a shift from largely automated monitoring to active manual control of critical process parameters, demanding extensive up-skilling of operators and a hands-on approach to ensure production continuity. Maintenance schedules evolve from a single annual shutdown to a more fragmented structure with one extended full shutdown and multiple shorter stops, reflecting the complexity and safety demands of the new installations. Safety protocols become significantly more stringent due to hydrogen's flammability, high pressures, extreme temperatures, and working at heights. This necessitates specialized training, protective equipment, and the establishment of a Hydrogen Committee to oversee safety guidelines, emergency procedures, and regulatory compliance.

Externally, the stakeholder landscape changes as BF-related utility providers exit and Original Equipment Manufacturer (OEM)s gain prominence during design, commissioning, and initial operations. Tata Steel may need new contractual arrangements with specialized maintenance providers to handle the technical complexity of the new systems. Regulatory bodies impose evolving environmental and safety standards that require integrated compliance efforts across legal, technical, and community relations functions.

Internally, operator roles shift towards more active engagement with process variables, increasing cognitive and physical workloads and heightening risks of operational errors and product variability. Maintenance personnel require new qualifications and protocols to work safely in high-risk environments. The need for extensive documentation and integration of approximately 40,000 new equipment components into asset management systems poses a major administrative challenge. The transition also faces uncertainties such as lower-than-expected automation levels in the DRP-EAF setup, evolving hydrogen safety regulations, and unknown long-term maintenance requirements for new installations. Workforce capacity and skill gaps may necessitate outsourcing certain maintenance tasks and renegotiating contracts.

9.2. Conclusion to main research question

To conclude, this thesis has explored how large energy-intensive plants can transition towards de-carbonization in practice with a case study on Tata Steel IJmuiden and a focus on O&M. The aspects examined throughout this thesis, as outlined above, collectively contribute to answering the main research question:

"How can large energy-intensive industries transition towards de-carbonization in practice?"

Large energy-intensive industries can transition towards de-carbonization in practice by adopting a strategically phased and operationally grounded approach that integrates multiple interdependent strategies. As demonstrated by the case of Tata Steel IJmuiden, this transformation is not simply a matter of technological substitution; it requires the reconfiguration of entire industrial systems, the alignment of supporting infrastructure, the reskilling of workforces, and the redesign of O&M routines, all under conditions of profound uncertainty.

Tata Steel's environmental transition strategy centers on the substitution of legacy carbon-intensive production technologies (the BF-Basic Oxygen Furnace (BOF) system) with hydrogen-based DRI and electric arc furnaces (EAF), alongside a phased shift in fuel sources, from natural gas to green hydrogen. While this shift is technologically essential, the feasibility of the transition is shaped by a broader, interconnected set of contextual factors ranging from social and environmental pressure to infrastructure readiness and regulatory clarity as well as to spatial limitations, market dynamics, and workforce capacity. These systemic conditions not only influence long-term planning, but actively shape the day-to-day feasibility of operations at the plant level, meaning that the success of the transition hinges critically on how O&M evolves in response. In this context, O&M does not merely support the transition, it actively shapes and is shaped by it. The transformation of O&M as practice, based on the Tata Steel case, can be understood through three interlocking pillars:

1. **Technical adaptation and digitalization:**
   The shift to hydrogen-based production introduces newer, less mature technologies that are not yet fully automated. This regression in automation maturity places greater emphasis on manual process control, troubleshooting, and real-time decision-making. While predictive maintenance and digital monitoring remain important, their effectiveness is contingent on years of iterative learning, digital integration, and equipment refinement.
2. **Safety and workforce competency transformation:**
   Hydrogen introduces new operational risks: flammability, leakage, and explosion, that demand comprehensive safety training and new organizational routines. At the same time, the increased manual nature of operations requires extensive re-skilling in process control, equipment handling, and emergency response. Competence development, not just technology deployment, becomes central to success.

3. **Organizational restructuring and stakeholder integration:**
   Less predictable systems require tighter coordination across internal teams (operations, maintenance engineers, emergency teams) and with external partners (OEMs, regulators, contractors). Maintenance scheduling becomes more fluid, and supplier collaboration becomes critical for software refinement, failure-mode learning, and compliance alignment.

By looking at O&M as practice, it becomes evident that achieving meaningful de-carbonization requires more than just technical upgrades, it necessitates a strategic transformation of how industries are organized, operated, and maintained. Translating environmental goals into daily industrial practice involves system-wide shifts that align engineering solutions with organizational routines, workforce capabilities, and infrastructure readiness.

Despite growing momentum, significant barriers remain. High upfront investments, uncertain regulatory trajectories, spatial limitations, and unresolved questions around long-term carbon handling continue to challenge the pace and predictability of change. Among these, the deployment of hydrogen technologies stands out as a particularly complex and uncertain variable. Its role as a potential cornerstone of deep de-carbonization is complicated by the lack of mature infrastructure, fluctuating supply prospects, and unresolved economic models. These uncertainties make hydrogen not just a technical challenge, but a strategic inflection point, one that could accelerate or stall industrial transitions depending on how public and private actors coordinate their efforts.

Moreover, the analysis reveals that industrial transformation is inherently complex and cannot be accomplished through singular or linear pathways. Insights from both theory and the Tata Steel case demonstrate the importance of managing multiple strategies in parallel, leveraging synergies, carefully sequencing interventions, and addressing inherent trade-offs. The typology of interactions, complementary, sequential, substitutive, contradictory, and independent, provides a lens to understand how these strategies relate and influence one another. Among these, digitalization emerges as a foundational enabler, offering the tools for optimization, monitoring, and adaptability across all strategies. However, its growing complexity necessitates integrated oversight to prevent misalignment and contradictions.

By reshaping the technical, operational, and digital foundations of industrial systems, the substitution of old technologies facilitates the implementation of broader de-carbonization efforts. Substitution allows for the integration of other strategies, such as hydrogen use, electrification, and CCUS, by replacing legacy infrastructure that is incompatible with low-carbon technologies. This often initiates ripple effects across operational domains: substitution leads to new digital requirements, new safety risks, and new opportunities for efficiency, each of which demands a corresponding adaptation in O&M. These implications were displayed in Table 8.1.

In summary, Tata Steel's de-carbonization journey highlights the complex nature of transitioning energy-intensive industries towards sustainability. The adoption of hydrogen, electrification, CCUS, recycling, and digitalization requires not only technological innovation but also significant shifts in O&M practices. Critical O&M implications include the need for enhanced cross-departmental coordination to maintain process synchrony, proactive and condition-based maintenance to manage increased equipment wear, specialized safety training to handle hydrogen risks, and new skill sets for managing advanced electrical and digital systems. Additionally, the integration of CCUS demands careful maintenance of chemical and pressurized units, alongside coordinated shutdowns to minimize production disruptions. Substituting legacy technologies further necessitates reconfiguring maintenance routines, developing new digital literacy, and implementing cyber-resilient systems. These operational challenges emphasize that de-carbonization is a layered transformation where effective O&M is essential to ensure system reliability, safety, and efficiency.

The lessons learned from Tata Steel's transition provide valuable insights for other industries, underscoring that successful de-carbonization depends on aligning technological advances with robust and adaptive operational management strategies. By embedding sustainability into the daily fabric of industrial operations and maintenance, firms can move beyond ambition and toward resilient, scalable, and integrated transformation. Building on these findings, the following section reflects on the interview process and overall research approach to critically assess how these insights were generated, and to identify limitations and opportunities for further inquiry.

9.3. Reflection

Now the research has been concluded, I would like to reflect on the research process by first reflecting on the interview process and afterwards on the research process in general and how my positionality has shaped this research.

9.3.1. Reflection on interviews

To gain a multidimensional understanding of Tata Steel's environmental transition and the implications for O&M, this research was enriched by nine semi-structured expert interviews that spanned a broad range of perspectives and domains. Interviewees came from academia, consultancy, the financial sector, and Tata Steel. Their contributions provided a rich empirical foundation that informed all chapters of the thesis. This cross-sectional input allowed the research to address not only the technical and operational aspects of Tata Steel's transition but also the economic, regulatory, resource availability, societal pressures and stakeholder dynamics shaping its feasibility.

Despite a wide range of interviews, access was uneven. All interviews were secured via personal or professional connections, primarily through Arcadis colleagues or TU Delft supervisors. Direct approaches to experts, without a trusted intermediary, were generally unsuccessful or met with guarded responses. One individual at Tata Steel, approached through the Green Steel consortium was reluctant to respond to questions, citing concerns about Arcadis's involvement. Though some questions were answered via email, others were declined outright. By contrast, a representative contacted via Tata Steel's website was more willing to engage. After an initial conversation, this contact provided responses to the same questions declined by the Green Steel representative and shared helpful internal documents and construction plans.

Two additional Tata Steel employees agreed to full interviews after being approached through personal contacts of an Arcadis colleague, again highlighting the importance of existing relationships in navigating gatekeeping structures. In addition, some TU Delft professors contacted through the Green Steel network declined interviews, stating their work focused on the molecular-level Research and Development (R&D) aspects of green steel, which fell outside the scope of this thesis. However, a Leiden University professor contributed useful documentation and insights on hydrogen-related aspects of the transition. These experiences reflect the politically sensitive and commercially confidential nature of industrial transitions. Even when individuals were willing to speak, their ability to provide open responses often depended on their organizational role, legal constraints, and affiliation with the research.

9.3.2. Reflection on the process and positionality

Looking back on the process of this thesis, both the research journey and my own background played an important role in shaping the outcome. The project began by mapping out the transition toward a future steel production facility. This meant learning how the new production chain would work, especially the shift from the current BF-BOF process to a hydrogen-based DRP-EAF setup. This helped me build up my technical knowledge of steelmaking and better understand how new technologies will change the way steel is made. As the research progressed, it became clear that the transition is not only a technical challenge but also a broader systems change. It involves important factors such as permitting procedures, construction challenges, hydrogen supply, and emerging safety risks. This widened my perspective and highlighted the complex and interconnected nature of the transition.

Later in the project, the focus shifted to O&M, a topic that often receives less attention but is crucial for running and adapting industrial plants during a transition of this scale. Investigating how O&M practices will need to evolve provided insight into the organizational and human aspects of sustainable transformation. A particularly valuable moment was visiting Tata Steel IJmuiden, which helped translate abstract system diagrams and technical literature into a tangible sense of place, process, and scale. Throughout the research, my dual role as a student at TU Delft and an intern at Arcadis strongly influenced how I approached the work. This position gave me access to professional networks, internal documents, and practical expertise. At the same time, it required ongoing reflection to balance academic independence with professional engagement. Depending on the setting, I took on the role of a student focused on learning, or that of an intern aligned with organizational priorities. This flexibility helped build trust with different stakeholders and allowed me to gain richer insights.

Being Dutch influenced my working style, I tend to communicate directly, organize clearly, and focus on getting results. While this was helpful in many project settings, I also learned that different cultural and professional contexts require more flexibility. Through interactions with international colleagues and stakeholders from various backgrounds, I became more aware of how diverse expectations and working styles can be. This taught me the value of adapting my approach depending on the people and situations I encountered.

From a methodological perspective, this project brought several key learning moments. Coming from a technical background, I had no prior experience with qualitative research. Learning to conduct interviews, analyze transcripts, and interpret subjective data was completely new and significantly enriched my understanding of social research. Managing the supervision process between the different TU Delft supervisors and Arcadis also taught me to navigate feedback from different perspectives and to communicate clearly across academic and professional settings. Finally, one of the most important insights I gained is that technical solutions alone are not enough to make sustainability transitions work. They must be embedded in broader organizational, regulatory, and cultural contexts. Being involved in both academic and professional environments helped me connect theory with practice and made the research more relevant to real-world initiatives like *Groeien met Groen Staal*. These experiences will continue to influence how I approach interdisciplinary challenges in the future, by combining analytical thinking with practical relevance, and by remaining attentive to the social and organizational dynamics behind sustainable change.

9.4. Contributions

This thesis makes both theoretical and practical contributions to the emerging field of industrial sustainability transitions, with a specific focus on the operational implications of de-carbonization in energy-intensive sectors. By examining the case of Tata Steel's hydrogen-based transition, the research advances our understanding of how long-term climate goals are translated into daily operational realities within complex industrial environments. The contributions are elaborated in two parts: the first Section (9.4.1) addresses the advancement of academic knowledge, and the second Section (9.4.2) outlines implications and guidance for real-world application.

9.4.1. Contribution to science

This thesis has addressed a key knowledge gap in the literature on industrial de-carbonization by investigating how strategic transformations, particularly hydrogen and new technology integration in the steel sector, are enacted at the micro operational level in practice. While existing studies have largely focused on the macro-policy and technical design aspects of de-carbonization, this research has shown that the successful implementation of low-carbon technologies depends equally on the day-to-day practices of O&M teams. By applying a Strategy as Practice (SasP) perspective at industrial de-carbonization, the study has provided insight into how strategy is not only formulated at the corporate level but also interpreted, adapted, and enacted by practitioners within the organization. The research made a layered contribution by analyzing the transition at multiple levels:

- **Chapter 4** presented the Tata Steel case as a practical example of an energy-intensive industry undergoing a de-carbonization transition. It laid the foundation for the thesis by translating theoretical concepts into a real-world industrial setting and offering a macro-level narrative of the strategic shift. This chapter highlighted the complexity, contradictions, and uncertainties involved in transitioning to hydrogen-based steelmaking.

- **Chapter 5** linked the macro context to organizational change at micro level by examining meso- and macro-level factors that influenced the transition, including hydrogen and electricity supply, regulatory pressures, cost structures, and safety requirements.

- **Chapter 6** focused on the future of operational management practices at the micro level. It explored how stakeholders as practitioners, such as process owners, safety managers, and control operators, need to adapt their routines, roles, and tools. This chapter linked the abstract strategy to the everyday activities of practitioners at the micro plant level, aligning it closely with the core of the SasP perspective.

- **Chapter 7** provided a detailed comparison between current and envisioned O&M practices. It examined misalignments, skill gaps, and organizational tensions that arose as the transition progressed. This chapter brought the analysis back to the micro level and highlighted how strategy can be enacted through situated adaptations, feedback loops, and ongoing implementation challenges.

- **Chapter 8** contributed to scientific understanding by demonstrating how de-carbonization strategies interact through distinct relational types, complementary, sequential, substitutive, contradictory, and independent, highlighting the systemic complexity of industrial transitions.

Taken together, these chapters constructed a multi-scalar account of the de-carbonization transition, from institutional and technological framing to local adaptation and sense-making.

Importantly, this thesis also proposes a novel analytical framework for assessing the role of O&M in sustainability transitions. This framework distinguishes between different phases of the O&M lifecycle, design, planning, execution, and feedback, and identifies the roles and responsibilities of various stakeholders throughout each phase. It enables a structured understanding of how strategic goals are operationalized over time and how O&M functions as a site where strategic tensions, trade-offs, and innovations are continually managed. This approach makes a conceptual contribution to both the SasP and industrial transition literature by foregrounding the temporal and actor-based dimensions of O&M within complex socio-technical change.

Beyond the plant level, this thesis has also examined the macro-level pressures that shape and enable strategic change. Regulatory requirements, environmental imperatives, hydrogen infrastructure development, permitting processes, and evolving societal pressures all contribute to the conditions under which strategy is formulated and enacted. The hydrogen infrastructure and tailored agreements with the government and regulators, essential for securing legal, financial, and infrastructural support, are shown to be critical enablers of the de-carbonization strategy. These external forces not only set constraints but also open up possibilities for strategic innovation. In doing so, the thesis responds to ongoing calls within the SasP literature for approaches that connect the micro with the macro. It provides empirical evidence of how institutional, technological, and societal dynamics filter into and reshape daily organizational routines, and how internal actors make sense of and act upon these pressures. In this way, the thesis has expanded the SasP framework by applying it to a context that remains underrepresented in existing research: industrial sustainability transitions. While SasP has been applied to sectors such as consulting, education, and IT, its use in high-risk, asset-intensive environments like steel production is still limited.

This study demonstrates how SasP can be used to understand not only who is involved in strategizing (practitioners), but also what tools and routines guide them (practices), and how strategic outcomes emerge from their situated, adaptive behaviors (praxis). It thus contributed to theory by illustrating how strategy is performed under conditions of technological complexity, regulatory uncertainty, and operational risk. The research also mapped the complex web of internal and external stakeholders whose actions shape the unfolding strategy. Internally, these include the hydrogen committee, field and control operators, the maintenance organization, installation managers, and process owners, each with a distinct role in translating strategic direction into local routines. Externally, original equipment manufacturers, regulatory bodies, emergency services, local communities, partner firms, and customers exert additional pressures and constraints. This multi-actor environment reinforces the importance of understanding strategy as a dynamic and negotiated process that cuts across organizational boundaries.

Overall, this thesis has demonstrated that industrial de-carbonization is as much about organizing, coordinating, and sense-making as it is about technological substitution. By integrating O&M into the broader sustainability discourse and applying a SasP lens to industrial transformation, it offers both theoretical insight and practical guidance. It repositions O&M not as peripheral or technical, but as a strategic domain that shapes the very possibility of sustainability transitions.

9.4.2. Contribution to practice

This thesis contributed to industrial practice by offering a structured framework that connects de-carbonization strategies with O&M implications across all phases of the transition. It identified the distinct roles of stakeholders during each phase, from planning and implementation to re-optimization and provides clarity on who must act, when, and how.

By mapping out the interdependencies between different de-carbonization measures, the thesis has shown how certain technologies can be effectively combined, while others may introduce conflicts or operational trade-offs. This systems-level understanding helps practitioners make more coherent and coordinated strategic choices, rather than pursuing isolated technological upgrades.

In addition, the study directly responded to the European Commission's call for actionable and context-specific transition pathways. It showed that successful de-carbonization strategies must incorporate O&M considerations from the outset and highlights how these operational realities influence the pace, feasibility, and direction of transition efforts. Maintenance planning, safety procedures, and workforce retraining are not secondary concerns but central components of strategic implementation.

The thesis translated abstract de-carbonization ambitions into practical, industry-specific actions. It illustrates what de-carbonization means in day-to-day operations, shedding light on hidden complexities such as skill shifts, maintenance routines, system integration, and re-optimization needs. Through this, it equips managers in energy-intensive sectors with tools and recommendations to better align long-term climate targets with short-term operational realities. Ultimately, the thesis bridges the gap between high-level sustainability goals and on-the-ground execution, supporting more resilient, informed, and feasible industrial transitions.

9.5. Limitations of the research

While this thesis provides in-depth insights into the O&M implications of Tata Steel's transition toward environmental sustainability, several limitations must be acknowledged, which in turn suggest avenues for future research.

9.5.1. Scope limitations

This analysis was specifically limited to the reduction of Scope 1 emissions, which include direct greenhouse gas emissions from sources owned or controlled by the company, particularly those associated with core production processes. The study focused on how changes in O&M within the core production processes can support de-carbonization, with a focus on the DRP as it is central to Tata Steel's transition to low-carbon steelmaking. Scope 2 emissions, indirect emissions from purchased electricity or hydrogen, were excluded, as they relate to external energy supply and procurement strategies rather than on-site operational practices. While the future DRP depends on renewable electricity, the broader implications of electricity sourcing were considered outside the O&M focus. Scope 3 emissions, which cover all other indirect emissions in the value chain such as raw material sourcing, transportation, product use, were also beyond the scope of this study. These emissions fall largely outside the direct influence of O&M and require a much broader systemic approach. Additionally, the analysis did not include supporting systems within the plant such as wastewater treatment, CO_2 capture and cleaning, or utilities, which involve different maintenance needs. Although these systems are increasingly important in sustainability planning, they warrant separate, focused research.

Furthermore, while the growing role of steel recycling was acknowledged, the technical and operational impacts of increased scrap use, such as sorting, quality control, and metallurgical variation, were not examined in detail. Future work should address these elements as Tata Steel moves toward incorporating up to 40% recycled content.

A final scope limitation of this thesis is that it did not consider how competitors' strategies might shape, accelerate, or impede Tata Steel's own de-carbonization pathway. In reality, rival firms can choose faster, incremental upgrades of incumbent technologies, rather than switching immediately to fully low-carbon solutions, to gain an early cost or market advantage and "win the race" before Tata Steel completes its full transition. Omitting these competitive dynamics means the present analysis cannot assess how technology substitution timing, learning-curve effects, or shifting market shares could either reinforce or undermine the benefits of Tata Steel's preferred route.

9.5.2. Strategic and technological boundaries

Several de-carbonization strategies cited in broader literature were not covered in depth due to their limited relevance in the Tata Steel context or their emerging status in the steel sector. These include raw material substitution, bioenergy with CCS, and sustainable packaging. As these strategies mature and are increasingly adopted across heavy industry, future research could evaluate their specific implications for operational workflows, safety procedures, and asset management.

9.5.3. O&M coordination with hydrogen suppliers

One important consideration that fell outside the scope of this study is the coordination of O&M planning between industrial users and hydrogen providers. Unlike natural gas, where supply can be adjusted relatively easily, such as by "closing the tap", hydrogen systems are less flexible due to limited storage capacities, supply intermittency (particularly with green hydrogen), and the complexity of restarting certain hydrogen infrastructure. This creates a scenario where mismatches between industrial hydrogen demand and supply stability can cause significant operational disruptions.

From an O&M perspective, this adds an inter-organizational dimension: maintenance and production schedules at industrial sites like Tata Steel may need to be co-developed with upstream hydrogen suppliers to ensure continuous, safe, and efficient operations. Future research could explore how such coordination mechanisms might be structured, the role of real-time data sharing, and what contractual or regulatory frameworks would support synchronized maintenance windows and contingency planning.

9.5.4. Generalizability and case study focus

This research was conducted as a single case study focused on Tata Steel IJmuiden, which limits the generalizability of the findings. Although some conclusions may be cautiously extended to other steel producers and other energy-intensive industries, particularly those in similar regulatory and geographical contexts, the uniqueness of Tata Steel's technological choices, stakeholder landscape, and national policy environment constrain broad extrapolation. Future research could benefit from comparative case studies across multiple steel producers, both within and outside Europe. Such cross-case analyses would help identify shared and divergent challenges in de-carbonization, particularly in relation to O&M practices. Extending this further, studies could compare the steel industry with other energy-intensive sectors, such as cement, chemicals, or refining, to assess whether transitions in O&M follow similar trajectories across industrial domains.

9.5.5. Methodological constraints

The research was shaped by limitations in stakeholder access. While the nine semi-structured interviews provided valuable insights, they were obtained primarily through personal and professional networks. Cold outreach attempts often proved unfruitful, particularly when potential interviewees were concerned about confidentiality, corporate sensitivities, or conflicts of interest. This may have introduced a degree of selection bias, favoring respondents who were more willing or able to engage in open dialogue. Future research may benefit from early-stage institutional partnerships, formalized access agreements, or participation in consortia such as Green Steel to enable more comprehensive stakeholder engagement. This would also help capture a more diverse range of perspectives, including those of operators, trade unions, and government regulators.

9.5.6. Temporal and implementation uncertainty

Finally, given the evolving nature of Tata Steel's transition plans, some findings reflect preliminary or aspirational configurations rather than implemented changes. As technologies mature and construction progresses, actual operational realities may diverge from current expectations. Longitudinal studies tracking the implementation phase, including ramp-up challenges, O&M adaptation, and workforce responses, would offer valuable real-time insights into how complex de-carbonization plans materialize over time.

9.6. Recommendations

This final section provides actionable recommendations based on the findings of this thesis. It is divided into two parts: first, it outlines practical guidance for managers in energy-intensive industries aiming to implement low-carbon technologies through adapted O&M practices; second, it presents directions for future academic research to address unresolved challenges, limitations, and strategic uncertainties identified throughout the study. These recommendations aim to support both immediate decision-making and the broader development of knowledge around industrial de-carbonization.

9.6.1. Practical recommendations

This thesis provides actionable guidance for industrial managers navigating de-carbonization in energy-intensive sectors. Recognizing that de-carbonization is a phased journey involving varying degrees of technological and organizational change, the following recommendations are organized into three strategic categories: (1) *incremental de-carbonization measures*, implemented within existing systems with minimal disruption; (2) *radical de-carbonization measures*, requiring fundamental reconfigurations of core processes and infrastructures; and (3) *post-transformation re-optimization*, necessary after new systems are in place to stabilize and enhance performance. This classification enables managers to pursue near-term improvements, plan for transformative changes, and prepare for ongoing refinement after major transitions. Incremental actions might include retrofits or process optimizations, while radical measures demand the replacement of entrenched technologies and adoption of entirely new production paradigms (Wesseling et al., 2017). Following such shifts, digital integration and system-wide re-optimization become essential. The three categories below structure the recommendations, offering a staged, strategic approach to guide practical de-carbonization planning.

1. ***Incremental de-carbonization measures:***
   These are interventions that can be integrated into existing production systems with minimal disruption. They focus on improving current operations through retrofits, enhanced monitoring, or efficiency upgrades. While relatively low-risk and fast to deploy, they often require careful planning to avoid unintended interactions with existing processes.

   - **Energy efficiency:** Industries implementing energy recovery should plan for system re-optimization and assess the operational trade-offs between energy retention and continuous operations. Synchronizing tightly integrated subsystems requires new O&M coordination routines.
   - **Carbon Capture, Utilization, and Storage CCUS:** The addition of CCUS systems introduces critical equipment such as compressors and capture units whose uptime is essential. Industries must plan specialized maintenance protocols and ensure access to skilled service providers.
   - **Electrification of processes:** The shift to electrical systems demands new competencies, spare parts inventories, and diagnostic tools. Sectors like cement or ceramics must enhance resilience to grid instability or control failures.
   - **Digitalization and Industry 4.0:** While enabling predictive maintenance and efficiency, digital tools require their own maintenance infrastructure. Digital literacy, sensor calibration, and cyber-resilient frameworks are crucial.
   - **Recycling and circularity:** Recycling requires high-quality sorting and pre-treatment systems with unique O&M needs. Industries producing quality-sensitive materials like steel, glass, or ceramics must invest in quality assurance to avoid degradation.

2. ***Radical de-carbonization measures:***
   These strategies involve replacing or radically reconfiguring existing production systems. While they offer the deepest de-carbonization potential, they also bring higher complexity, operational risk, and investment needs. Such transformations demand entirely new competencies, organizational models, and maintenance strategies.

   - **Hydrogen adoption:** Maintenance strategies need to account for hydrogen embrittlement, leakage detection, and explosion risk. Existing hydrogen-handling experience must be scaled and retraining programs adapted accordingly.
   - **Fuel switching and alternative feedstocks:** New fuels may bring unfamiliar risks such as combustion instabilities or material incompatibilities. Maintenance teams must be trained in hazard mitigation and new safety standards, particularly when switching away from legacy carbon-intensive inputs.
   - **System overhaul with new technologies:** Transitioning to fundamentally new systems, such as the DRP–EAF pathway in steel, requires building O&M programs from scratch. This includes mapping new failure modes, developing training for less-automated environments, and evolving operational knowledge alongside novel technologies.

3. ***Re-optimization after transformational shifts:***
   Major technological transitions, such as the adoption of hydrogen-based production or a full system overhaul, do not conclude the de-carbonization process; rather, they reset the operational baseline. Once implemented, these transformations necessitate a renewed focus on foundational aspects such as energy use and digital integration, as prior optimizations may no longer apply. These re-optimization steps are not one-time actions but part of an ongoing cycle of adaptation. Two areas in particular must be revisited:

   - **Energy efficiency:** New equipment configurations and process parameters can introduce unexpected inefficiencies or altered energy balances. Industries must re-optimize energy recovery systems, heat integration schemes, and process controls to fit the new technological context.
   - **Digitalization:** Legacy digital tools may become incompatible or inadequate for the new system architecture. Predictive maintenance models, automation routines, and monitoring dashboards must be recalibrated, upgraded, or completely restructured to ensure reliability and maximize system performance.

9.6.2. Future research directions

Based on the contradictions and uncertainties identified in this thesis, as well as insights from the literature, and the limitations of this research, several directions for future research can be proposed. These suggestions are grouped thematically to reflect the different aspects of the hydrogen transition and broader industrial de-carbonization challenges.

1. **Hydrogen as the core uncertainty**

   - **Scaling and infrastructure development:** Research is needed to investigate the real-world timelines and challenges of scaling green hydrogen production, transport, and storage infrastructure to meet industrial demand. Understanding how hydrogen rollout aligns with industry de-carbonization plans is crucial to managing transition risks.
   - **Coordination between hydrogen suppliers and industrial users:** Studies should explore practical models for aligning hydrogen supply and demand, including contract structures, hydrogen hubs, and buffer strategies to reduce supply interruptions and improve reliability for industries such as steelmaking.
   - **Geopolitical and policy risk analysis:** Future work could focus on how global market dynamics, shifting policies, and geopolitical events might disrupt hydrogen availability or pricing. Understanding these risks will help design more adaptive and resilient industrial transition strategies.

- **Scenario modeling for hydrogen supply reliability:** Research could focus on how industries can deal with uncertain hydrogen supply, for example through multi-supplier strategies, buffering, and better monitoring tools.

2. **Technological and organizational challenges in hydrogen-based steelmaking**

   - **Operational validation of 100% hydrogen DRI processes:** Independent pilot projects are needed to test whether full hydrogen-based DRI works reliably in practice. This includes understanding metallurgical effects, system stability, and whether OEM claims hold up under real conditions.
   - **Automation-readiness in hydrogen-based steelmaking:** Research should explore how DRI-EAF systems can be automated effectively. OEM's often promise advanced control systems, but in reality, manual intervention is still required. Future work could focus on identifying automation gaps and improving process control so that full automation becomes realistic over time.
   - **Technology-specific O&M needs:** Additional studies could look at operation and maintenance practices for other technologies related to the transition like CCUS or water treatment plants. As well as for other substituting technologies in alternative energy-intensive industries.
   - **Impact of de-carbonization scope 2 and 3:** Future research could examine how decarbonizing Scope 2 and 3 emissions influences internal operations, such as process stability, material handling, and equipment wear.
   - **O&M coordination with hydrogen suppliers:** Since Tata Steel depends on external hydrogen, it becomes important to align production schedules and maintenance planning with the availability of hydrogen. More research is needed on how to structure this coordination.
   - **Organizational adaptation across internal functions in steel:** Beyond O&M, other internal groups such as engineering, safety, procurement, and environmental compliance also play key roles in implementing de-carbonization strategies in practice. Future research should examine how these departments respond to the transition. Do they undergo similar restructuring, reskilling, or shifts in responsibility? Or do their unique roles lead to distinct adaptation paths? Investigating these dynamics can support more comprehensive and function-specific transition planning within the steel industry.
   - **Timing and competitive dynamics of technology substitution:** Some industries may choose to replace old technologies with improved versions of the existing technology instead of fully switching to new low-carbon solutions, which can take longer to implement. This faster, incremental substitution might allow them to gain a competitive advantage and "win the race" before industries like Tata Steel complete their full transition. Future research could explore how the timing of these substitution choices affects competitiveness and transition success. Understanding why and when industries delay full adoption or pursue phased approaches can reveal important insights about winners and losers in the push toward de-carbonization.
   - **Digital transformation and automation gaps:** Industries transitioning to new processes, like hydrogen-based DRI, could discover that initial setups are less automated than expected. Research should look into how digital tools (e.g. predictive maintenance, real-time monitoring, and digital twins) can be used to re-automate these systems in a realistic way after the transition phase.
   - **Managing transitional quality fluctuations and downstream effects**: During the initial phases of adopting new production setups like hydrogen-based DRI, reduced automation may lead to temporary variations in steel quality. Future research should examine how industries, especially those in high-spec sectors such as automotive or aerospace, can anticipate, evaluate, and adapt to such transitional quality fluctuations. Understanding how downstream industries can support or accommodate transitional phases without compromising product integrity will be essential to aligning industrial de-carbonization with supply chain resilience.

3. **Social and organizational change**
   - **Labor dynamics and transition governance:** Future studies could examine how issues like trust, communication, and union engagement affect transitions, especially when earlier promises (e.g. no layoffs) are not kept. Understanding how to manage change on the plant level is key to successful implementation.
   - **Re-skilling and internal change management:** There's a clear need for research on how to retrain workers and reallocate tasks during major shifts in technology. This is especially relevant when new systems require both digital skills and hands-on process knowledge.
4. **Exploring de-carbonization practices in other industries**
   - **Sector-specific transition pathways:** While this thesis has used Tata Steel as a case study, other energy-intensive industries, such as cement, chemicals, glass, and oil refining, may pursue fundamentally different de-carbonization trajectories. Future research should investigate how contextual factors like process chemistry, feedstock dependencies, regulatory pressures, and market structures shape their transition choices and constraints.
   - **Cross-sectoral variation in implementation practices:** Beyond high-level strategies, future studies should explore how different sectors translate de-carbonization into day-to-day practice. Which actors take the lead in operationalizing change? What kinds of routines, coordination structures, or risk mitigation tools are used? Comparing how sectors execute transitions can reveal whether implementation bottlenecks are systemic or sector-specific.
   - **Learning from cross-sectoral O&M strategies:** A focused comparison of how different sectors approach O&M during de-carbonization can offer valuable insights. Identifying shared challenges or successful solutions in areas like maintenance planning, workforce reskilling, or digital integration can help avoid duplicated efforts and foster cross-industry learning.
5. **Policy, economics, and comparative insights**
   - **Techno-economic analysis of CC options:** Comparative research could evaluate different CO_2 storage options, on-site, pipeline, or shipping, based on cost, geography, and regulatory feasibility.
   - **Comparative regulatory analysis:** Another area for future work is how national or EU-level policy frameworks shape O&M standards and transition timelines. This could help explain why some countries or sectors move faster than others.

These research directions aim to build on the findings of this thesis and support a better understanding of how industrial transitions can be made more feasible, reliable, and socially responsible. By addressing these gaps, future research can build on the foundation laid by this case study to more fully understand the complex interplay between technology, operations, maintenance, and sustainability in industrial transitions.

However, ultimately, research alone cannot drive transformation. The challenges outlined, ranging from high capital costs and regulatory uncertainty to infrastructural constraints and complex material dependencies, highlight the pressing need for coordinated action. While Tata Steel offers a rich example, it is not a universal model. Other energy-intensive sectors will chart different pathways, shaped by their unique process constraints and value chains. What generalizes is the conclusion that de-carbonization is not merely a technical upgrade, it is a strategic reconfiguration across technological, organizational, and operational layers.

Thus, the key to industrial de-carbonization lies in aligning long-term vision with operational pragmatism. Strategies must be sequenced, not just selected; technologies must be integrated, not merely adopted; and O&M must evolve from a reactive function to a strategic capability. By embedding de-carbonization into the everyday practices of O&M, industries can bridge the gap between high-level ambitions and on-the-ground execution, turning environmental intent into sustained industrial transformation.

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A

Energy consumption

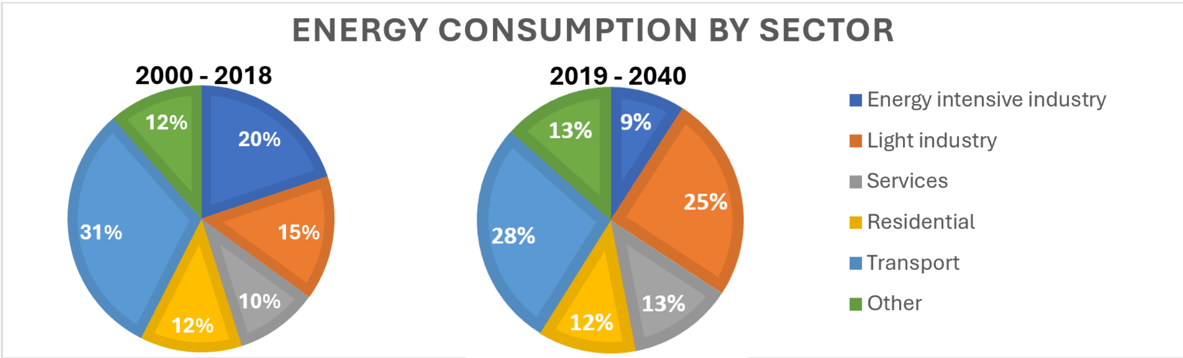

Figure A.1: Energy consumption divided per sector. Figure created with data obtained from International Energy Agency, n.d.

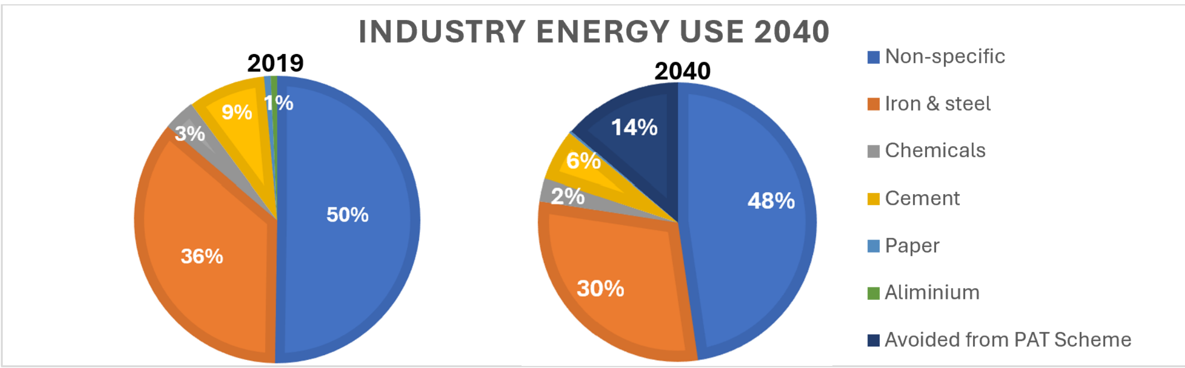

Figure A.2: Industry specific energy consumption. Figure created with data obtained International Energy Agency, n.d.

B

Literature review on de-carbonization strategies

Table B.1: An overview of decarbonization strategies mentioned per article, including possible barriers, benefits and the industries the literature review was based on.

Article	Decarbonization Options	Barriers	Benefits	Industries
Kim et al., 2024	Energy efficiency, industrial electrification, low carbon fuels, hydrogen, feedstock and energy sources, recycle and reuse, Carbon Capture Utilization and Storage (CCUS)	Economic, organizational and institutional, behavioural, technological	Environmental, cost savings, positive economic spillovers	Cement, steel and iron, chemicals, oil refining, food and beverage, pulp and paper, glass, ceramics
Vargas Colwill (2022)	Fuel switch, hydrogen, process optimization and energy efficiency, electrification, CCUS, digitalization & flexibilization, circularity	Technological, business, financial, regulatory and policy	Not mentioned	Cement and lime, chemicals, iron and steel, other sectors
Griffiths et al. (2023)	Energy efficiency, digitalization, using renewable energy / switching fuels, hydrogen, efficient use of materials (recycling), Carbon Capture and Storage (CCS)	Institutional, infrastructural, financial and economical, managerial and organizational, end-use	Reduction of greenhouse gas emissions, reduction of other environmental impacts, improvements to human health	Cement
Chung et al. (2023)	Energy efficiency, using renewable sources, hydrogen, heat management technologies, process integration and optimization, Carbon Capture and Utilization (CCU), avoiding production of virgin materials (circularity), reducing waste, recycling	Technical and economical, organizational and political, behavioural	Energy and carbon savings, cost and financial savings, environmental co-benefits	Chemical
Del Rio et al., 2022	Process optimization, energy efficiency, renewable energy and electrification, waste recovery options, substitution of old technologies, use of by-products, CCS, bioenergy / biofuel with CCS, recycling	Complex nature of industry, financial and economic, training, capacity building and lack of knowledge, human and other environmental concerns	Not mentioned	Paper and pulp
Kim et al. (2022)	Energy efficiency, adoption of renewable sources or fuel switching, hydrogen, waste heat recovery technologies, process integration and optimization, CCUS, recycling	Financial and economic, organizational and managerial, behavioural barriers	Energy and carbon savings, cost and financial savings, environmental co-benefits	Iron and steel

Article	Decarbonization Options	Barriers	Benefits	Industries
Griffiths et al. (2022)	Waste-heat recovery and over-bottom pressure recovery technology, new materials technology, process optimization technology, intelligent system scheduling optimization technology, circulating water system energy-saving technology, new equipment technology, hydrogen, CCUS, operational and institutional measures	Technological, organizational and managerial, political, market, consumers	Energy savings from decarbonization, carbon savings and GHG emission reduction, reduction of environmental hazards and health impact, potential reduction of land use and water demand	Oil refining industry
Del Rio et al., 2022	Raw materials optimization, electrification, heat recovery, hydrogen, novel formulas, furnace substitution (technology substitution), recycling	Manufacturing, managerial and infrastructure, lack of information, knowledge and skills, financial and economical, regulations	Not mentioned	Ceramics
Del Rio et al., 2021	CCUS, batch preheating, waste heat generation, biofuels, electrification, hydrogen, innovations in heating and melting, recycling or reuse, energy efficiency	Financial costs and funding, carbon markets and prices, inconsistent infrastructural support	Not mentioned	Glass
Sovacool et al., 2021	Automation, process optimization, thermal management and heat recovery, adoption of renewable electricity and heat/fuel switching, energy efficiency, sustainable packaging	Financial and economic, organizational and managerial, behavioural and consumer barriers	Energy and carbon savings, cost and financial savings, environmental co-benefits, worker satisfaction and health	Food and beverage

Table B.2: Overview of decarbonization options, number of times mentioned in literature, and industries where they are applied.

Decarbonization Option	**Times Mentioned**	**Industries**
Energy efficiency	9	Cement and lime, steel and iron, chemicals, food and beverage, pulp and paper, glass
CCU/S	8	Cement and lime, steel and iron, chemicals, food and beverage, pulp and paper, glass, oil refining
Recycling and reuse	8	Cement and lime, chemical, paper and pulp, iron and steel, ceramics, glass
Use of hydrogen	8	Chemical, oil refining, ceramics, glass, iron and steel, cement and lime
Process optimization	6	Cement and lime, chemicals, iron and steel, paper and pulp, oil refining, ceramics, food and beverage
Electrification	5	Cement and lime, chemical, paper and pulp, iron and steel, ceramics, glass
Fuel switching	5	Cement and lime, iron and steel, paper and pulp, glass, food and beverage
Heat recovery and management	6	Chemical, iron and steel, oil refining industry, ceramics, glass, food and beverage
Digitalization	2	Cement and lime, chemicals, iron and steel
Circularity	3	Cement and lime, chemicals, iron and steel, oil refining
Substitution of old technologies	3	Paper and pulp, oil refining, ceramics
Raw material optimization	2	Chemical and ceramics
Bioenergy with CCS	1	Paper and pulp
Use of by-products	1	Paper and pulp
Novel formulas	1	Ceramics
Batch preheating	1	Glass
Sustainable packaging	1	Food and beverage

Table B.3: Barriers for decarbonization with the frequency and industries in which it was mentioned.

Barrier Category	**Times Mentioned**	**Industries**
Economical and financial	9	Cement and lime, chemicals, iron and steel, paper and pulp, ceramics, glass, food and beverage
Organizational and managerial	7	Cement, steel and iron, chemicals, oil refining, food and beverage, pulp and paper, glass, ceramics
Behavioural	4	Cement, steel and iron, chemicals, oil refining, food and beverage, pulp and paper, glass, ceramics
Technological	4	Cement, steel and iron, chemicals, oil refining, food and beverage, pulp and paper, glass, ceramics
Infrastructural	3	Cement, ceramics, glass
Institutional	2	Cement, steel and iron, chemicals, oil refining, food and beverage, pulp and paper, glass, ceramics
Regulatory and policy	1	Cement and lime, chemicals, iron and steel
Political	2	Chemical, oil refining
Training, capacity building and lack of knowledge	2	Ceramics, paper and pulp
Business	1	Cement and lime, chemicals, iron and steel
End-use	1	Cement
Complex nature of industry	1	Paper and pulp
Human and environmental concerns	1	Paper and pulp
Market	1	Oil refining
Manufacturing	1	Ceramics
Carbon market and prices	1	Glass

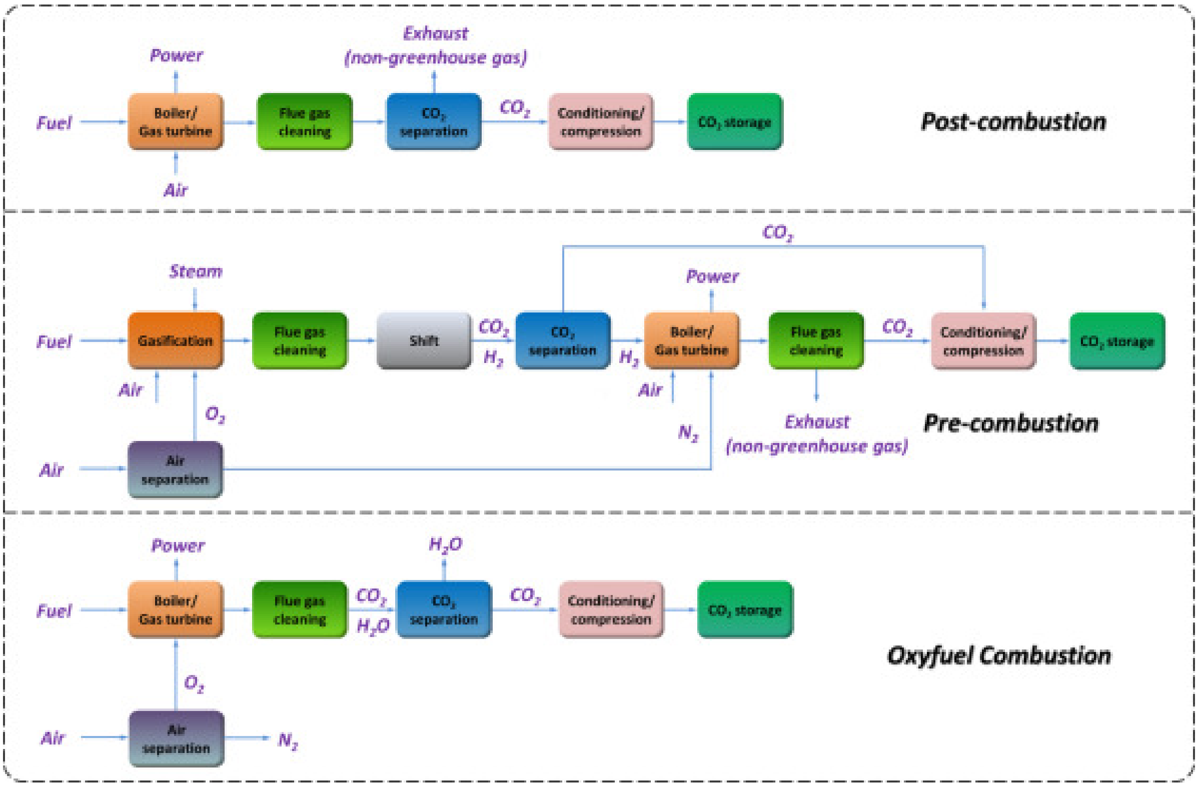

Figure B.1: Visual representation of pre-combustion, post-combustion and oxyfuel capture techniques. Figure obtained from Song et al., 2018.

C

Literature search

C.1. Approach to literature search

Search query:	systematic AND review AND of AND sociotechnical AND systems AND industrial AND decarbonization
Results:	12 documents
Screening:	1 paper excluded for focusing on greenhouse gas emissions instead of production processes. 2 papers excluded for reviewing hydrogen and CCUS as specific strategies rather than pathways. These papers were used in sections discussing hydrogen and CCUS.

Table C.1: Overview of search query, results, and screening process of literature regarding decarbonization strategies in energy-instensive industries.

Search query:	decarbonizing AND iron AND steel AND European AND industry AND hydrogen
Results:	5 documents
Screening:	Titles and abstracts of the results were reviewed for relevance to the research topic. Boldrini et al., 2024 was chosen as the most relevant document, offering insights into the impact of de-carbonization in the European steel industry on power and hydrogen systems.
Search query:	ammonia AND energy AND green AND steel AND technology
Results:	26 documents
Screening:	Titles and abstracts were reviewed. The articles by El-Kadi (2024) and Ma (2023) were selected due to their relevance to the topic of de-fossilization in industries in Europe.
Search query:	hydrogen AND electrolyzer sustainable AND energy AND production AND technologies
Results:	18 documents sorted by relevance
Screening:	Titles and abstracts were scanned. Arsad et al., 2023 was selected due to its comprehensive review of hydrogen electrolyzer technologies for sustainable energy production.

Table C.2: Overview of search queries, results, and screening processes of literature focused on the de-carbonization strategies for the steel industry and Tata Steel specifically.

A search for previous master thesis projects was conducted using Google Search to obtain relevant previous thesis on Tata Steel's sustainability transition: "Thesis clean steel industry Netherlands" The thesis by Dijkstra, 2024 was selected based on its direct relevance to the sustainability transition of the Dutch steel industry, as well as Keys et al., 2019.

Search query:	industrial AND maintenance AND strategies AND literature AND reviews
Database:	Scopus
Timespan:	2015–2025
Results:	18 documents
Screening:	7 papers excluded due to restricted access. 2 papers excluded for focusing solely on data mining or machine learning rather than broader maintenance strategies. 2 papers excluded for focusing on internet infrastructure instead of industrial settings. 1 paper excluded due to focus on offshore wind rather than general industrial context.
Inclusion criteria:	English language, publication year between 2015–2025, industrial relevance, direct application in maintenance strategies, availability of full text.
Final selection:	6 papers included in the review

Table C.3: Overview of search query, database, results, and screening process of literature regarding industrial maintenance strategies.

C.2. Citation tracking

In addition to the systematic search, citation tracking was used to identify additional references. This method allowed the discovery of influential sources cited within other key articles:

Vargas Colwill et al., 2022 was identified through citation tracking in J. Kim et al., 2024 and was selected based on its relevance to de-carbonization strategies for energy-intensive industries.

Boldrini et al., 2023 and Somers, 2022 were identified through citation tracking in (Boldrini et al., 2024). These articles provided further insight into de-carbonization technologies and strategies for the steel industry and were included in the review based on their relevance.

Morlanés et al., 2020 and Pashchenko, 2024 were identified through citation tracking in Dijkstra, 2024. Morlanés et al., 2020 provided insights into ammonia-based energy systems and missing technologies, while Pashchenko, 2024 explored the efficiency of green hydrogen for power plant fuel. Both were relevant for discussions on sustainable energy economies.

C.3. Opportunistic discovery

Opportunistic methods complemented the systematic and snowballing approaches by incorporating insights gained from interviews, colleague recommendations, and industry resources: References such as Elderkamp, 2023, Geelen et al., 2023, and FNV, n.d. were tipped by colleagues and interviewees during discussions about the steel industry and its de-carbonization challenges. Hoeger et al., 2021 and Song et al., 2018 were identified during interviews related to Carbon Capture and Storage (CCS) technologies. Van den Berg et al., 2022 was recommended by colleagues as a governmental document detailing the economic and employment contributions of Tata Steel. Beetsma, 2025 and van Tulder, 2025 were identified through a government debate regarding Tata Steel, based on advice from an Arcadis colleague. References such as Green Steel Plan, n.d. were obtained directly from Tata Steel's website, which documents the company's sustainability transition plans.

D

Tata Steel's de-carbonization transition

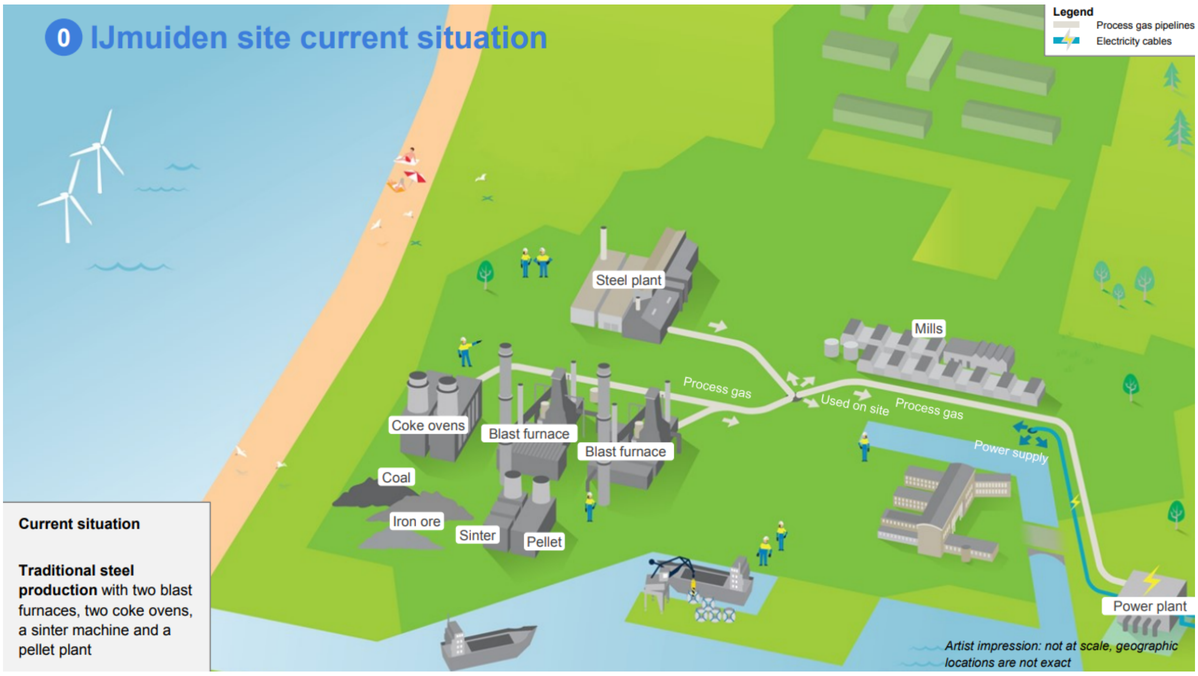

Figure D.1: Visual representation of the current iron and steel production at Tata Steel IJmuiden.

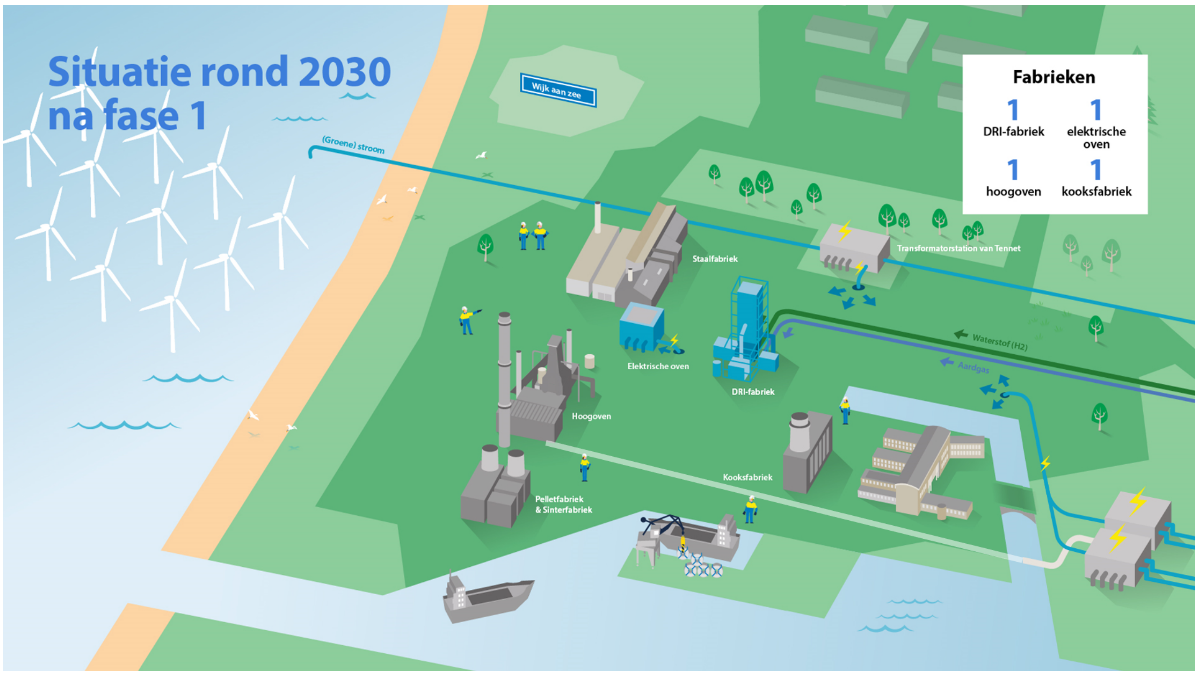

Figure D.2: Visual representation of the transition stage of Tata Steel IJmuiden.

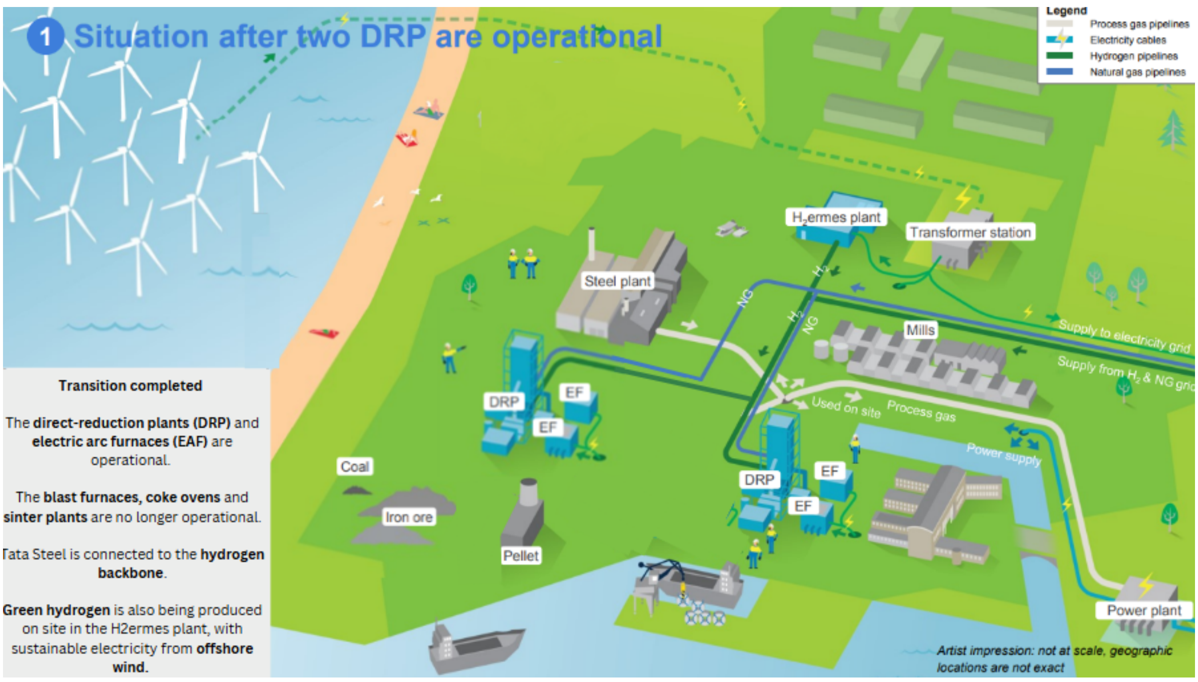

Figure D.3: Visual representation of the decarbonized iron and steel production at Tata Steel IJmuiden.

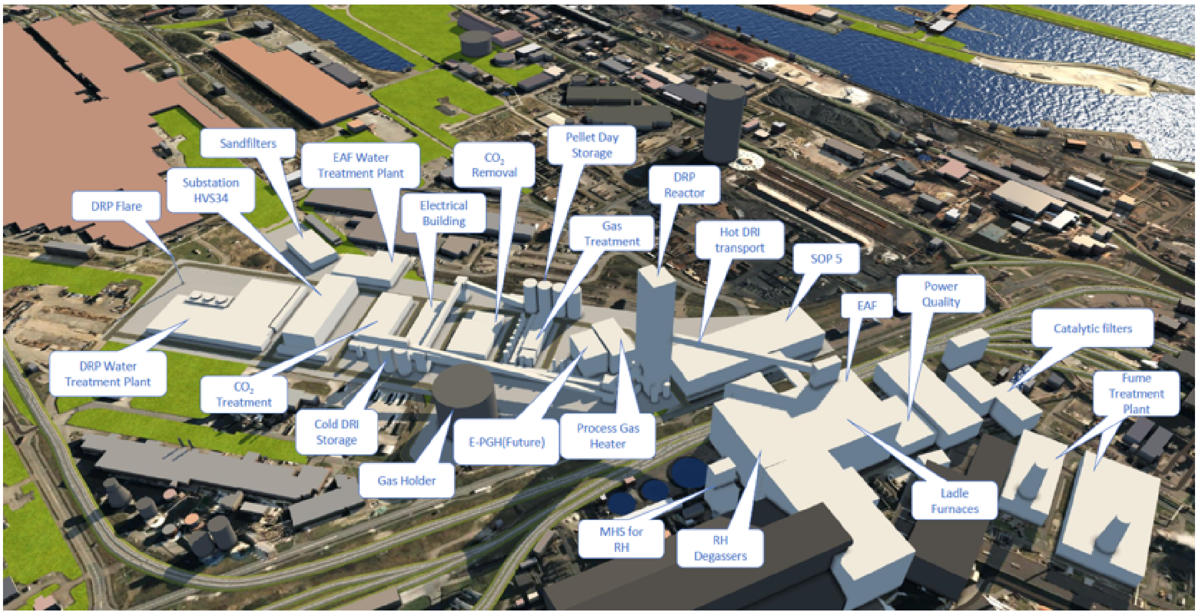

Figure D.4: Visual representation of the new plant including all extra installations needed for the DRI production.

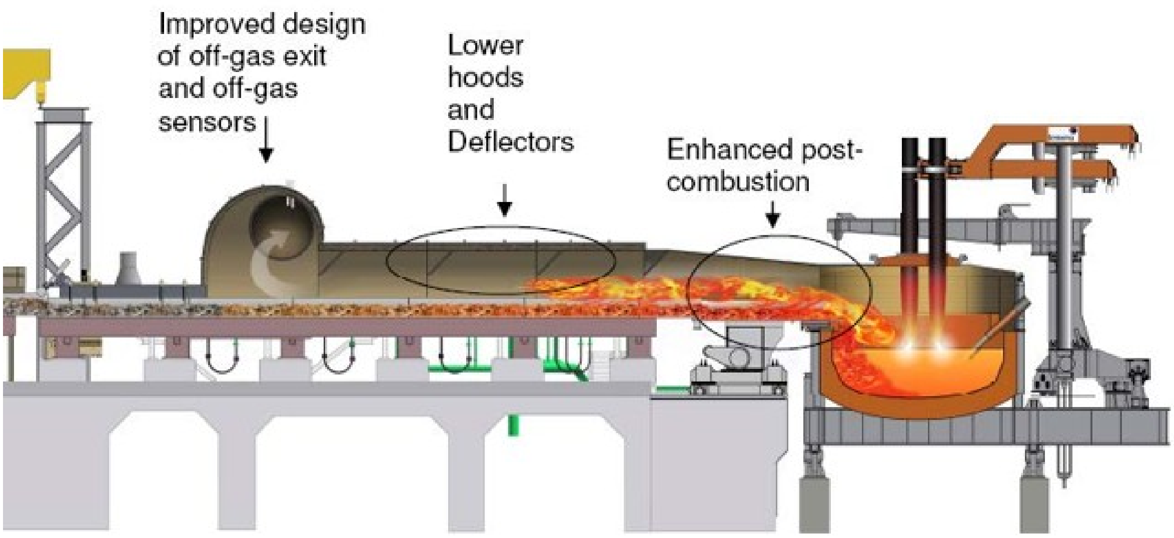

Figure D.5: Schematic overview of the EAF. Figure obtained by Tata Steel, 2025c.

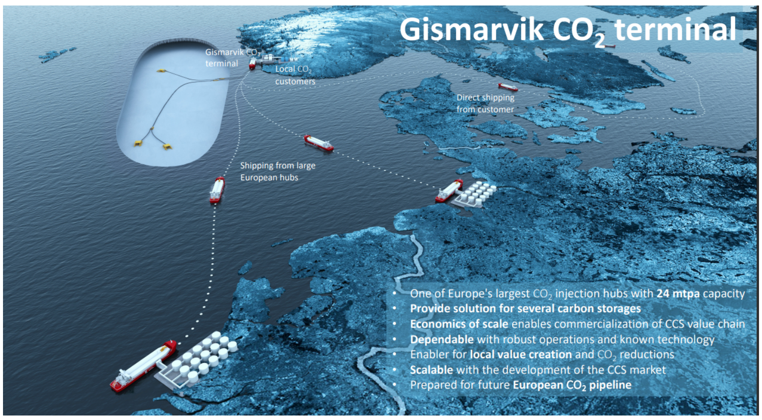

Figure D.6: Transport route and storage location of the Gismarvik CO_2 hub. Obtained by Horisont Energi, 2023.

Figure D.7: Visual representation of the ECOLOG ship. Obtained by CCUS - ECOLOG, 2024.

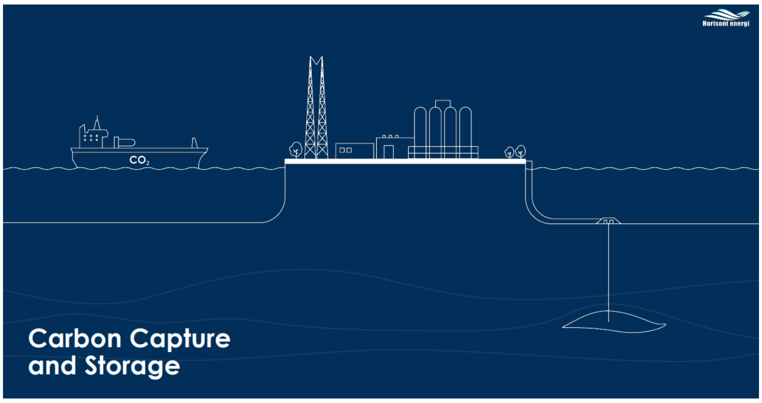

Figure D.8: Transport route and storage location of CO_2. Obtained by Horisont Energi, 2023.

E

Contextual factors

Figure E.1: Connection new pipeline to Tata Steel on the map. Figure obtained from Hynetwork, n.d.

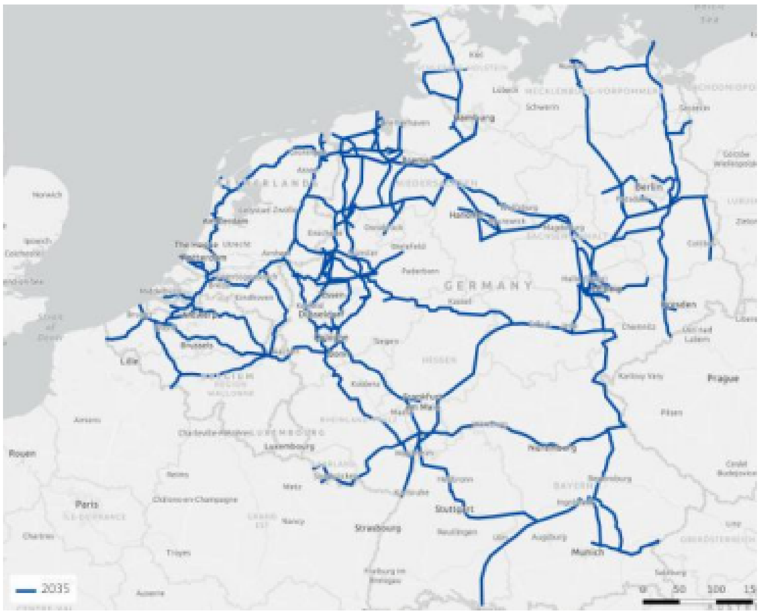

Figure E.2: Visual representation of the planned north western European hydrogen pipeline network in 2035. Figure obtained by (TNO & Arcadis, 2025).

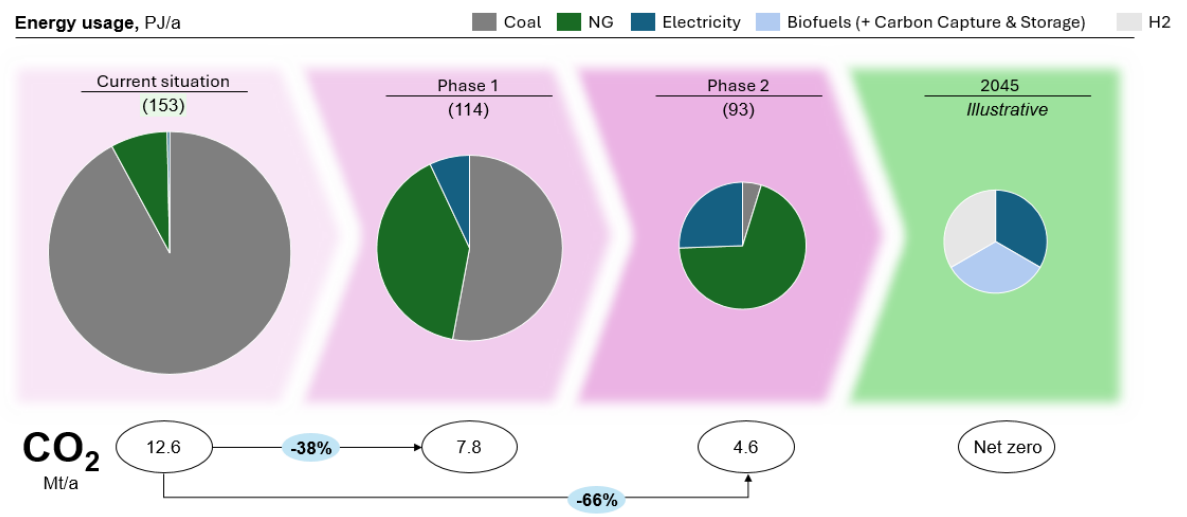

Figure E.3: The changes in Tata Steels energy consumption during the transition phases. Figure obtained by Tata Steel, 2025b.

Figure E.4: The transportation route of the modules are indicated in red. The orange section is the construction site. Obtained by Tata Steel, 2025a.

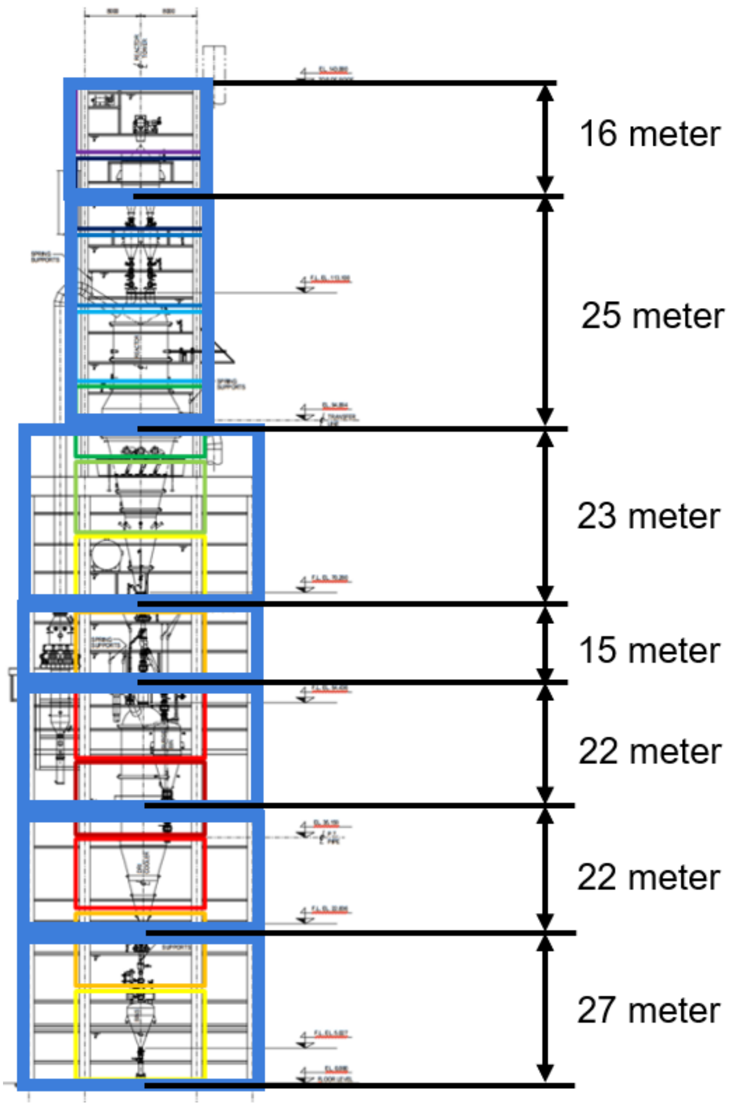

Figure E.5: Construction of the DRP in modules. Obtained by Tata Steel, 2025a.

Figure E.6: An example of how the modules will be transported to the right location on site. Obtained by Tata Steel, 2025a.

F Stakeholder analysis

Freeman, 1984 stakeholder theory defines stakeholders as both internal and external entities with a vested interest in an organization. Internal stakeholders include employees, managers, and owners, while external stakeholders encompass customers, suppliers, the community, government, and shareholders. For this analysis, these groups were considered in relation to their roles in Operations and Maintenance (O&M) for the future factory. However, shareholders, while influential in deciding whether the transition to the new production process should occur, are less involved in the actual phases of O&M. Therefore, they were excluded from this analysis. Additional stakeholders emerged during interviews, leading to a more detailed categorization. Employees were divided into distinct roles: field operators, control operators, and installation managers. As one interviewee explained:

> *"There are two types of operators. You have the people who work in the field, in the factory, walking around and doing their job. And you have the people who sit behind a series of screens all day, operating and monitoring the process."* (Interview 8)

The installation manager, as another key internal stakeholder, is responsible for overseeing maintenance activities and receiving notifications about issues.

> *"That SAP-notification goes to the manager, the person responsible for the maintenance of the installation."* (Interview 8)

Beyond employees, Tata Steel's own maintenance organization was identified as a critical stakeholder. This central maintenance organization includes approximately 1,000 employees dedicated to maintaining the reliability of equipment and systems. As described in the interviews:

> *"We have our own central maintenance organization where approximately 1,000 people work."* (Interview 8)

Another important group within Tata Steel is the hydrogen committee, which plays a growing role in ensuring safe and efficient operations with hydrogen. This committee focuses on monitoring hydrogen-related legislation, staying informed about developments in the field, and applying this knowledge to the practical use of hydrogen. As one interviewee noted:

> *"Now that we are transitioning to steel production based on hydrogen, we decided we need a hydrogen committee. [...] This committee focuses on monitoring legislation related to hydrogen, keeping track of developments in that field, but also on the practical application and use of hydrogen."* (Interview 8)

The process owner was identified as Tata Steel IJmuiden, representing the local ownership and leadership responsible for the operation and maintenance of the installations. However, the broader owner of Tata Steel IJmuiden, Tata Steel Limited, was excluded from this analysis, as their involvement is at a corporate level rather than operational. Suppliers, particularly technology providers, also emerged as significant stakeholders. For example, the Original Equipment Manufacturer (OEM) plays a role in shaping the maintenance concept by providing equipment manuals and making adjustments based on Tata Steel's expertise:

> *"So first, we work from the OEM's manual, and then we adjust it using the knowledge and experience we already have here."* (Interview 8)

Firms responsible for physical maintenance were also highlighted as key stakeholders. These external companies are often local to the area and are hired to perform the hands-on maintenance tasks that Tata Steel outsources. As noted in the interviews:

> *"The actual hands-on work, the physical maintenance, is often outsourced. We hire numerous firms for that, often companies from the area around our business."* (Interview 8)

Finally, the government, described here as regulatory bodies, was identified as a crucial external stakeholder. These bodies define the operational and maintenance regulations, ensuring compliance with environmental and safety standards. Multiple regulatory authorities oversee different aspects of the factory, from environmental impact to worker safety, and play a key role in determining inspection frequencies and legal obligations. This comprehensive stakeholder analysis incorporates both internal and external perspectives, ensuring a holistic understanding of the roles and responsibilities that contribute to the successful operation and maintenance of the future factory. All internal and external stakeholders are displayed in Figure F.1.

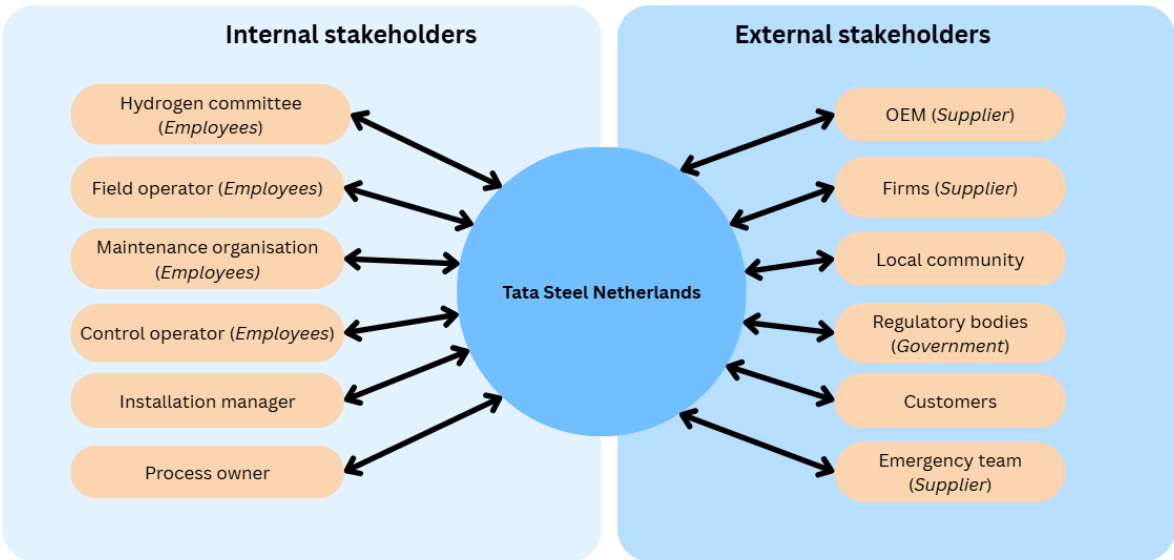

Figure F.1: Visual representation of the different stakeholders based on the stakeholder theory and the interviews.

G
Informed consent

Participant Information Sheet

Research Study Title:
From Fossil to Green: Driving the Sustainable Transition of Energy-Intensive Industries in the Netherlands

Researcher:
Ylse Wind, MSc Candidate, TU Delft (y.c.wind@student.tudelft.nl)
Supervisors: prof. Dr. Roland Ortt and Dr. Jenny Lieu

Purpose of the Study:
This research explores the operational and maintenance changes required, environmental impacts, and risks associated with transitioning energy-intensive industries—such as Tata Steel—from fossil fuels to green hydrogen. The goal is to provide practical recommendations for safe and sustainable operations during this transition. This study is done in collaboration with Arcadis Netherlands.

What Will Participation Involve?
If you agree to participate, you will be invited to a 60-minute interview, which will be audio recorded and transcribed, where you will answer questions related to your expertise and perspectives on the transition to green hydrogen. Participation is entirely voluntary, and you may opt out at any time without any consequences.

Potential Benefits:
This research may contribute to advancing sustainable energy practices in energy-intensive industries, benefiting the environment and society.

Voluntary Participation:
Your participation is entirely voluntary. You can withdraw at any time, and your data will be deleted upon request unless it has already been anonymized. Declining to participate will have no impact on your professional relationships.

Data Management and Confidentiality:
Your personal data (e.g., name or email address) will only be used for arranging the interview and will not be shared without your consent. All data will be anonymized during transcription and stored securely on encrypted devices or approved institutional platforms. Transcripts will be deleted after the project is complete, except for anonymized data retained for academic purposes.

Contacts for Questions or Concerns: In case of concerns or complaints the people below can be contacted.

- **Researcher**: Ylse Wind, MSc Candidate, TU Delft
- **Supervisors**: Dr. Roland Ortt, TU Delft and Dr. Jenny Lieu, TU Delft
- **Ethics Committee**:

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves an audio-recorded interview which will be transcribed into text. These recordings will be destroyed after the completion of the research in July 2025.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
4. I understand that taking part in the study involves the following risks emotional or psychological distress and privacy related risks. I understand that these will be mitigated by the possibility to skip any question or stop the interview at any time. The data will be anonymized, encrypted and stored securely. Personal identifiers will be removed during analysis and reporting.	☐	☐
5. I understand that taking part in the study also involves the collection of specific Personally Identifiable Information (PII), such as my name, email address, and job title, for the purposes of arranging and conducting the interview, as well as associated Personally Identifiable Research Data (PIRD), including my responses to interview questions and professional insights. I acknowledge that there is a potential risk of my identity being revealed in the event of a data breach or unauthorized access to the data. However, I understand that steps will be taken to mitigate this risk, including the anonymization of my responses, secure storage of data on encrypted devices, and restricted access to the data by authorized personnel only.	☐	☐
6. I understand that some of the Personally Identifiable Research Data (PIRD) collected during this study is considered sensitive data within the scope of GDPR legislation. Specifically, the following issues apply: • Data concerning professional opinions or practices that could be linked to workplace policies or organizational decisions may be discussed, which, while not explicitly sensitive under GDPR, could indirectly lead to reputational or professional risks if misused or re-identified. • Data concerning potential ethical concerns or risks related to industry practices may arise, such as discussions of compliance with environmental or safety regulations. These may include indirect references to criminal activities, though no explicit collection of criminal records is intended.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
7. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: • **Anonymization**: Personally Identifiable Information (PII), such as my name and contact details, will be removed or replaced with unique identifiers during data processing to ensure that I cannot be directly identified in the research findings. • **Secure Data Storage**: All data will be stored on encrypted devices and secure institutional servers with access restricted to the researcher. • **Limited Access**: Only the researcher will have access to identifiable data. • **Transcription and Blurring**: Transcriptions of interviews will be anonymized, and any identifying details (e.g., names, job titles, organization-specific information) will be removed or generalized during the transcription process.	☐	☐
9. I understand that personal information collected about me that can identify me, such as my name, email address, or job title, will not be shared beyond the TU Delft study team. This includes my contact details, which will only be used for arranging interviews and will not be disclosed to any third parties. I further understand that identifiable information will be stored securely and will be deleted after the study is concluded.	☐	☐
10. I understand that the (identifiable) personal data I provide will be destroyed after completion of the research, in July 2025.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the summary of the interview will be used for: • **Interview summary**: After the interview I will write a short technical summary of the interview that I will share with you to review. You are welcome to suggest any changes to the summary. • **Reports and Academic Publications**: The findings of this research will be included in the researcher's Master's thesis which will be publicly available and may also be published in academic journal articles. These outputs will focus on the sustainable transition of energy-intensive industries and will not include any identifiable personal information. • **Policy Development and Decision-Making**: The results of this study may inform decision-making processes or policy recommendations related to the transition to green hydrogen and sustainable industrial practices. • **Knowledge Sharing for Public Benefit**: The anonymized findings may be shared with broader stakeholders, such as sustainability-focused organizations or industry partners, to contribute to service or product development aimed at addressing sustainability challenges.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
12. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

I have read and understood the information above and I consent to participate in the study and to the data processing described above.

Signatures

______________________________ _____________________________ _________

Name of participant [printed] Signature Date

Study contact details for further information: Ylse Wind, y.c.wind@student.tudelft.nl

Or the thesis supervisor: Roland Ortt, j.r.ortt@tudelft.nl

H Interviews

H.1. Translation of original quotes

All interviews, except for interview 4 which was in english, were conducted in Dutch. To ensure transparency in how interview data were used, this appendix presents examples of one original quotes from all interviews alongside their English translations, as they appear in the thesis. In a few cases, slight adjustments were made to the translated text to ensure clarity and readability in English, while preserving the original meaning. The quotes are organized by interview number for ease of reference.

#	Quote as used in the thesis	Original (Dutch)
1	”The theory suggests that it is possible, but there are not many Direct Reduced Iron (DRI) installations that actually operate on 100% hydrogen yet. It presents an additional challenge because you are not adding carbon to the iron, but you need carbon to produce steel, as steel is an alloy of iron and carbon. So, if carbon is not added during the DRI process, it must be added during melting or in the steelmaking plant.”	"De theorie zegt wel dat het kan, maar er zijn nog niet heel veel grootschalige DRI's die ook echt op 100% waterstof draaien. En het brengt ook nog een extra uitdaging met zich mee, omdat je dan geen koolstof toevoegt aan het ijzer. Maar je hebt koolstof nodig om staal te maken, want staal is een legering van ijzer en koolstof. Dus als het niet bij het ijzer toegevoegd wordt, dan moet het dus bij het smelten of bij de staalfabriek toegevoegd worden."
2	”If you use two materials that are both necessary for your process but have different properties, and you use them simultaneously, you must ensure that operators from plant A never work in plant B. If you put people in a situation where they have to work with A today and B tomorrow, there is a chance that something might go wrong.”	"Als je twee grondstoffen gebruik die beide noodzakelijk zijn voor voor je proces. Maar ze hebben verschillende eigenschappen en je gaat ze tegelijkertijd in je site gebruiken. De operators van plant A die komen nadat die plant dus overgegaan van brandstof een naar twee komen nooit meer in plant B. Want als je Mensen in die situatie brengt dat ze vandaag moeten werken met proces A en morgen met proces B, dan is de kans dat dat daar ergens misgaat is aanwezig."

#	Quote as used in the thesis	Original
3	”These tailor-made agreements are really about one central question: what conditions can we create to enable you to make your operations more sustainable? You have to imagine that sustainability efforts by a company happen on their own little patch within a larger patchwork. If you see the Dutch industry as one big patchwork of interlinked chains of activities, then each company operates on its own patch. So they can only make changes on their own site. But the real challenge is that the government, through its policies and frameworks, has to ensure coherence across the entire patchwork. And how does it do that? By creating the right enabling conditions.”	“Die maatwerkafspraken gaan echt over de vraag: welke randvoorwaarden kunnen wij creëren zodat jullie kunnen verduurzamen? Je moet je voorstellen dat zo’n verduurzaming voor een bedrijf plaatsvindt op hun eigen lapje binnen één grote lappendeken. Als je de Nederlandse industrie ziet als één grote lappendeken van ketens van activiteiten, dan voert elk bedrijf zijn processen uit op zijn eigen stukje. Zij kunnen dus alleen verduurzamen op hun eigen terrein. Maar het draait er natuurlijk om dat de overheid met beleid en randvoorwaarden zorgt voor samenhang binnen die hele lappendeken. En hoe doet ze dat? Door het creëren van de juiste randvoorwaarden."
4	”So I would say the next higher maturity technology in the Technology Readiness Level scale is a solid sorbant. [...] So now you have a selective solid sorbant that basically takes in CO2 from the flue gas.”	"So I would say the next higher maturity technology in the TRL scale is a solid sorbant. [...] So now you have a selective solid sorbant that basically takes in Carbon dioxide (CO_2) from the flue gas.”
5	”First, you must apply for a demolition permit because you will be demolishing more than twenty-five cubic meters. This requirement is outlined in the Building Environmental Regulations.”	"Allereerst moet je een sloopvergunning aanvragen omdat je meer dan vijfentwintig kuub gaat slopen en dat staat in het besluit bouwwerken leefomgeving"
6	”The technical risks are manageable. What is harder to prevent is the high temperature of combustion, the temperature of hydrogen compared to natural gas. This leads to higher Nitrogen Oxides (NOx) emissions, which is a sensitive issue in the Netherlands. You need to be aware that you are burning at a different temperature than natural gas.”	"De technische risico’s zijn managable. Wat je moeilijker kan voorkomen, is de hoge temperatuur van de branding, de temperatuur van waterstof vergeleken met aardgas. Dat leidt tot hogere Nox emissies. Dat is in Nederland een pijnlijk dossier. Je moet wel weten dat je gaat branden op een andere temperatuur dan aardgas."
7	"There is a bandwidth you need to take into account in terms of costs for hydrogen [...] Unfortunately, that’s the reality. Sometimes, you have to take those risks and see what happens.”	"Er is echt een bandwidth waar je rekening mee moet houden qua Kosten. [. . .] Dat is helaas de realiteit, soms moet je die risico’s nemen en zien wat er gebeurt."

#	Quote as used in the thesis	Original
8	"We had hoped: we are going to build the factory of the future. So we thought we would implement a highly advanced automated system, like what we are already accustomed to at Tata Steel. Here, we have factories that are already highly automated. But what we are seeing in practice is that the supplier of the DRI installation is actually providing a very basic level of automation, nowhere near the level we, as users, would like. [...] The operator will have to do more, for example, continuously adjust the temperature. He or she will have to monitor trends and deviations much more closely. Where deviations were normally corrected automatically, this will now have to be adjusted manually."	"Wij hadden gehoopt: we gaan de fabriek van de toekomst bouwen. Dus wij dachten dat we een zeer vergaand geautomatiseerd systeem zouden neerzetten, zoals we nu al gewend zijn bij Tata Steel. We hebben hier fabrieken die al heel ver geautomatiseerd zijn. Maar wat we in de praktijk zien, is dat de leverancier van de DRI-installatie eigenlijk een zeer basale automatisering levert, lang niet het niveau dat wij als gebruiker zouden willen. [..] De operator zal meer moeten doen, bijvoorbeeld continu de temperatuur bijsturen. Hij of zij zal veel meer naar trends en afwijkingen moeten kijken. Waar afwijkingen normaal gesproken automatisch werden gecorrigeerd, zal dat nu handmatig aangepast moeten worden."
9	"This is the step before you actually start planning. This is the design of your maintenance concept, and that concept says something about failure mechanisms, like frequency, what we need to do, especially the what and the how. So, essentially, it's like creating the maintenance manual for your car."	"Dit is eigenlijk de stap voor dat je het echt plant. Dit is het ontwerp van je onderhoudsconcept, dat concept zegt wat over faalmechanisme, dus frequentie wat we moeten doen, vooral het wat en het hoe. Dus eigenlijk is dit het maken van het onderhoudsboekje van je auto."

H.2. Example of interview analysis

The interview transcripts were examined using a structured yet adaptable approach designed to capture both predefined and emerging themes related to maintenance concepts and planning. By integrating deductive themes grounded in theory with inductively derived insights from the data, this method ensured that the analysis was both theoretically informed and responsive to the participants' unique perspectives, ultimately yielding comprehensive and insightful conclusions for the thesis.

H.2.1. First Step: Initial transcript analysis

In the first stage, the transcripts were systematically color-coded based on a combination of predetermined and inductively developed themes. Pre-established categories, such as planning, proactive maintenance, reactive maintenance, and operational aspects, were derived from relevant literature and research goals. Concurrently, additional key concepts, including the maintenance concept itself and detailed planning strategies, emerged inductively as new patterns and ideas surfaced from the interview data. Throughout this iterative coding process, the researcher continuously recorded observations and feedback to refine the thematic framework. This balanced approach enabled a thorough understanding that combined structured analysis with openness to novel findings. This process is illustrated in Figure H.1.

Interviewee 8:

When you break it down, you ultimately end up with all standard machine parts. In the end, it's pumps, compressors, rotating machines, filters, piping. If you look at it from that basic level, these are actually all familiar components. But together they form something new. That "new" actually applies more to us than to them (the companies).

Ylse Wind:

What role do suppliers play in drafting maintenance plans, which actually isn't that much as I understand it correctly? Apart from telling you it has to be done annually or that it's in the manual.

Interviewee 8:

We involve the firms at an early stage in the plans we develop. Once we reach the phase where we really start making the maintenance plans, we often also present those plans to the supplier or the firm that will carry out the maintenance. That way they can assess whether everything is correct or if they maybe see strange things that we still need to adjust.

Ylse Wind:

[...] Do you have an idea of which parts in a new installation require the most maintenance?

Interviewee 8:

Those will be installations that run continuously, where wear occurs. We work a lot with solids that need to be transported, such as iron ore. This concerns, for example, running belts or conveyor belts and ends up in screening systems. We are used to those kinds of processes. Equipment that comes into contact with those materials wears out, that is part of it. Parts like the conveyor belts themselves we know, for example, that they break after a year if you do nothing. So you have to replace them preventively, for example every nine months, to prevent problems.

Furthermore, there are rotating parts, such as fans and motors. Everything that moves wears out and needs regular maintenance. In addition, we work a lot with abrasive substances, which cause extra wear. Besides that, we have parts that get hot. Think, for example, of the large heaters in the system that warm gases before they enter the reactor. Those are systems with many burners and burner pipes that must be checked regularly.

We also monitor hotspots, pressure loss, and other changes in the system, such as with filter systems. Those also need regular maintenance. In short, it's about constantly monitoring and maintaining parts that experience wear due to movement, heat, and abrasive substances.

Figure H.1: An example of the color coding of the transcript.

H.2.2. Second Step: Organizing Extracted Data

Following coding, the extracted data segments were organized into an overview table using Microsoft Excel. This table was carefully structured to categorize information by interviewee, project phase, and to distinguish between current and future practices related to Operations and Maintenance (O&M). This organization facilitated systematic comparisons across different contexts and themes, aiding the identification of key trends, challenges, and opportunities within maintenance planning and execution. This step is depicted in Figure H.2.

	Maintenance concept	Planning	Proactive maintenance	Reactive maintenance	Operation	Feedback
Interview 8						
Current maintenance	Components requiring most maintenance for parts experiencing wear		External firms currently perform maintenance on familiar components	External firms currently perform maintenance on familiar components		
	Conveyor belts, screening systems, rotating parts, hot machines, contact with abrasive substances					
Future installations maintenance	Components requiring most maintenance for parts experiencing wear	Firms are involved in early-stage plan development	New components are familiar parts to the firms for maintenance	New components are familiar parts to the firms for maintenance	Composition of installations and operations is innovative for Tata Steel	After the review of the maintenance plans, they are improved or adjusted
	Conveyor belts, screening systems, rotating parts, hot machines, contact with abrasive substances	Maintenance plans are reviewed by suppliers and firms	Parts that wear due to movement need regular maintenance		Hotspots, pressure loss, changes in system need to be monitored	

Figure H.2: An example of the codes ordened per phase, interview and current or future state of the plant.

H.2.3. Third Step: Stakeholder-Based Analysis

In the final step, the organized codes were further analyzed using a matrix that categorized the data by stakeholder groups. This matrix differentiated between the current and future states of the plant, allowing for a nuanced understanding of perspectives across various roles. Selected examples of this stakeholder-focused analysis are shown in Figure H.3.

	Maintenance concept	Planning	Proactive maintenance	Reactive maintenance	Operation	Feedback
Process owner	Maintenance intensive units are identified such as rotating parts, conveyer belts, components that come in contact with abrasive materials.	Plan regular maintenance for parts that wear due to movement			Composition of installations and operations is innovative for Tata Steel	
Firms	Components requiring most maintenance for parts experiencing wear	Firms are involved in early-stage plan development	Perform maintenance on familiar components	Perform maintenance on familiar components		Provide feedback on the maintenance plan.
Control room operator					Monitoring hotspots, pressure loss, changes in system	
OEM (supplier)						Provide feedback on the maintenance plan.
...						

Figure H.3: An example of the codes ordened per phase and stakeholder in the future situation.

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