

TOWARDS NET-ZERO STEEL: DECARBONIZATION, GREEN STEEL VALUE
CHAIN AND SUSTAINABILITY IN THE MENA REGION

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Nasir Zooei, MBA

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by

Nasir Zooei

Supervised

by

Ivica Katavic, PhD

APPROVED BY

Iva Buljibasic

Dissertation chair

RECEIVED/APPROVED BY:

Renee Goldstein Osmic

Admissions Director

Dedication

This thesis is dedicated to my son, my wife, and my family, whose constant love, patience, and support carried me through this journey. Their faith in me was a continuous source of strength and inspiration.

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ABSTRACT

TOWARDS NET-ZERO STEEL: DECARBONIZATION, GREEN STEEL VALUE CHAIN AND SUSTAINABILITY IN THE MENA REGION

<Nasir Zooei >

<2026>

Dissertation Chair: <Chair's Name>

Co-Chair: <If applicable. Co-Chair's Name>

This study investigates the transition toward net-zero steel in the Middle East and North Africa (MENA) by examining decarbonization as a value-chain transformation problem rather than a single-technology substitution. The purpose of the research is to develop and operationalize a consortium-based value-chain model, supported by a KPI-driven stage-readiness framework, to guide green steel deployment under real-world constraints of infrastructure readiness, investment feasibility, and multi-actor coordination. A sequential mixed-methods design was adopted. In Phase 1, qualitative data were collected through 21 semi-structured interviews with MENA steel stakeholders and international technology suppliers. The data were analyzed thematically to identify

system-level constraints, feasibility conditions, and coordination logics shaping green steel implementation across upstream, midstream, and downstream stages. In Phase 2, these insights were translated into a three-stage consortium model and a structured KPI-based readiness framework with transparent scoring logic to support evidence-based assessment and decision-making. The findings show that green steel deployment in MENA depends on coordinated alignment across the value chain rather than isolated technology adoption. Decarbonization was found to be most feasible when feedstock security, renewable electricity, hydrogen and logistics infrastructure, credible measurement and verification systems, financing conditions, and supportive policy frameworks are aligned. The results further indicate that role specialization across countries, modular and upgradeable configurations, and auditable low-carbon product claims are critical to scaling green steel while preserving economic competitiveness. The study concludes that a staged consortium approach offers a more realistic and scalable pathway for green steel adoption in MENA by matching country-specific capabilities and constraints to appropriate roles within the regional value chain. The research contributes a practical decision-support architecture for policymakers, investors, and steel producers. While not presented as a final country-ranking model, the framework provides an operational basis for future readiness assessment, investment prioritization, and implementation planning.

Keywords: Net-Zero Steel, Decarbonization, Green Steel Value Chain, Sustainability, MENA Region

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CHAPTER I: INTRODUCTION

1.1 Introduction

The flexibility, power, and sturdiness of steel are indispensable in the infrastructural, transportation, and construction sectors for producing buildings, bridges, and green constructions. The contribution it makes to achieving sustainable objectives is appreciable as the steel industry achieves this through green processes, with recycling as a prime example (De'nan *et al.*, 2023). This commitment to recycling spans the entire supply chain. From sourcing materials to manufacturing and eventual use. This leads to a reduction in the need for new resources and energy consumption while minimizing environmental harm. The industry's strong focus on sustainability drives advancements and effectiveness at each stage of the value chain journey, starting from ore extraction all the way to delivering steel products to consumers (Knopp, 2022).

The traditional process of steelmaking raises concerns due, to the pollution from scrap steel and molten iron. Improving the use of these materials could have an impact on the environment within the steel industry. By addressing inefficiencies and emissions in areas there is potential for environmental advantages throughout the entire production process (Liu et al., 2020). The industry consumes an amount of energy using 20 TWh in 2019 (equivalent to 14% of global consumption) with coking coal making up around 65% of its energy source highlighting its heavy reliance on coal. This dependence emphasizes the necessity of transitioning towards energy sources, in steel production and

implementing systemic changes to boost energy efficiency and cut down on carbon emissions at each stage (Janjua -Manager, 2023).

To address these issues the sector places an importance, on recycling scrap steel to cut down on carbon emissions collaborates with initiatives and advocates for eco-friendly practices in the building and automotive sectors (Conejo, Birat and Dutta, 2020a).

Transitioning to "eco steel," which employs energy sources and novel techniques such as hydrogen-based steel production, is essential for mitigating greenhouse gas emissions and securing the industry's enduring viability and competitive edge. By embracing eco steel, the sector seeks to overhaul its entire value chain, thereby fostering greater environmental sustainability and future resilience (Muslemani *et al.*, 2021).

1.2 Background

The global efforts for sustainability have brought attention to the eco steel production process. With companies striving to lessen their footprint the steel industry is facing increased attention due to its historically high levels of carbon emissions and energy consumption. Shifting towards steel requires a change in behavior across the whole value chain from sourcing raw materials to production and eventual use with a focus on recycling, energy efficiency and renewable energy sources (Tolettini and Di Maria, 2023a). Recent studies have underscored the significance of green supply chain management within the steel industry, focusing on metrics that evaluate corporate integration of sustainable practices. For example, an evaluation of green supply chain management at a steel manufacturer revealed environmental performance indicators,

thereby demonstrating the company's commitment to its internal operations (de Oliveira et al., 2022).

Technological progress in green steel manufacturing further underscores the sector's commitment to mitigating greenhouse gas emissions, optimizing expenses, and enhancing product quality. Novel approaches to diminish CO₂ emissions and elevate steel quality encompass the utilization of iron-chromium alloys and molten oxide electrolysis (Singh and Rout, 2018a). Furthermore, the concept of residue valorization within the steel industries is gaining traction, with strategies aimed at reducing CO₂ emissions by up to 50% by 2030.

This method includes recycling steelmaking waste, using secondary carbon carriers, and creating circular economy business models. These are all ways that the industry is working toward more sustainable and competitive practices (Rieger et al., 2021).

The research done together gives an overview of the steel industry's shift toward sustainability, which is driven by problems and the need for new solutions. This change is a response to problems and an opportunity for the industry to lead the way to a greener future.

1.3 Statement of the Problem

Although global pressure to decarbonize heavy industries is increasing, the steel industry still faces many difficulties in moving toward green steel production. These difficulties are mainly related to the lack of coordinated actions, uneven policy support, weak or unclear market signals, and inconsistent definitions of what “green steel”

actually means. As a result, decision-making becomes more difficult and long-term investment planning becomes less effective (GlobeNewswire, 2023). One of the main issues is the gap between climate goals and the actual readiness of steel-producing regions and companies to adopt low-carbon technologies. Across the steel value chain, cleaner production routes such as hydrogen-based direct reduced iron (H₂-DRI) and renewable-powered electric arc furnaces (EAFs) require high capital investment. At the same time, limited access to affordable renewable electricity on a large scale creates serious operational and infrastructure challenges (Söderholm, 2020).

In addition, the progress of green steel development is not the same in all regions. Countries differ in terms of access to raw materials, financial resources, policy support, and regulatory frameworks. These differences increase uncertainty about future supply conditions and may exclude some developing regions from emerging green steel value chains unless specific supportive actions are introduced (Liu *et al.*, 2021).

This issue is especially important because conventional steel production is one of the largest industrial sources of CO₂ emissions. It is estimated that the steel sector accounts for around 7% to 9% of global emissions, mainly because it still depends heavily on coal-based blast furnaces and fossil-fuel-based energy systems (world steel association, 2021). If this production pathway continues, the sector will not be able to align with the net-zero targets of the Paris Agreement.

Therefore, a wide transformation of the steel industry is necessary. This transformation should not focus only on technological improvement, but also on economic feasibility, supply chain restructuring, and stronger policy coordination. The

success of this transition will largely depend on the specific conditions of each region, including the availability of renewable electricity, hydrogen and transport infrastructure, skilled human resources, and access to green finance.

Given these interrelated obstacles, a more concentrated academic inquiry is warranted. This research should assess the technological and environmental viability of green steel production methods across diverse geographical contexts, while also offering actionable guidance for both corporate entities and governmental bodies. As an illustration, a steel manufacturer situated in an area with limited water resources might be counseled against local hydrogen production investments, and instead encouraged to collaborate with nations possessing more favorable conditions, such as abundant renewable energy and water supplies. Consequently, investment strategies can be better harmonized with regional advantages and constraints, thereby mitigating risk and facilitating more efficient advancement toward low-carbon steel manufacturing.

1.4 Purpose of the Study

The purpose of this study is to develop and operationalize a consortium-based value-chain model that can guide the deployment of green steel across the MENA region under real-world constraints of infrastructure readiness, investment feasibility, and multi-actor coordination. Rather than treating decarbonization as a single-technology substitution, the study examines the transition from carbon-intensive steelmaking to low-emission alternatives as a value-chain transformation problem, where upstream inputs, midstream production routes, and downstream market requirements must be aligned with

credible measurement and verification and with financially executable delivery structures. Accordingly, the research aims

- (i) to identify the system-level constraints, feasibility conditions, and coordination logics that influence the implementation of green steel in the MENA region, and
- (ii) to convert these insights into a decision-oriented framework that facilitates the practical sequencing and prioritization of investments and policy interventions while maintaining economic competitiveness.

To accomplish this objective, the study used a sequential mixed-methods design organized into two interconnected phases. Phase 1 (qualitative) generates exploratory knowledge through expert interviews across the steel value chain and evidence synthesis, including interviews with major MENA steel stakeholders and international technology suppliers (Danieli, SMS group, and Primetals Technologies), to surface the dominant constraints, readiness requirements, and actor roles relevant to green steel deployment.

Phase 2 (analytical–operational) transforms the qualitative findings into a structured value chain model and a KPI-based readiness framework, supported by a transparent scoring method. In this phase, the study explains the calculation logic and aggregation formula used to assess KPI performance in a consistent way. This makes it possible to evaluate and compare countries systematically when the framework is applied, even though the present study does not provide a complete country-by-country matrix or final ranking results.

Overall, the study follows an abductive research strategy. This means that empirical insights from industry experts are used to develop the analytical model, which is then converted into measurable indicators and decision rules. The main objective is to provide practical guidance for policymakers, investors, and steel producers, based on value chain logic and operational feasibility, and to develop a transparent readiness ranking and implementation framework suitable for the MENA context.

1.5 Research Questions

The following essential questions light the route to thoroughly comprehending our subject and achieving our research goals.

RQ1. How can low-carbon technologies and operational practices be integrated across the steel value chain to reduce emissions while maintaining economic feasibility and competitive advantage?

RQ2. What technical pathways and infrastructure configurations, are required to scale green-steel production in MENA?

RQ3. How do country conditions, international regulatory frameworks, economic capabilities, technological readiness, and natural resource endowments, interact with policy instruments and international collaboration mechanisms to drive adoption of green-steel innovations across MENA?

1.6 Significance of the Study

This study is important because it addresses one of the most serious challenges in the steel industry: how to shift from carbon-intensive production to lower-emission and more sustainable practices without reducing economic performance. As international

climate targets become stricter, steel producers are under increasing pressure to cut emissions while still remaining competitive. This research contributes to this issue by offering a practical and region-focused perspective, instead of viewing the transition only as a technological matter.

The study is particularly relevant because it focuses on the MENA region, which has strong resource potential but uneven readiness for green steel adoption. By comparing country capabilities, examining key decarbonization technologies, and using evidence from industry stakeholders, including steel producers and technology suppliers, the research provides a clearer understanding of what progress may involve, where major constraints still exist, and which enabling conditions are still lacking.

The contribution of this study is not only theoretical. Its findings are intended to support real-world decision-making for firms that want to protect their future competitiveness, policymakers who are designing industrial transition pathways, and investors who are evaluating credible low-carbon opportunities. In practical terms, this includes guidance on issues such as where hydrogen infrastructure may be more feasible, how policy and regulatory changes can affect investment risk, and which technology pathways should be prioritized under different national conditions.

At the academic level, this research adds to the decarbonization literature by showing that regional differences are highly important. The transition to green steel is not a single model that can be applied in the same way everywhere. It requires context-sensitive planning, realistic evaluation of constraints, and cooperation among industry, government, and finance. Overall, the study aims to support a more realistic and

achievable transition for the steel sector, with wider benefits for climate goals and sustainable development.

1.7 Definition of Key Terms

In the world of steel production and the shift, from traditional methods to eco-friendly green steelmaking several key terms are commonly used in this field.

Carbon Emission Scopes: Carbon emissions are categorized into three scopes by the Greenhouse Gas (GHG) Protocol to help organizations measure and manage their climate impact:

- **Scope 1:** covers emissions that a company directly produces from its activities and controlled sources.
- **Scope 2:** includes the indirect emissions from energy the company buys, like electricity or heating. These emissions happen at the power plant, but the company using the energy is still responsible for them.
- **Scope 3:** It includes all other indirect emissions that come from a company's activities, things like raw material sourcing, transporting goods, employee travel, and even how customers use the products.

Carbon Footprint: It refers to the amount of greenhouse gases generated from actions that release carbon dioxide emissions (Suer, Traverso and Ahrenhold, 2021).

Energy Sources: These sources are resources that can be naturally replenished within a human lifetime, such as sunlight, wind and water (Energy, 2015).

Green Steel: This term describes steel products manufactured using eco techniques aimed at reducing greenhouse gas emissions (Muslemani et al., 2021).

Sustainability: Sustainability refers to maintaining the ability to meet needs without compromising future generations' ability to fulfill their own needs. Sustainability, in steel production entails minimizing impact preserving resources and securing long term viability, across the supply chain (Jaimes and Maroufi, 2020).

Traditional Steelmaking: It refers to processes such as Basic Oxygen Furnaces (BOF) and Open Hearth Furnaces (OHF) that heavily rely on coal as fuel resulting in carbon dioxide and pollutant emissions (Sugita, 2008).

Value Chain: The value chain encompasses all the stages involved in creating products starting from raw material extraction to product delivery to consumers (Conejo et al., 2020).

1.8 Summary

The steel industry currently faces a critical juncture. It is simultaneously confronted with escalating global demands to reduce carbon emissions while also striving to maintain its essential contribution to industrial and economic expansion. This chapter will explore the significance of steel as a fundamental component in infrastructure, transportation, and construction. Conversely, steel production is recognized as one of the most energy- and carbon-intensive sectors globally. Given the intensifying nature of international climate objectives, traditional steelmaking methods are no longer viable in the long term. Consequently, a transition towards greener and more sustainable steel production is both imperative and essential. This study examines how green steel technologies and low-carbon strategies can be applied across the steel value chain, with a particular focus on the MENA region. It considers the upstream, midstream, and

downstream stages, and shows that decarbonization is not only a matter of adopting new technologies. It also depends on important enabling conditions, such as access to renewable electricity, hydrogen infrastructure, skilled labor, and supportive policy frameworks. In the MENA region, these conditions are not equally available in all countries. As a result, the pace and direction of the green steel transition may vary from one country to another.

The aim of this study is to connect global climate ambitions with regional realities by proposing practical solutions that are suitable for the MENA context. The research adopts a sequential mixed-methods approach. It includes a qualitative phase, supported by comparative analysis and semi-structured interviews with industry experts and technology suppliers, as well as an analytical-operational phase that translates the qualitative findings into a structured value chain model. This approach helps the study compare different countries while also providing deeper insight into company strategies, challenges, and decision-making processes.

The research questions presented in this chapter guide the overall investigation. They focus not only on the integration of technologies across the value chain, but also on broader issues such as policy support, infrastructure readiness, and market demand for credible low-carbon products. The importance of this study lies in its ability to support more practical decision-making for steel companies, policymakers, and investors involved in this complex transition.

Finally, this chapter defined key terms such as green steel, sustainability, and value chain in order to make their meanings clear and avoid confusion. In the following

chapters, these concepts will be examined in greater detail through deeper analysis and evidence-based recommendations to support the green steel transition in the MENA region and in other regions as well.

CHAPTER II: REVIEW OF LITERATURE

2.1 Introduction

This chapter examines the existing research on modern steelmaking methods, their environmental impacts, and the different approaches used to create steel sustainably. The main themes discussed in this section include the development of steel manufacturing methods, the role of the steel industry in sustainability efforts, the environmental challenges linked to conventional steelmaking, and recent progress in green steel technologies. The chapter also provides an overview of important information sources that explain the main methods, technological developments, practical examples, and regional experiences. This chapter aims to strengthen the research's credibility by presenting clear, verifiable, and well-supported information. In this way, it also creates a strong foundation for the next stages of analysis and discussion.

2.2 Documentation

To establish a holistic contextual framework through which to analyze the vitality of the transition underway and assess new trends and expectations pertaining to the green steel narrative, the sources reviewed were organized into five primary thematic dimensions of investigation. These narratives were designed to establish a solid understanding and methodological strategy for interpreting the steel industry's civilization saga, which is pivoting progressively along the sustainability quintet's transformational dimension. These dimensions are intended to frame the socio-

environmental-technical transition dynamics associated with the green steel shift. Within the thematic technology dimension, the focus on drivers and barriers in steel production technological evolution is highlighted, with an emphasis on clean technologies innovation trends and the knowledge landscape for breakthrough technologies. The environmental dimension investigates the historical, contemporary, and future-visioned carbon and material cycle perspectives integrated in the evolution of the steel industry in MENA, while the strategic industry dimension explores the transition arena dynamics, including value creation innovations and entrepreneurial ecosystems impacts on the global steel industry supply chain, outlining sustainability challenges and opportunities for the MENA strategic industry. The regional dimension of MENA green steel zooms in on organic and technical innovation development patterns in transformative projects and explores selected existing greening industrialization cases, providing conceptual guidelines in the transitional governance context for a greener economy. The fifth thematic dimension introduces the theoretical approach: theoretical perspectives on the socio-technical transitions describe the sociological and organizational dynamics that drive shifts in the strategic metal industry regime.

Table 2.1
Summary of References

Publication Type	Count	2020- 2024	2010- 2020	2000- 2010	Before 2000
Journal Articles	55	30	20	5	0
Reports	16	10	4	2	0
Books	7	2	3	2	0
Conference Articles/Proceedings	12	5	4	3	0
Magazine Articles	10	3	5	2	0
Theses	1	0	1	0	0

Table 2.2

Summary of the Nature and Sources of References

Author(s)	Nature of references	Sources
Holappa, L., & Nava, A. C.(2024)	Green Steel Technology	Treatise on Process Metallurgy (Second Edition)
Lundmark, R., Wetterlund, E., & Olofsson, E.(2024)	Green transformation of the iron and steel industry: Market and competition	Biomass and Bioenergy
Agrawal, Mohanty, Agarwal, Dixit, & Agrawal (2023)	Sustainable green supply chain management.	Environment, Development and Sustainability
Deâ€™nan, F., Lau, J. S., Mohamade Ounahe, A., Kamel, M. I., & Hashim, N. S.(2023)	Stability Consideration in Design of Steel Structures	Electronic Journal of Structural Engineering
Ledari, M. B., Khajehpour, H., Akbarnavasi, H., & Edalati, S.(2023)	Greening steel Management	International Journal of Hydrogen Energy
Lopez, G., Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C.(2023)	Green Steel Supply chain options	energies
Majumder, A., & Phani, M. K.(2023)	Green Steel Technology	Metallurgical Engineering, Indian Institute of Technology
Sharma, M., Anand, A., & Sharma, S. K.(2023)	Green Steel Social Responsibility	Green Chemistry, its Role in Achieving Sustainable Development Goals, Volume1
Tolettini, L., & Di Maria, E.(2023)	Environmental Sustainability in the Steel Sector	Sustainability
de Oliveira, U. R., Lemos, M. L. K. B., Canedo, A. C. D. B. A., & de Abreu, P. A. F.(2022)	Green Supply Chain Management	Revista de GestÃ£o Social e Ambiental
Knopp, E.(2022)	Greening the Steel Value Chain	EDISON Energy
Tezer, Ö., Karaba?, N., Öngen, A., Çolpan, C. Ö., & Ayol, A.(2022)	Sustainable energy production	International Journal of Hydrogen Energy
Fedorova, V. A., & Mitryaykina, A. O.(2021)	Green Steel Technology	IOP Conference Series: Materials Science and Engineering
Hall, W., Millner, R., Rothberger, J., Singh, A., & Shah, C.(2021)	Green Steel Technology	teri, The Energy and Resource Institute

Hofstetter, J. S., De Marchi, V., Sarkis, J., Govindan, K., Klassen, R., Ometto, A. R., & Vazquez-Brust, D.(2021)	Sustainable Global Value Chains	Circular Economy and Sustainability
Liu, Z., Li, R., Zhang, X. T., Shen, Y., Yang, L., & Zhang, X.(2021)	Green Steel Regional Disparities	Sustainability
Rieger, J., Colla, V., Matino, I., Branca, T. A., Stubbe, G., Panizza, A., ... Snaet, D.(2021)	Green Steel Sustainable Solutions	Metals
Andersén, J. (2021)	Green product innovation	Technovation

2.3 Theoretical Framework of the Steel Making Industry

The shift, towards a steel industry and green value chain is backed by important theories. Some of the most important frameworks are as follow:

Corporate Social Responsibility (CSR): Corporate Social Responsibility (CSR) framework, highlights the responsibility of steel companies to prioritize social objectives in addition to their own (Sharma, Anand and Sharma, 2023). CSR motivates businesses to incorporate initiatives, like cutting carbon emissions and improving recycling practices into their operations (Agrawal *et al.*, 2023).

Stakeholder Theory: Stakeholder Theory, emphasizes the significance of businesses considering the needs of all parties involved such, as employees, customers, suppliers and the local community. This theory highlights the value of working along the steel value chain to reach sustainability objectives as stakeholders are instrumental in promoting and enacting friendly initiatives (Salih, 2024).

Resource-Based View (RBV): The Resource-Based View (RBV) highlights the strategic advantage gained from unique resources and capabilities, such as advanced green technologies and efficient recycling processes. This theory suggests that firms that

invest in sustainable innovations and leverage their unique resources can achieve a competitive edge while contributing to environmental goals (Andersén, 2021; Hofstetter *et al.*, 2021)

Ecological Modernization Theory (EMT): Ecological Modernization Theory suggests that advancements in technology and industry can enhance the environment while still promoting growth. Within the green steel value chain, EMT promotes the use of technologies, like carbon capture, utilization, storage (CCUS), and hydrogen-based steelmaking to decrease the carbon emissions associated with steel manufacturing (Lahti, Wincent and Parida, 2018; Hofstetter *et al.*, 2021).

Circular Economy Concept: Circular Economy concept is crucial emphasizing closed loop systems to minimize waste and promote recycling of materials. Implementing these principles, in the steel industry means optimizing resources extending product lifecycles and reducing waste by using scrap steel in arc furnaces (Nechifor *et al.*, 2020).

These theories together form a basis, for comprehending and advancing sustainability, in the steel sector stressing the significance of incorporating factors into corporate strategies and activities. In the following sections, we delve into the aspects of both steelmaking and the innovative green steelmaking processes illustrating how these theories are applied in practice.

2.4 Evolution and Environmental Impact of Steelmaking

Steelmaking has undergone a remarkable transformation since the 1800s. What started as a collection of inventive trials has evolved into a massive, globally significant industry. The Bessemer process, the first method capable of producing steel on a large

scale, marked a pivotal moment in the late 1850s. This technology was independently developed by William Kelly in the United States and Henry Bessemer in England.

Blowing air into molten pig iron helped to remove impurities, which significantly reduced both production time and costs (Fruehan, 1998).

The open-hearth furnace, which came out not long after, was another big change that changed the landscape. Karl Wilhelm Siemens developed this method in 1868. Sometimes called the "pig and ore" process, it used iron ore to oxidize carbon in molten pig iron. This method allowed for better control over the steel's composition. As a result, it became the most common method in Europe, gradually replacing the Bessemer process (Endurasteel Admin, 2023).

The 20th century saw even more changes, such as the Basic Oxygen Furnace (BOF), which used pure oxygen instead of air, and later the Electric Arc Furnace (EAF), which mostly uses recycled steel scrap and electricity. These new ideas not only made things work better, but they also made it possible to make things in a cleaner and more flexible way.

The steel industry finds itself at a critical juncture once more, though the focus has shifted. This time, it's not solely about efficiency or expense; it's about environmental responsibility. Accounting for roughly 7–9% of global carbon dioxide emissions, the sector plays a significant role in the broader climate change battle. Consequently, the industry is navigating a three-pronged green transition:

- Optimizing current processes to reduce emissions wherever possible.

- Adopting low-carbon technologies, such as hydrogen-based direct reduction and renewable-powered EAFs.
- Pursuing carbon-neutral steelmaking, aiming for net-zero emissions across the full production cycle.

This isn't just about a new technology; It's a sign that the industry is poised to change, to come up with new ideas, and to recognize the effect it has on the world around it. To fully understand the current steel value chain and compare the two main steelmaking methods—the traditional Blast Furnace–Basic Oxygen Furnace (BF-BOF) process and the more environmentally friendly Electric Arc Furnace (EAF) method—a historical overview is essential (IEA, 2020a, 2020b, 2022)

2.4.1 Steel Making Value Chain

Since Michael E. Porter came out with his value chain model in 1985, the steel production business has changed a lot. Porter's original framework had five main activities and four support activities. However, the steel industry is so different that this model has had to be changed. Recent study has broadened the value chain for steel manufacturing to encompass five primary and six supporting activities, as seen in Figure 2.1, highlighting the industry's complexity and the necessity for sustainability and growth plans (Acharyulu, Subbaiah and Rao, 2015).

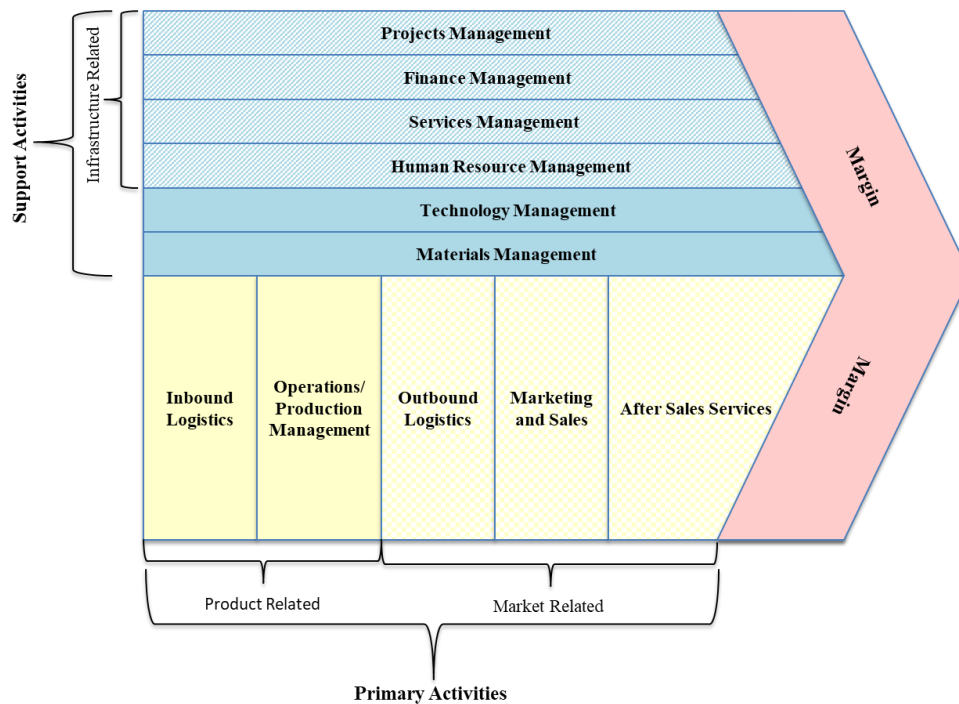


Figure 2.1
Porter value chain model for the steel industry, (Acharyulu, Subbaiah and Rao, 2015)

The main activities in the steel manufacturing value chain are all the steps that are directly related to making and delivering the product. They start by getting raw materials such coal, iron ore, and scrap metal. Then they use either the Blast Furnace (BF/BOF) or Electric Arc Furnace (EAF) pathways for the main production steps. Then, product development involves refining and alloying steel to fulfill specific needs. Efficient distribution and logistics make sure that deliveries are on time and at a reasonable cost. Strong customer service collects input to help the company develop all the time and keep up with changing market needs (Mallett and Pal, 2022).

Support activities are the unsung heroes that keep the core operations humming, ultimately boosting their efficiency and lifespan. This encompasses a range of tasks, from

the upkeep of sophisticated infrastructure – think of it as maintaining the engine room of a ship – to the careful management of human resources, which involves everything from recruitment to the ongoing development of skilled personnel.

The emergence of new technologies leads to new ways of making things, while good procurement techniques get you high-quality materials and services at the best prices. Environmental management reduces the effects on the environment, including waste and pollution, while regulatory compliance makes sure that companies follow the rules set by the industry and the law. Together, these two things help companies stay competitive and strong over the long term (Conejo, Birat and Dutta, 2020a; Knopp, 2022).

2.4.2 BF vs. EAF Steel Production Processes

There are three steps in the process of manufacturing steel: upstream, midstream, and downstream (Dixon, 2023).

Getting, preparing, and processing vital raw resources including iron ore, coal, and scrap steel are all part of the upstream stage. The middle stage is when primary steel is made. It turns raw materials into steel products that are only half-finished. The two major ways it does this are the Blast Furnace/Basic Oxygen Furnace (BF/BOF) or the Electric Arc Furnace (EAF). The downstream stage includes secondary refining, casting, forming, finishing, and distribution. This technique finally makes steel goods that are meant to be used in certain industries. Figure 2.2 displays the whole process in a clear way, showing each step from creating iron to processing steel (Dixon, 2023)

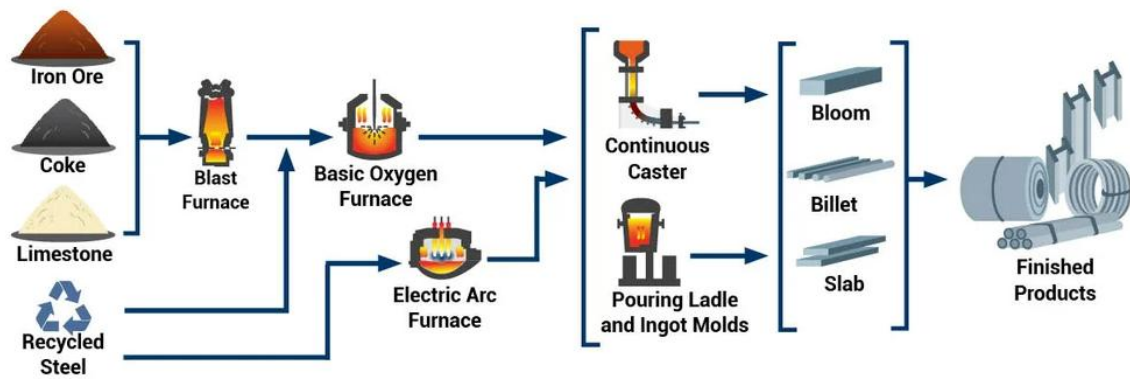


Figure 2.2
Steelmaking Process, (Dixon, 2023)

Blast Furnace (BF) Route: The Blast Furnace (BF) route is the most prevalent way to make steel all around the world. It made up 73.2% of all steel output in 2020, which is roughly 1,371.2 million tons (Cappel *et al.*, 2022). Getting and preparing raw materials is the major thing that happens in the upstream stage. Iron ore is mined from the ground and then processed to remove impurities. This includes crushing, grinding, and concentrating. As a result, the iron ore concentrate is of good quality (Weigel *et al.*, 2016). Bentonite and other binders are used to turn this concentration into pellets or sinter. Coke is created from coal, which is both a fuel and a reducing agent. Also, fluxing agents like dolomite and limestone are ready to aid get rid of impurities throughout the smelting process.

The heart of steelmaking happens in the intermediate phase. The blast furnace receives iron pellets or sinter, along with coke and fluxes. Everything is introduced at extreme temperatures, roughly 2200°C. Within the furnace, a series of chemical reactions transforms iron ore into molten pig iron.

These reactions also release carbon dioxide (CO₂) since coke burns and reacts with oxygen (Bergström and Jonsson, 2023). The pig iron, which is full of carbon and other impurities like silicon and phosphorus, is then moved to a Basic Oxygen Furnace (BOF) to make steel. To control the temperature in the BOF, scrap steel is added, and high-purity oxygen is injected through a lance to oxidize impurities, which then combine with lime to make slag (Voraberger *et al.*, 2022). The amount of carbon is brought down to the right level (usually between 0.02% and 1.5%), and alloying elements can be added to make certain grades of steel (Ghosh and Chatterjee, 2008). Subsequently, the steel undergoes secondary steelmaking processes, encompassing deoxidation, desulfurization, degassing, ladle injection, and temperature regulation, all aimed at further refining its composition and properties (Holappa and Nava, 2024). In the subsequent phase, the purified molten steel is cast into semi-finished forms, including slabs, billets, or blooms. These intermediate products are then transformed into structural components such as sheets, bars, and beams through primary forming techniques, primarily hot rolling. Furthermore, to enhance mechanical characteristics and accommodate specific dimensional or aesthetic requirements, secondary forming procedures such as cold rolling, machining, welding, and surface treatments are employed. Afterward, the finished steel products go through quality control, are packaged, and are then distributed to meet the diverse needs of various industries, including construction, manufacturing, and automotive sectors (Louhenkilpi, 2024).

Electric Arc Furnace (EAF) Route: The Electric Arc Furnace (EAF) process, which is more flexible and environmentally friendly, accounts for about 26.3% of the

world's steel production (Cappel *et al.*, 2022). Unlike the Blast Furnace method, the EAF process skips the iron extraction step, using recycled steel scrap as its main material (Yellishetty, Ranjith and Tharumarajah, 2010; Fenton, 2014). In the initial stage, scrap metal, often Heavy Melting Scrap (HMS), is collected, sorted, and then processed.

To enhance quality or supplement scrap shortages, alternative iron sources such as Direct Reduced Iron (DRI), sponge iron, and briquetted forms like Hot Briquetted Iron (HBI) or Cold Briquetted Iron (CBI) are added to the raw material mix (Cavaliere, 2019). These inputs require minimal preprocessing, making the EAF route resource-efficient and suitable for circular steelmaking.

In the midstream phase, raw materials are introduced into the Electric Arc Furnace, where they are subjected to melting through the application of high-intensity electric arcs. These arcs are established between graphite electrodes and the furnace charge, a process that swiftly yields molten steel, frequently with reduced emissions relative to conventional techniques (Muslemani *et al.*, 2021). Following the liquefaction of the steel, secondary steelmaking is initiated to attain desired mechanical and chemical characteristics. This refinement involves ladle stirring, alloying, deoxidation, desulfurization, degassing, and temperature regulation, all of which are essential for producing steel that meets specific grade requirements (Holappa and Nava, 2024). Subsequently, the refined steel is continuously cast into semi-finished forms, including billets, blooms, or slabs, thereby preparing it for subsequent processing.

In the downstream stage, these semi-finished steel products are shaped into final forms by using primary forming techniques like hot rolling. After that, secondary forming

is done, which includes cold rolling, machining, welding, or surface treatments. These steps enhance surface quality, dimensional precision, and structural properties of the final products. The steel is then checked for quality, packed, and sent out for use in industries like construction, automotive, appliances, and manufacturing (Louhenkilpi, 2024). The EAF route depends a lot on recycled materials, is flexible in production, and is good in energy efficiency. This makes it very appealing for today's sustainable steelmaking operations. Table 2.3 gives summary of all processes that happen in the Blast Furnace and Electric Arc Furnace steelmaking methods. It includes inputs, important processes, and outputs at every stage of the value chain.

Table 2.3
Steelmaking Value Chain: BF vs. EAF Route

Stage	BF Route	EAF Route
Upstream	Input: • Iron ore • Coal (for coke) • Limestone/Dolomite • Water & binders (for pellets) Processes: • Crushing, grinding • Concentration to produce iron ore concentrate • Pelletizing or sintering • Coking Output: • Pellets or sinter • Coke • Fluxes (lime/dolomite)	Input: • Scrap steel (HMS) • Direct Reduced Iron (DRI) • Hot Briquetted Iron (HBI) • Cold Briquetted Iron (CBI) Processes: • Scrap collection/sorting • Iron ore reduction (for DRI/HBI) Output: • Prepared charge mix (scrap + DRI/HBI/CBI)
Midstream	Input: • Pellets/sinter • Coke • Fluxes Processes: • Blast furnace smelting (~1500–2000°C, with peaks near 2200°C) • Production of pig iron • BOF steelmaking (oxygen blowing)	Input: • Scrap + DRI/HBI/CBI Processes: • Melting in Electric Arc Furnace (EAF) • Secondary metallurgy (alloying, refining, degassing) Output: • Molten steel

	• Secondary metallurgy (alloying, refining) Output: • Molten steel • Slag • Gases (CO/CO₂)	• Slag • Off-gases
Downstream	Input: • Molten steel Processes: • Continuous casting • Hot rolling • Cold rolling • Machining, welding, coating Output: • Final steel products (sheets, bars, beams, etc.)	Input: • Molten steel Processes: • Continuous casting • Hot and cold rolling • Surface finishing Output: • Final steel products (custom-formed as per demand)

2.4.3 Environmental Impact of Current Steelmaking Process

Steelmaking remains one of the most carbon-intensive industries in the world today. Despite decades of technological advancement, the environmental footprint of traditional steel production continues to raise serious concerns. The Iron and Steel sector was the 2nd largest final energy consumer in 2019, delivering to other sectors (8%) of end-user demand but also emitting by its own activities a huge amount of worldwide CO₂ release accounted for about equal 7% share from whole CO₂ emissions (Beck *et al.*, 2023).

Figure 2.3 shows the global steel industry's CO₂ emissions in 2019 (Kumar, 2023). Most of these emissions come directly from the energy-intensive nature of the production process and its heavy reliance on fossil fuels, primarily coal.

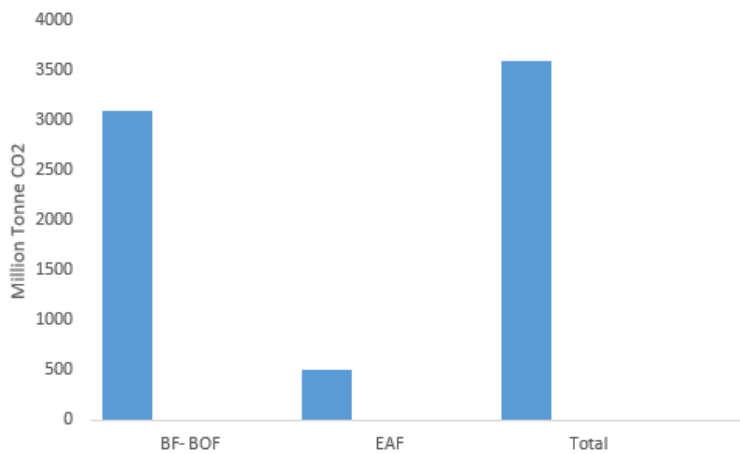


Figure 2.3
Global steel industry's CO₂ emissions in 2019, (Kumar, 2023)

The Blast Furnace-Basic Oxygen Furnace (BF/BOF) process, the predominant global method for steel production, is characterized by considerable environmental pollution. This iron extraction technique relies on coke, which functions as both a fuel and a reducing agent. Consequently, substantial quantities of carbon monoxide are generated at various stages, encompassing raw material processing, iron production, and the ultimate steel refining phase. While the Electric Arc Furnace (EAF) presents a less detrimental alternative, it is not entirely devoid of environmental impact. By primarily utilizing recycled steel, this process substantially mitigates CO₂ emissions relative to the BF/BOF method. However, its environmental footprint may still be considerable in areas where fossil fuels represent a substantial component of the power grid (J. Li et al., 2023).

Figure 2.4 outlines these high-emission points in the BF/BOF flow (Perpiñán *et al.*, 2023).

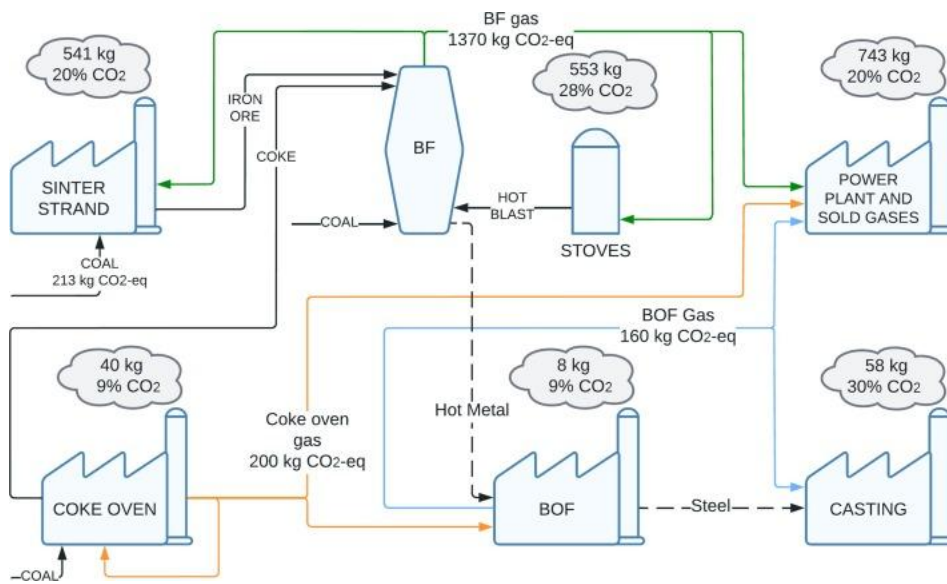


Figure 2.4
CO₂ Emission Source Steps in BF/BOF Process, (Perpiñán et al., 2023)

Furthermore, contemporary steel production, irrespective of the specific technique employed, is characterized by its substantial energy consumption and resource demands, necessitating considerable quantities of iron ore, coal, limestone, and water. These manufacturing processes also exacerbate other environmental concerns, including air pollution, the generation of solid waste, and thermal pollution of water bodies (Yusfin, Chernousov and Nedelin, 2001). Consequently, although steel is essential for modern infrastructure, its prevailing production methods are significantly linked to environmental harm.

2.5 Sustainability Imperatives and Green Steel Transition

The steel sector needs to move toward sustainability right now because of growing worries about the environment and worldwide efforts to fight climate change. Steelmaking has been one of the biggest sources of carbon emissions from industry in the

past, but new rules, changing stakeholder expectations, and new technologies are changing the future of the industry. People no longer see sustainability as something they may choose to do; it is now a main strategic goal. This part talks about the most important outside factors that are affecting the industry's green transition. Then it talks about the changes and needs that are happening inside the steel sector itself.

2.5.1 Global Environmental Governance and Policy Trends

Over the past two decades, international efforts to combat climate change have significantly influenced the steel industry's shift toward more sustainable practices. The World Trade Organization's (WTO) Green Rules, introduced in 2005, constituted an initial example of international regulations intended to prompt industries to align economic pursuits with environmental protection (Wen-yi, 2005).

Subsequently, the 2015 Paris Agreement amplified this imperative by mandating that countries restrict global warming to well below 2°C relative to pre-industrial levels, with an even more ambitious target of 1.5°C (United Nations, 2015). Consequently, this pivotal agreement exerted mounting pressure on steel manufacturers to embrace low-carbon technologies and adopt cleaner production methodologies.

In addition, the European Green Deal, launched in 2019, set out an ambitious roadmap for achieving a climate-neutral continent by 2050. In sectors like steel manufacturing, this transition precipitated the imposition of more demanding emission regulations, coupled with financial incentives for sustainable innovations and more comprehensive carbon evaluations throughout the supply chain (Vogl, Åhman and Nilsson, 2020). These converging regulatory changes have, consequently, fostered a

global trend toward steel decarbonization, thus positioning environmental compliance as a key determinant of competitive advantage.

2.5.2 Sustainability and Strategic Transformation in the Steel Industry

Faced with intensifying external pressures, the steel industry is in the midst of a strategic overhaul, with sustainability and decarbonization at its core. Steelmakers are increasingly aware that their future viability hinges on significantly cutting carbon emissions, incorporating renewable energy, and developing new, less harmful production techniques.

Decarbonization has become a key element of industry strategy, driven not just by regulatory demands, but also by the need to satisfy investors, adhere to ESG standards, and maintain their social license to operate. Companies are exploring three primary avenues: refining existing steelmaking processes to reduce emissions, implementing groundbreaking technologies such as hydrogen-based reduction and electrification, and ultimately achieving carbon-neutral operations by the middle of this century (USGS, 2021; IEA, 2022).

This strategic pivot represents a fundamental reimagining of the steel sector's value, connecting economic achievement with environmental responsibility and heralding a new chapter in global industrial sustainability. In response to mounting external pressures, the steel industry is undergoing a strategic transformation centered on sustainability and decarbonization. Steel producers increasingly recognize that long-term competitiveness depends on drastically reducing carbon emissions, embracing renewable energy sources, and innovating new low-impact production methods.

2.5.3 Three-Phase Journey Towards Green Steel Production

As a significant emitter of carbon dioxide, the steel sector confronts significant challenges in reducing GHG emissions to meet the Paris Agreement's net-zero goal (Bataille *et al.*, 2018).

In response to ecological issues, green steelmaking has evolved as a sustainable solution to reduce the environmental impact of steel production (Singh and Rout, 2018b). Steel produced this way is more environmentally friendly than steel made using traditional methods. However, this change won't happen all at once. Experts in steelmaking expect the process to happen in three stages (Fleischanderl, 2023).

Optimization Phase: The initial step focuses on boosting efficiency and cutting carbon emissions in current steelmaking operations. This will be achieved by upgrading technology and using more scrap metal.

To this end, various advanced techniques are utilized. Methods include using torrefied sawdust briquettes to reduce carbon consumption and CO₂ emissions at the blast furnace (Mousa *et al.*, 2019). Heating air before combustion and using burners that produce less flame help enhance combustion efficiency and lessen fuel usage. Increasing oxygen levels within blast furnaces and implementing heat recovery systems like gas recovery turbines significantly reduce energy waste and emissions (Mariños Rosado *et al.*, 2020). Other improvements involve utilizing scrap steel heated beforehand to enhance its usefulness in production processes and converters that blow from the bottom to increase scrap utilization while decreasing CO₂ emissions (EPA, 2012). Incorporating control systems after combustion aids in managing and optimizing off-gas burning

procedures, leading to effective energy utilization and decreased emission of harmful gases. Moreover, deploying sensor networks ensures a controlled production environment with minimal waste (Zhou *et al.*, 2022). These combined strategies demonstrate a way to modernize steel production, aligning it with current sustainability goals.

Transition phase: In the transition toward sustainable steel production, diverse innovative strategies are being prioritized to modernize the steelmaking process, enhance its sustainability, and mitigate CO₂ emissions. A particularly noteworthy technology is the Direct Reduction of Iron Ore (DRI), specifically via the MIDREX process (Bhaskar, Assadi and Nikpey Somehsaraei, 2020a). This method has gained considerable global prominence, largely because of its efficacy in reducing CO₂ emissions during the production of Hot-briquetted iron (HBI).

HBI's value stems from its ease of transport and its compatibility with current steel production systems (Daghagheleh *et al.*, 2023). Furthermore, MIDREX facilities, which are designed to operate exclusively on gas, possess a distinct advantage; they can transition to utilizing 100% hydrogen, thereby supporting the goals of a future hydrogen-based economy (Salemi, Torabi and Haghparast, 2022).

Apart from DRI, the electrification of steel production through Electric Arc Furnaces (EAFs) provides an alternative to traditional techniques. EAFs support the utilization of scrap metal and enable plants to adapt to environmental regulations swiftly (Saboohi *et al.*, 2018).

Another innovative strategy in this realm is adopting Endless Strip Production (ESP) technology, which combines casting and rolling processes into an operation. This

fusion process saves energy by eliminating the need to reheat materials, which speeds up production. As a result, it allows for the direct creation of final products from liquid metal in a compact form (Arvedi *et al.*, 2011).

Although Scrap-based steel production utilizing EAF has gained popularity due to significantly propelling the industry towards efficient steel manufacturing during a crucial transition phase, the rising demand for steel means that recycled steel will not be enough to fulfill future demands (Bataille *et al.*, 2018). Furthermore, significant obstacles related to the collection, sorting, and processing of recycled steel persist, thereby constraining the capacity to utilize scrap-based steel for decarbonizing the sector (Hall, et al., 2021). Considering these advancements and impediments, the attainment of green steel transcends a mere strategic choice; it constitutes an essential step towards effectively realizing the industry's sustainability goals and addressing the escalating global demand for environmentally responsible steel production.

Achieving green steel: The final phase aims to eliminate rather than reduce carbon emissions. Unlike conventional steel, green steel is made only with electricity derived from renewable energy sources (Kim *et al.*, 2022). Moreover, the process employs environmentally friendly reducing agents instead of carbon. The first known substitute, which allows for an emission decrease of up to 50%, is using biomass and/or natural gas as the reducing agent (Suopajarvi *et al.*, 2018).

The steel industry is under pressure to overhaul its supply chain practices from sourcing materials to disposing of products to fulfill the Paris Agreement emission

reduction targets. This includes a 45% cut in emissions by 2030 and transitioning to zero emissions by 2050 to limit temperature to a maximum of 1.5°C (United Nations, 2015).

The upcoming section delves into tactics and technological advancements driving the advancement of eco steel production across the whole value chain.

2.6 Technological Innovations Driving Decarbonization

In 2020 the International Energy Agency (IEA) introduced a plan outlining advancements in iron and steel technologies based on industry trends and initiatives (IEA, 2020b). This roadmap specifically targets four technology areas to improve the sustainability of the steel sector; Carbon Capture Utilization and Storage (CCUS) Hydrogen based Reduction, Direct Electrification and Biomass Energy Solutions (Bhaskar et al., 2020; Khasraw et al., 2024; Wang et al., 2021).

2.6.1 Carbon Capture Utilization and Storage (CCUS)

The 2030 Sustainable Development Goals aim to achieve a carbon balance by focusing on ten, out of the seventeen goals endorsed by the United Nations. These targets are strongly linked to the adoption of Carbon Capture Storage (CCS) and Carbon Capture Utilization and Storage (CCUS) technologies to reduce CO₂ emissions and tackle climate change. The introduction of the Paris Agreement in 2015 and the Kyoto Protocol in 1997 has paved the way, for the implementation of these Development Goals (Sustainable Development Goals, 2023).

CCS involves three stages; capturing carbon dioxide, from power plants or industrial activities compressing it and then moving it to storage sites to prevent its release, into the air. On the side CCUS goes a step beyond by storing the CO₂ in

formations and utilizing it for various purposes beforehand. The major contrast lies in how CCUS aims to generate income from the captured carbon than solely focusing on emission reduction efforts (Huo *et al.*, 2022).

In North America and the Asia Pacific region, carbon capture and storage (CCS) is mainly used in saline formations and for enhanced oil recovery (Lake, Lotfollahi and Bryant, 2019). In contrast, carbon capture, utilization, and storage (CCUS) focuses on using CO₂ from industrial processes, such as those in natural gas and fertilizer production.

Europe incorporates strategies such as combining biomass with CCS in initiatives like Zero Carbon Humber in the UK, which align with practices (Clery and Gough, 2022). Conversely, the geographical distance between emission sources and storage locations across Russia and Central Asia has necessitated the formulation of targeted strategies, including LNG decarbonization, to curtail carbon emissions (Fedorova and Mitryaykina, 2021). These region-specific endeavors serve as examples of the global application of CCS and CCUS technologies, which are utilized to reduce greenhouse gas emissions and address the complexities of climate change (Latif *et al.*, 2024).

Based on previous efforts, Qi Zhang *et al.*'s (2024) study provided an optimization model for organizing Carbon Capture Utilization and Storage (CCUS) systems. This approach focuses on the disregarded features of geological variability, such as longitudinal and transverse permeability ratio, heterogeneity coefficient, and mobility ratio. The model's improvements in CCUS efficiency, achieved by optimizing pipeline

lengths and increasing crude oil production, lead to higher total revenues (Zhang *et al.*, 2024).

2.6.2 Hydrogen-Based Reduction

For green steel, the most important thing is to reduce damage and target zero emissions when producing. According to Lopez *et al.*, this is the preferred option, so that steel making utilizes hydrogen-based methods (Lopez *et al.*, 2023). One such method is Hydrogen Direct Reduction (HDR) that allows iron reduction to take place with hydrogen as opposed to carbon materials. When combined with EAFs powered by clean energy sources this approach to carbon recycling requires little virgin resource input. Steel Production Without Fossil Fuels can be used (grey and blue hydrogen) to produce hydrogen, or it might be produced weather-sustainably via electrolysis, which is a process that divides water into its origin components of oxygen and hydrogen utilizing electricity as the source of power from renewable sources such as wind and solar, both known as green hydrogen. This approach would secure steelmaking from any carbon emissions (Pimm, Cockerill and Gale, 2021).

Figures 2.5 (Vogl, Åhman and Nilsson, 2018) and 2.6 (POSCO, 2020) show the Hydrogen Direct Reduction (HDR) process and different types of hydrogen.

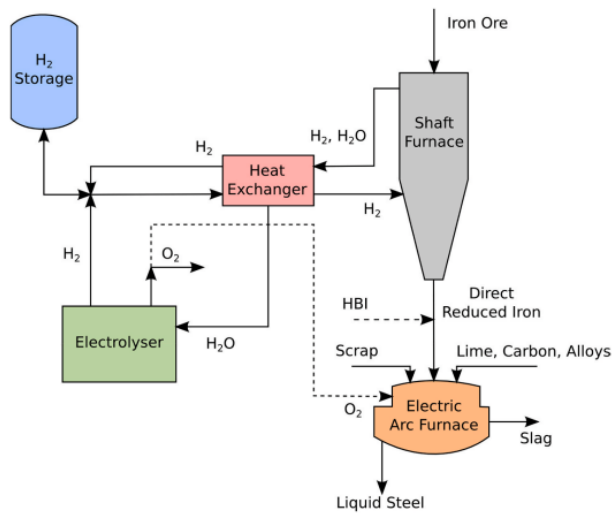


Figure 2.5
HDR/EAF Steel-Making Process, (Vogl, Åhman and Nilsson, 2018)

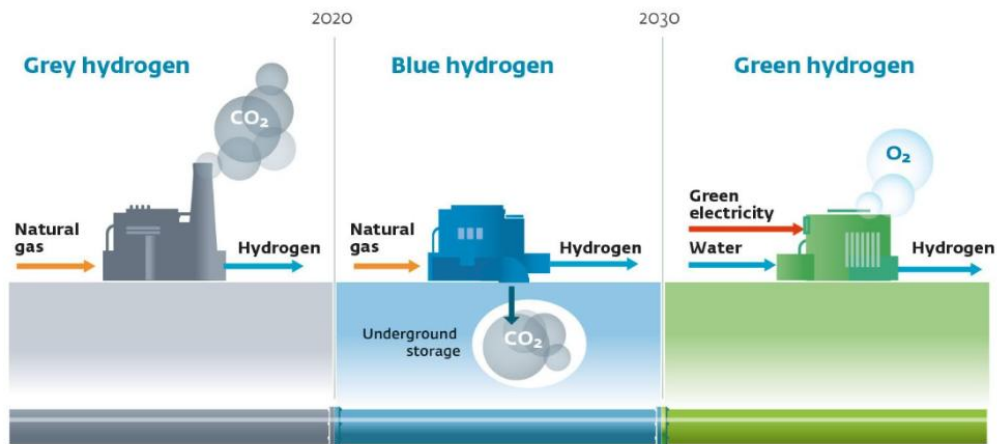


Figure 2.6
Gray, Blue, and Green Hydrogen, (POSCO, 2020)

2.6.3 Direct Electrification

The effort focuses on replacing carbon processes with electric alternatives, significantly reducing the direct emissions associated with steelmaking. The introduction and operation of new technologies, such as arc furnaces (EAFs) based on energy sources

with their liquid metal baths, combined with the usage of advanced technologies like Modular Multilevel Converters, all aimed at achieving increased operational effectiveness or reliability, are among the most significant advances in the field (Andrioli *et al.*, 2023). Providing a novel technology for steel recovery by electrochemical reduction or electrolytic iron production in alkaline media, this can dramatically reduce CO₂ emissions due to their low operational temperatures and eliminating the need of using electricity beyond that required. Such kind of innovative nature not only helps in mother earth reduction but also scales well with its clean source (renewable energy) approach making the entire steelmaking process a lot more sustainable (Lopes *et al.*, 2022).

2.6.4 Biomass Energy Solutions

Biomass is an alternative form of energy that offers a more promising avenue for mitigating the environmental impacts produced by industrial processes. Reducing agents are needed in EAFs, especially coal and coke for deoxidizing iron from iron ore, which means that CO₂ is released significantly (Khasraw *et al.*, 2024). Now, using biomass as a reductant in steel production has been studied intensively to increase sustainability and efficiency in resource utilization. The study by Kumpa and Kongkarat (2023) dealt with the use of mill-scale-based biomass pellets (MBPs) in EAF steel production. In their study, they report on rubber tree bark-assisted iron reduction/metallization rates using the example of the steel industry to advance a circular economy (Kumpa and Kongkarat, 2023). Similarly, Kim *et al.* (2023) introduced iron-bearing biomass coke (IBC). This innovative material, as a new type of resource integration form carrier, when prepared for

CO catalysis related biomass/pulverized coal co-firing combustion, can enhance the utilization efficiency of split-off carbon monoxide (CO) and its reducibility while significantly reducing atmospheric pollution. Their work suggests a replacement for carbon sources in industrial applications (Kim *et al.*, 2023). A similar result was made by Wang *et al.* (2023) regarding biochar use in iron-making processes. The application of biochar can be clearly defined as a highlight, developed to ease waste and also promote energy conservation, along with emission reduction (S. Wang *et al.*, 2023).

New European initiatives are more about using eco-technologies in the steel industry as part of efforts to meet sustainability targets. For instance, green hydrogen produced by electrolysis of water with electricity from renewables has been considered in the i3Upgrade European project to be used at steel mills (i3Upgrade, 2022). Zaccara *et al.* (2020) examined the possibility of using steel manufacturing off-gases to promote more sustainable steel plants. They studied several methods of hydrogen production like Polymer Electrolyte Membrane (PEM) electrolysis (Hübner *et al.*, 2021), Solid Oxide Electrolyzer Cell (SOEC) (Hauch *et al.*, 2020), and Biomass Gasification (Tezer *et al.*, 2022), which is amenable to integration within the steelworks. The use of Aspen Plus® simulations showed that the preferred processing pathways are electrolyze-based instead of biomass-based processes, due to the fact that Biomass Gasification produces less pure hydrogen while generating a significant amount of CO₂ (Zaccara *et al.*, 2020). Bampaou *et al.* (2021) scrutinized the compatibility of hydrogen-enhanced syngas for the methods using an AspenPlus flowsheet simulation. This has proven that recycling unreacted hydrogen can lead to substantial increases in methanol production, thereby reducing CO₂

emissions from steel plants (Bampaou *et al.*, 2021). Furthermore, Bampaou *et al.* (2022) evaluated the economic costs of multiple methane- and methanol-synthesizing pathways, showing that electricity prices considerably influence production costs. These developments underpin the transition to greener iron and steelmaking and open the path for using biomass feedstocks in cost-effective ways of producing steels. (Bampaou *et al.*, 2022).

2.7 Strategic Industry Enablers: Technology Suppliers' Role

As industrial decarbonization increasingly shapes global climate governance, technology suppliers have transitioned from peripheral actors to crucial participants in the steel industry's broader transformation (Bataille, 2020). Companies including Danieli, SMS Group, and Primetals Technologies have become significant facilitators of the green steel transition, offering solutions like hydrogen-based ironmaking, Electric Arc Furnace (EAF) optimization, and AI-driven process digitalization. Their influence extends beyond the mere provision of equipment.

Furthermore, the framework encompasses backing for innovation ecosystems, lifecycle services, and emissions traceability, thereby facilitating the alignment of steel value chains with circular economy tenets and Environmental, Social, and Governance (ESG) goals (Åhman *et al.*, 2018; Vogl, Åhman and Nilsson, 2021).

2.7.1 Hydrogen-Based Ironmaking

The shift toward green steel production is contingent upon the development of low-carbon ironmaking processes, particularly hydrogen-based Direct Reduced Iron (H₂-DRI) methods. Danieli's Energiron® technology, a product of collaboration with Tenova,

enables the creation of DRI utilizing exclusively green hydrogen. This approach can achieve a reduction in CO₂ emissions of up to 95% compared to traditional blast furnace-basic oxygen furnace (BF-BOF) techniques, provided that renewable energy sources are employed (SGRO, 2022; Lapasin, 2023).

Energiron's commercial viability is supported by Technology Readiness Levels (TRLs) of 8–9, as demonstrated by pilot projects such as GravitHy in France, which aims for 2 Mt/year of green steel production by 2027 (GravitHy, 2022; Garcia, 2025).

Furthermore, Primetals Technologies is progressing hydrogen-based ironmaking through its HYFOR (Hydrogen-based Fine Ore Reduction) process, which obviates the need for palletization and sintering by directly reducing iron ore fines with hydrogen (Fleischanderl *et al.*, 2021).

SMS Group, in contrast, emphasizes modular solutions, including Paul Wurth's hydrogen-ready blast furnace retrofits and Electric Smelting with Carbon-free Reduction (ESCR) systems, which facilitate a gradual decarbonization of existing infrastructure (Kinzel and Wurth S.A., 2022; Kleier, Hansmann and Koppenburg, 2023). These advancements are consistent with industrial ecology principles, wherein primary production transitions from carbon-heavy inputs to processes powered by renewable energy. Nevertheless, their implementation is contingent upon the availability and economic viability of green hydrogen, which is anticipated to achieve a price of \$1.5–2/kg by 2030 to compete with natural gas-based DRI (Maka and Mehmood, 2024; Simões and Júnior, 2024).

2.7.2 Electrification and Scrap Recycling Technologies

Electrification of steelmaking through Electric Arc Furnaces (EAFs), alongside scrap recycling, constitutes a fundamental strategy for decarbonization, thereby diminishing dependence on both virgin iron ore and fossil fuels (Echterhof, 2021). Danieli's Q-One and Q-Melt systems contribute to EAF efficiency improvements via digital power stabilization and AI-driven furnace control, resulting in electricity consumption reductions of up to 10% (Burin, 2023). SMS Group's CONDOOR scrap preheating and electrode control systems enhance metallic yield by 15–20%, which in turn lowers specific energy demand (SMS, 2023). Furthermore, Primetals Technologies' Through Process Optimization (TPO) integrates casting, rolling, and emissions tracking, facilitating predictive maintenance and energy optimization (Jax and Zhai, 2025).

From a circular economy standpoint, these technologies optimize scrap as a high-value secondary input, thus mitigating Scope 3 emissions linked to raw material extraction (Ward *et al.*, 2019). However, challenges persist, including variations in scrap quality and the need for advanced sorting technologies to reduce the presence of unwanted materials.

2.7.3 Digitalization and Industry 4.0 in Green Steel

The advent of Industry 4.0 technologies, encompassing the Industrial Internet of Things (IIoT), artificial intelligence (AI), and digital twins, has fundamentally altered steelmaking, transforming it into a data-centric, self-optimizing procedure (Tolettini and Di Maria, 2023b). Danieli's Digimelter platform utilizes reinforcement learning to enhance furnace operations in real-time, thereby diminishing Scope 1 emissions and associated energy expenditures (Burin, 2023). Furthermore, Primetals Technologies' TPO

utilizes multi-variable regression and anomaly detection to synchronize production with decarbonization Key Performance Indicators (KPIs) (Jax and Zhai, 2025).

These platforms facilitate not only operational enhancements but also Scope 3 traceability via blockchain-based material passports and Environmental Product Declarations (EPDs), thereby addressing market requirements for green steel certification. Environmental Product Declarations (EPDs) often use Life Cycle Assessment (LCA), a standardized method for evaluating environmental impacts across a product's life cycle, including assessments from the beginning to the end of its production. Buyers are increasingly demanding EPDs to substantiate green-steel assertions (Datta and Bhattacharjee, 2020; Rangelov *et al.*, 2021). Consequently, digitalization functions as a link between operational activities at the plant level and broader sustainability objectives, thereby strengthening the systemic significance of technology providers.

2.8 Economic Aspects of Green Steel Transition

Switching from creating steel in a way that is not good for the environment to making steel in a way that is good for the environment has been very hard on the economy. The expenses of energy sources and the use of new technology are primarily to blame for these economic problems.

2.8.1 Investment Challenges in EAF Adoption

Transitioning from basic oxygen furnaces (BOFs) to electric arc furnaces (EAFs) within the steel sector, all in the name of crafting greener, more sustainable steel, demands meticulous financial strategizing.

The electric arc furnace (EAF) method, which uses arcs to melt recycled steel scrap and direct reduced iron (DRI), produces less CO₂ than the basic oxygen furnace (BOF) method. However, this change requires a financial investment, which presents various financial challenges (Carvalho, 2024).

The cost of transitioning from BOF to EAF is quite high. Firstly, EAFs require setting up infrastructure and modifying facilities. These expenses involve establishing DRI plants and adjusting manufacturing methods to integrate the new technologies (Fan and Friedmann, 2021). Furthermore, the effectiveness of EAF technology is significantly dependent on electricity production from different sources, resulting in higher operational costs (Hall *et al.*, 2021). Additionally, EAF production largely relies on stable supply chains for scrap steel and DRI/hot briquetted iron (HBI) inputs. Concerns about long-term scrap availability and quality can prevent investments in EAF capacity (Marks, 2023).

A further important economic consideration pertains to the effects on labor and employment. The implementation of Electric Arc Furnace (EAF) technology could potentially lead to a decrease in job availability, stemming from the automation and improved efficiency that characterize this technological transition. As a result, areas reliant on steel production jobs might experience economic instability, which would then require the enactment of policies aimed at alleviating these social consequences (McKinsey&Company, 2020).

In the United States, the pace of transition has been comparatively sluggish. This delay is attributable to a combination of factors: community concerns about stability, the

complex nature of technological and political adjustments to industrial practices, and resistance from corporations. Consider, for instance, Dearborn, Michigan, a locale once dominated by the steel industry, where a hesitance to adopt change persists, fueled by anxieties concerning employment and economic repercussions. Consequently, this situation highlights the necessity of enacting governmental policies and actively engaging communities to expedite this transition (Estevez *et al.*, 2024a).

2.8.2 Economic Impacts of Renewable Energy, Biomass and Hydrogen Production

Even though the steel industry still uses coal and natural gas, which are often cheaper than biomass, solar, wind, or hydroelectric power (Devlin *et al.*, 2023). To make steel production environmentally friendly, we need to invest in renewable energy infrastructure and use new technologies. These include electric arc furnaces and hydrogen-based direct reduction methods (Estevez *et al.*, 2024b).

The generation of hydrogen often depends on electrolysis, a method that can harness energy from diverse sources. These sources include fossil fuels, natural gas, or biomass. The production of hydrogen can result in three types. The environmental impact of hydrogen depends on its production method and the energy sources used (Kilner, 2022). Shifting towards eco-friendly steel manufacturing includes using fuels like biomass and hydrogen, significantly impacting market dynamics. As the iron and steel sector aims to decrease its carbon emissions, there is an expected surge in demand for forest biomass, resulting in price changes (Salimbeni *et al.*, 2023). Lundmark and his team found that the increased demand could have effects beyond just higher prices for biomass, especially for materials like harvesting leftovers and industrial by-products. In

contrast, the price of roundwood might not rise as much, possibly because of its higher initial cost (Lundmark, Wetterlund and Olofsson, 2024).

The price escalation will inevitably yield repercussions. Anticipated is a surge in demand for biomass resources, which will subsequently affect industries dependent on these materials. Consequently, sectors including forestry, sawmilling, district heating, and wood pellet production could experience escalating expenses, stemming from competition with the iron and steel industry for biomass supplies (Mousa *et al.*, 2016). This heightened competition could reduce the feasibility of using biomass for some sectors, prompting them to seek resources or scale back their operations (Suopajärvi *et al.*, 2017).

In this scenario, it is important to consider policy and investment factors. Shifting towards eco-friendly steel production could decrease the demand for emission permits within the EU Emissions Trading System (ETS). This shift may bring advantages by either generating income if permits are carried over or cutting down production expenses if permits are bought on the market (Vogl, Åhman and Nilsson, 2021). On the other hand, it's important to consider the advantages, in comparison to the drawbacks linked to biomass usage and the possible necessity of contracts for procuring biomass to maintain stable prices. Additionally, decision makers need to evaluate the economic impacts of higher levels of biomass extraction such as effects, on forest ecosystem services and biodiversity, as outlined by (Kumar *et al.*, 2022).

Regarding using hydrogen as a renewable fuel in steel manufacturing, the number of proposed initiatives for manufacturing low-emission hydrogen is increasing, with an

estimated yearly production of 38 million tons by 2030, assuming all projects are completed, including 17 million tons from early-stage projects. This capacity exceeds the IEA's Global Hydrogen Review 2022 forecasts by 50%. In 2022, global hydrogen utilization increased by over 3% to 95 million tons, driven mostly by growth in consumption regions other than Europe, which saw lower activity due to high natural gas prices. This increase reflects energy trends rather than explicit regulatory initiatives aimed at increasing hydrogen use (IEA, 2023).

The current cost of producing hydrogen ranges from \$4.5 to \$6.5 per kilogram. To ensure the economic feasibility of steel production, the associated cost must decrease to a range of \$2.5 to \$4.0 per kilogram by the year 2030. Despite the initiation of numerous projects, their advancement has been impeded by inflationary pressures and escalating financial constraints, thereby exacerbating the existing complexities (Basirat, 2024b).

The feasibility of producing environmentally friendly steel is also influenced by geographical factors. Projects situated near energy sources, like hydropower, are progressing more rapidly. These areas benefit from lower energy costs and a reliable energy supply, both of which are crucial for producing green hydrogen (Basirat, 2024a). For example, Australia is currently working on hydrogen production, which could position the country as a leader in environmentally friendly steel manufacturing (C. Wang *et al.*, 2023).

In summary moving towards EAF technology is crucial, for decreasing the carbon emissions in the steel industry. However, it's important to weigh the factors involved such as initial investments, ongoing expenses and societal effects. Effective planning and

favorable policies are necessary to address these issues and facilitate a shift, towards friendly steel manufacturing. (Basirat and Nicholas, 2023a).

2.9 Global Leaders and Best Practices in Green Steel

Green steel is a trend that aims to cut down on carbon emissions, in the steel industry. Many companies and countries are pushing for this change investing in eco methods and resources to boost the production of eco steel. Here are a few examples worth mentioning.

“H2 Green Steel” a company headquartered in Stockholm, Sweden and founded in 2020 is taking the lead in utilizing hydrogen, for steel production to carbon emissions. Their goal is to establish a large-scale facility in Boden, Sweden by 2030 that will manufacture 5 million tons of steel each year. This cutting-edge facility will use hydrogen as a reducing agent in the reduction process generated through electrolysis powered by energy sources. While some natural gas will be used initially, H2 Green Steel plans to transition to bio-based or synthetic gas, for carbon neutrality in the future (Ledari *et al.*, 2023). With significant investments already secured, the company plans to expand its operations across Europe, Brazil, and North America, establishing itself as a frontrunner in steel production (Temple, 2023).

“HYBRIT (Hydrogen Breakthrough Ironmaking Technology)” is a collaborative project spearheaded by Swedish companies SSAB, LKAB, and Vattenfall, and it has been based in Stockholm since 2017. Its goal is to change the steel industry by using fossil hydrogen from coking coal in the process of creating steel from iron ore. The HYBRIT process makes water instead of carbon dioxide, which cuts down on the carbon footprint

of steel manufacturing by a lot (Majumder and Phani, 2023). This method uses renewable energy to make hydrogen through electrolysis. The hydrogen is then utilized to turn iron ore into sponge iron. Using electric arc furnaces fueled by energy sources, the sponge iron can be turned into steel (Rossi, 2022).

“Boston Metal”, based in Woburn, Massachusetts, is a company founded in 2012 that focuses on molten oxide electrolysis (MOE). This cutting-edge technology efficiently reduces metal oxides through electricity, eliminating the reliance on carbon methods such as coking coal. By utilizing electricity sources, the MOE technique effectively reduces carbon emissions and energy usage while generating metal goods and oxygen gas as its sole residual output (Osen *et al.*, 2023). The technology can use grades of iron ore, including lower-quality ores, making it very adaptable and less dependent on high-purity materials. Its modular and scalable design, along with this capability, enables MOE to be cost-effective and flexible for production sizes without subsidies. This positions it as a solution to achieving zero emissions by 2050 (Boston Metal, 2024).

ArcelorMittal, headquartered in Luxembourg and founded in 2006, is a major player in the steel industry. The company operates in 60 countries and employs over 10,000 people. The company is dedicated to lessening its footprint by focusing on Green Steel technologies to reduce carbon emissions. Through investments in hydrogen-based steel production and carbon capture and storage (CCS) methods (Mandova *et al.*, 2019), ArcelorMittal drives forward its Smart Carbon initiative, aiming for a 30% decrease in CO₂ emissions by 2030 and striving for carbon neutrality by 2050. This strategy involves leveraging bioenergy sources and recycling carbon gases from waste as part of the

company's commitment to pioneering steel production practices for an eco-friendly future (Temple, 2023; ArcelorMittal, 2024).

These corporations, along with the more successful instances detailed in Table 2.1, are setting industry standards within the steel sector through the adoption of advanced technologies and environmentally conscious practices. They are achieving significant progress in minimizing carbon emissions and promoting sustainability through the implementation of green hydrogen, electrolysis, AI-driven optimization, and other sophisticated techniques. Consequently, by integrating alternative energy sources and novel methodologies, these companies are leading the transformation of steel production into a more sustainable and efficient domain.

This collaborative endeavor represents an advance toward meeting climate targets and securing a sustainable future for steel manufacturing. Table 2.4 summarizes these companies (McKinsey&Company, 2020; Rossi, 2022; Temple, 2023; ArcelorMittal, 2024; Boston Metal, 2024; FEDERAL STEEL SUPPLY, 2024; Israely and Becker, 2024).

Table 2.4
Leading Green Steel Companies and Their Innovative Technologies

Company	Founded	Location	Main Technology	Main Features
Gravithy	2022	Paris, France	Green Hydrogen	- Produces green hydrogen via water electrolysis - Uses renewable energy sources - Replaces fossil fuels as a reducing agent in steelmaking - Significantly cuts carbon emissions

H2 Green Steel	2020	Stockholm, Sweden	Green Hydrogen	- Uses green hydrogen via electrolysis powered by renewable energy - Avoids carbon-intensive coking coal
Electra	2020	Colorado, USA	Electrolysis	- Uses electrolysis process to produce steel - Eliminates the need for coal - Drastically reduces greenhouse gas emissions
Carbon Re	2020	London, UK	AI-driven Optimization	- Uses AI to optimize steel production - Enhances energy efficiency - Minimizes carbon emissions - Integrates advanced sensors and data analytics
Smart Steel	2019	Düsseldorf, Germany	Digital Solutions	- Provides advanced sensors and machine learning algorithms - Optimizes steel manufacturing processes - Reduces energy consumption - Minimizes waste - Lowers emissions
Helios	2018	HaMerkaz, Israel	Helios Cycle	- Implements zero-emission iron extraction using sodium - Operates at lower temperatures - Reduces energy consumption by 50% - Lowers production costs by 20% - No direct CO2 emissions
HYBRIT	2017	Stockholm, Sweden	Hydrogen Breakthrough Ironmaking	- Replaces coking coal with hydrogen gas - Hydrogen produced using renewable energy - Emits water instead of CO2

Boston Metal	2012	Woburn, Massachusetts, USA	Molten Oxide Electrolysis	- Uses molten oxide electrolysis (MOE) - Reduces metal oxides using electricity - Eliminates the need for carbon based reducing agents - Significantly reduces greenhouse gas emissions
ArcelorMittal	2006	Luxembourg	Hydrogen and CCS	- Invests in hydrogen-based steelmaking - Uses carbon capture and storage (CCS) - Captures CO2 emissions from steel manufacturing facilities
JSW Steel	1982	Linz, Austria	Hydrogen and Renewables	- Uses hydrogen to reduce iron ore emissions - Explores renewable energy sources like wind and solar power - Reduces dependence on fossil fuels
SSAB	1978	Stockholm, Sweden	HYBRIT Technology	- Uses hydrogen instead of coal for iron ore reduction - Produces sponge iron with minimal CO2 emissions - Uses electric arc furnaces with renewable energy
Voestalpine	1938	Linz, Austria	Hydrogen Reduction	- Develops hydrogen-based reduction technologies - Uses electric arc furnaces with renewable energy - Uses renewable energy sources to power steel plants

2.10 MENA: A Strategic Region in the Green Steel Industry

When it comes to steel manufacturing the MENA region is notable, for its emphasis on energy as a key resource for producing environmentally friendly hydrogen. The MENA region is uniquely positioned to capitalize on the shift, towards lowering

carbon emissions in the steel industry leveraging a mix of environmental and economic advantages (Basirat, 2023).

The MENA region presents promising opportunities, for energy, solar power due to its advantageous geography and climate. With some of the radiation levels countries in the MENA region are increasingly focusing on large scale solar initiatives to capitalize on this potential (Nicholas and Basirat, 2023). For instance, the Mohammed bin Rashid Solar Park in the UAE aims to generate 5,000 MW by 2030 showcasing the regions commitment to energy practices (Sustainability & Innovation Centre, 2024). Similarly Saudi Arabias NEOM project, valued at \$500 billion involves investments in energy and features plans for one of the largest green hydrogen production facilities, in the world (Abuljadayel, 2023).

The global steel industry, valued at over \$870 billion annually, presents a lucrative market for economies that invest in green technologies. From the economic viewpoint, MENA can attract foreign investment, create jobs, stimulate economic growth, and position itself as a leader in green steel production (Basirat and Nicholas, 2023b).

The MENA region is experiencing a rise, in investments from companies focused on steel production, energy and hydrogen manufacturing. Notably Vale, a mining company known for being the global producer of DR grade iron ore pellets has announced its plans to set up the Middle East "green iron Mega-Hubs" (Yermolenko, 2023). These hubs are designed to supply DR grade pellets to direct reduced iron (DRI) plants. Vale recently signed a Memorandum of Understanding (MoU) with Saudi Arabias National Industrial Development Center to build a 4 million ton/year iron ore pelletizing

facility in Ras Al Khair Industrial City (Yermolenko, 2023). Additionally, Vale is looking to establish three iron ore concentrators in Saudi Arabia the United Arab Emirates (UAE) and Oman to supply pellets for DRI plants, in the region (Basirat and Nicholas, 2023b; Nicholas and Basirat, 2023).

Major steel producers like Rio Tinto and POSCO are also investigating green hydrogen initiatives and sustainable iron/steel production in the MENA region, driven by the region's renewable energy potential. Other international companies investing in the region's green steel and renewable energy include Emirates Steel Arkan (UAE), which is working with Japan's ITOCHU (iron ore supplier) and JFE Steel (DRI consumer) on a DRI production project in Abu Dhabi using renewable energy, and Oman Jindal Shadeed Iron and Steel (India), which is investing \$3 billion in a green hydrogen-powered steel plant in Oman's Duqm Economic Zone, targeting 5 million tons/year capacity.

In essence, the MENA region is well positioned to lead the green steel industry with its energy sources focused investments and favorable geographical location. By making progress and committing financially MENA can reap economic benefits contributing significantly to the effort to cut down on carbon emissions, in the steel industry.

2.11 Summary

This chapter presented a thorough examination of the existing scholarship concerning the steel industry's shift towards sustainability. Initially, it established a theoretical framework, drawing upon concepts such as Corporate Social Responsibility (CSR), Stakeholder Theory, the Resource-Based View (RBV), Ecological Modernization

Theory (EMT), and the Circular Economy. The chapter subsequently traced the progression of steelmaking technologies, from conventional techniques like the Bessemer and open-hearth processes to contemporary production methods, including Blast Furnace–Basic Oxygen Furnace (BF/BOF) and Electric Arc Furnace (EAF) systems, thereby underscoring the industry's considerable environmental footprint. The final part of this chapter examined the importance of sustainability, explaining the global governance systems that have helped promote green steel production. These systems include the WTO Green Rules, the Paris Agreement, and the European Green Deal.

This study described the three main steps toward carbon-neutral steel production and evaluated new technologies. These technologies included Carbon Capture, Utilization and Storage (CCUS), hydrogen-based direct reduction, direct electrification, and biomass energy solutions. The chapter further examined the strategic contributions of technology providers such as Danieli, SMS Group, and Primetals Technologies to industrial decarbonization, highlighting the economic obstacles inherent in the shift towards green steel production, especially concerning the integration of renewable energy sources and hydrogen. A review of best practices from leading global companies was conducted, alongside an analysis of the MENA region's strategic capacity to foster green steel projects. These combined perspectives provide a crucial basis for understanding the industry's current direction and prepare the reader for the empirical investigations detailed in the following chapters.

CHAPTER III: METHODOLOGY

3.1 Introduction

This chapter describes the methods used to study the shift from traditional steel production to green steel methods across the entire value chain in the MENA region. The steel sector was selected as the primary subject of this investigation because of its significant role in global carbon emissions, alongside its potential for reform through the adoption of low-carbon technologies. The industry's substantial environmental footprint, coupled with increasing regulatory pressures and international climate goals, has placed steelmaking at the center of sustainability discussions, particularly in resource-rich but policy-diverse regions like MENA.

Consequently, the increasing emphasis on decarbonization within the global steel sector is presenting both challenges and opportunities for MENA nations. In contrast, traditional steelmaking methods, particularly those using coal-powered blast furnaces, are facing increasing regulatory and market challenges. Simultaneously, the region's strategic advantages encompass access to solar energy, hydrogen potential, and raw material reserves; if these resources are utilized efficiently, the area could potentially become a future hub for green steel manufacturing. These conflicting factors highlight the need for a more thorough understanding of how industry players, technological progress, infrastructure improvements, and policy structures interact to enable this change.

This research endeavors to examine the steel sector's transition from conventional, carbon-heavy production techniques to environmentally sound methodologies across the entire value chain, focusing on the creation of a context-sensitive, decision-making framework specifically designed for the MENA region. To achieve this objective, the study analyzes key factors, including technological readiness, environmental constraints, economic feasibility, and institutional capacities.

Figure 3.1 presents the sequential research process adopted in this study, illustrating the key phases from global review to stakeholder interviews and framework development.

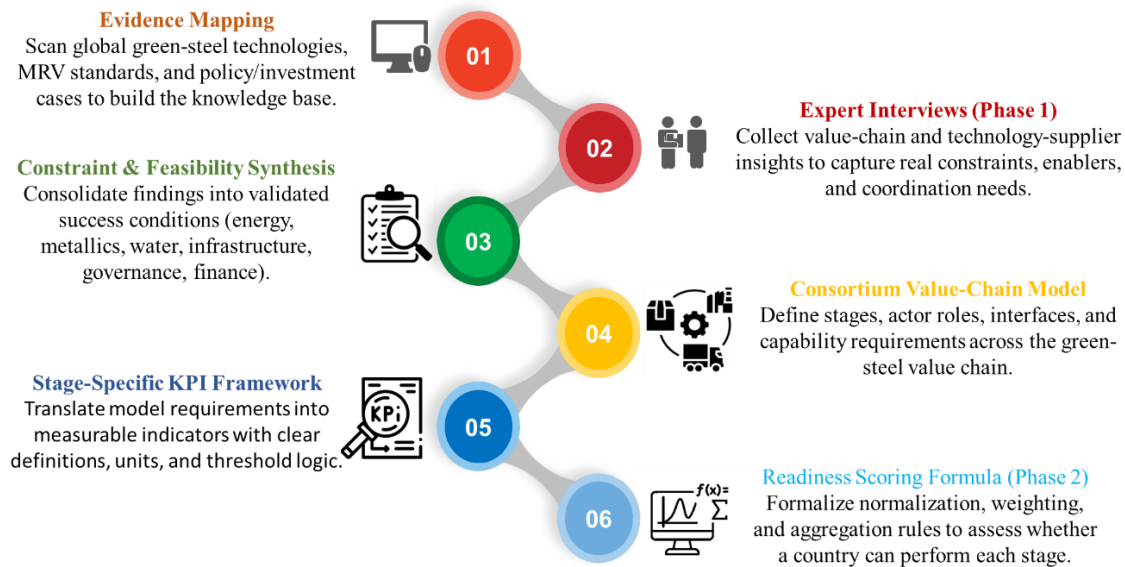


Figure 3.1
Structured Process Followed in This Study, (Designed by Author)

3.2 Research Purpose and Questions

The research questions developed in this study are closely aligned with both the purpose and the problem statement, ensuring coherence throughout the research design.

RQ1. How can low-carbon technologies and operational practices be integrated across the steel value chain to reduce emissions while maintaining economic feasibility and competitive advantage?

RQ2. What technical pathways and infrastructure configurations are required to scale green-steel production in MENA?

RQ3. How do country conditions, international regulatory frameworks, economic capabilities, technological readiness, and natural resource endowments, interact with policy instruments and international collaboration mechanisms to drive adoption of green-steel innovations across MENA?

3.3 Research Design

The goal of this study is to construct and put into reality a value-chain model based on a consortium for green steel deployment in the MENA region. It uses a mixed-methods design in sequence. There are two parts to the method approach:

In Phase 1 (qualitative), we will learn more about the topic by interviewing experts. This is to learn about the system-level limits, the conditions that make green steel possible, and the rules for coordinating it.

Phase 2 (analytical-operational): This phase is about turning qualitative information into a structured value chain model, a preparedness framework based on KPIs, and a scoring system that is clear.

The general rationale is based on a research approach called “abductive.” It uses information from specialists in the field to help develop an analytical model. Then, this model is turned into decision rules and observable indicators.

3.4 Population and Sample

There are two study populations and samples: (a) technology suppliers, and (b) steel producers in MENA.

A. International Technology Suppliers Population and Sample

Population: The study's population comprises the foremost global suppliers of steel technology, specifically those engaged in the design and provision of sophisticated technologies for the production of low-carbon and green steel. These entities are responsible for the development, supply, and implementation of process equipment, environmental solutions, digital systems, and comprehensive plant engineering services for steel producers globally, with a particular focus on the MENA region.

The global population comprises approximately 10 major technology suppliers, including companies such as “Danieli” (Italy), “SMS Group” (Germany), “Primetals Technologies” (Austria-Germany), “Tenova,” “Midrex,” “Paul Wurth,” “Hatch,” and “Siemens Metals.” These companies are recognized for their role in steel decarbonization efforts, digitalization of operations, and regional project support, particularly in emerging markets.

Sample: From this population, the study selected 3 of the most prominent technology suppliers: “Danieli”, “SMS Group”, and “Primetals Technologies”.

Danieli Group: Danieli a full-line supplier from direct reduction and EAF meltshops to flat/long rolling and finishing positions its *“Intelligent, Competitive Green Metal”* portfolio as an integrated pathway to lower-carbon steelmaking (Danieli, 2023).

SMS Group: SMS group frames itself as a systems supplier able to deliver “*all climate-neutral processes from a single source,*” covering hydrogen-based direct reduction, EAF steelmaking, BF/BOF conversions, and downstream process electrification and efficiency upgrades, supported by X-Pact® digital/automation solutions (Fleschen, 2024).

Primetals Technologies: Primetals Technologies as a full-line metallurgical plant builder advances both yield/quality platforms and novel reduction routes. On the finishing side, continuous casting and rolling, like Arvedi ESP, are being used with automation to increase production and reduce energy use. In ironmaking, the development of HYFOR, a hydrogen-based method for directly reducing fine ore that avoids agglomeration, and the HYFOR+smelter concept are being explored as alternatives to the blast furnace. These concepts are currently being tested and expanded (Fleischanderl *et al.*, 2021).

Including these suppliers strengthens the study by capturing upstream-to-downstream technology perspectives that steel producers alone cannot provide, particularly regarding implementation constraints (engineering readiness, retrofit limits, project execution, and integration risks) and diffusion mechanisms (how technologies are transferred, financed, standardized, and scaled across countries). Their established global project experience also provides a credible basis for comparing how major suppliers frame feasibility, infrastructure requirements, and transition sequencing in relation to RQ1–RQ3, which is central to interpreting MENA’s practical decarbonization options.

B. Steel Producers Population and Sample

Population: The steel producers' population across the steel industry value chain consists about 36 (n=36) major steel corporations in the MENA steel industry, with annual production capacity exceeding 500,000 tons, based on data from the World Steel Association, Arab Iron & Steel Union, corporate reports, and industry databases. The selection criteria for corporations include:

- (a) minimum annual production capacity of 500,000 tons.
- (b) strategic importance to national and regional steel supply chains.
- (c) technological advancement and operational scale significance.
- (d) integration across multiple value chain stages (upstream mining, midstream steelmaking, downstream processing).
- (e) significant contribution to regional steel trade and export markets.
- (f) exposure to decarbonization pressures and sustainability initiatives.

Sample: For in-depth analysis, a purposive sample of 18 major companies was selected to represent the full steel value chain, covering upstream, midstream, and downstream activities. The selected companies are:

Upstream mining and pelletizing: Mobarakeh Steel Company (MSC), Bahrain Steel (GIIC / Bahrain Steel BSCC E.C.), Erdemir (OYAK Mining & Metallurgy), SNIM – Société Nationale Industrielle et Minière.

Midstream steelmaking and Downstream processing and specialized products: Mobarakeh Steel Company (MSC), Saudi Iron & Steel Company (Hadeed), Emirates Steel (EMSTEEL), Erdemir (OYAK Mining & Metallurgy), Jindal Renewables

LLC, Qatar Steel, Tosyalı Algeria, and Jindal Steel Duqm LLC – formerly Vulcan Green Steel.

These companies were chosen based on their production capacity, strategic role in MENA's steel ecosystem, operational diversity, and their relevance to decarbonization and sustainable development challenges in the MENA context. Table A.1 reported these 36 steel producer companies.

3.5 Instrumentation and Data Analysis

The study employs semi-structured interviews and content analysis of the secondary data (relevant literature, the study corporations' reports, and other publicly available sources).

In the first phase, 21 semi-structured interviews were conducted: three in-depth interviews with representatives from Danieli, SMS Group, and Primetals Technologies to explore current green steel technologies, and 18 interviews with executives/technical experts from 18 steel companies to assess their readiness for low-carbon operations and operational challenges. Then to analyze the interviews, this study employed a thematic analysis approach guided by Braun and Clarke's (2006) six-step framework (Braun and Clarke, 2006). This method was chosen because it effectively identifies, categorizes, and explains the meanings found in the interview data.

This approach is especially useful for studying complex topics, like the adoption of low-carbon technologies, the readiness of infrastructure, and the operational policies in the steel industry of the Middle East and North Africa.

Considering the dataset's modest scope – just three detailed interviews – and my position as a sales manager at a worldwide steel technology firm, I opted for a manual analysis. I didn't rely on any qualitative analysis software. As noted by Nowell et al. (2017), “Thematic analysis can be conducted manually or with the assistance of software programs. Manual methodologies are frequently employed and deemed appropriate for datasets of limited to moderate size, particularly when the researcher is able to establish a transparent audit trail (Nowell *et al.*, 2017). In this particular case, the manual approach fostered a more direct interaction with the data, thus allowing for the application of considerable domain knowledge to interpret industry-specific language, contextual elements, and operational nuances. Conversely, for the larger dataset, which encompassed eighteen interviews with steel production companies, NVivo software was utilized to facilitate and organize the qualitative analysis.

The thematic analysis followed the six established steps:

- 1. Familiarization:** The full interview transcripts and summary dataset were read and annotated multiple times to develop an initial understanding of the participants’ perspectives. Early reflections and sector-specific patterns were recorded during this phase.
- 2. Open Coding:** Key statements and phrases from each interview were systematically coded line-by-line. Codes captured operational, technological, and policy-related concepts directly relevant to the research questions.
- 3. Axial Coding:** Related codes were grouped into conceptual categories based on commonalities and relationships.

- 4. Theme Development:** From these conceptual categories, broader themes were developed that reflected convergent ideas across the interviews. Themes were only confirmed if supported by multiple codes across more than one participant.
- 5. Theme Definition and Refinement:** Each theme was carefully defined to ensure clarity, distinctiveness, and alignment with the research questions. Redundant or overlapping themes were revised or merged accordingly.
- 6. Reporting:** The final themes were presented in Chapter 4.

This process ensured that the resulting themes were not only analytically sound but also grounded in the real-world experiences of leading technology suppliers engaged in the transition to green steel.

In the second phase, secondary data were collected from authoritative sources to identify 19 critical KPIs and to operationalize a formula-driven assessment process for evaluating each MENA country's readiness across value-chain stages of the green steel transition. Building on Phase 1 insights, the KPIs were mapped to stage-specific constructs, and an AHP-based weighting procedure was used to derive criterion importance, supported by explicit mathematical formulations for indicator normalization, weighting, and aggregation into stage-level readiness scores and an overall readiness profile. An abductive logic integrated the two phases by returning to qualitative themes whenever quantitative stage scores appeared inconsistent with interview evidence, prompting targeted checks of KPI definitions, data provenance, and stage-to-KPI mapping to maintain conceptual alignment.

Table 3.2 summarizes the study’s data-collection strands, technology supplier and steel producer interviews (Phase 1) and the secondary-data, stage-based country readiness assessment (Phase 2), including instruments, population frames, sampling and final samples, data collected, and analytical methods.

Table 3.2
Study Instruments, Samples, and Analyzes

Strand / Instrument	Population & Sample	Data Collected	Analysis
Interviews: Technology Suppliers (Phase 1)	~10 global suppliers 3 companies	20-item guide documented executive synthesis	NVivo thematic + manual; mapped to RQ1–RQ3
Interviews: Steel Producers (MENA) (Phase 1)	36 producers (up/mid/down) 18 companies	22-item guide documented executive synthesis	NVivo thematic + manual; mapped to RQ1–RQ3
KPI Framework & Formula Design (Phase 2)	Authoritative secondary sources criterion-based 19 KPIs	KPI definitions/units stage–KPI mapping normalization rules AHP pairwise inputs	AHP-weighted, formula-based scoring

Overall, the two-phase approach translates interview-derived constructs into an AHP-weighted KPI formulation and a stage-based value-chain model for structuring a green steel consortium.

3.6 Research Design Limitations

The study was conducted in two phases and is subject to several methodological limitations. In Phase 1, the qualitative component drew on 21 in-depth interviews; although these interviews provided rich, practice-grounded insights, the sample may not fully reflect the diversity of the MENA steel industry, particularly smaller firms, under-represented countries, or less visible actors across the value chain. Phase 2's efforts concentrated on constructing a Key Performance Indicator (KPI) framework, driven by

formulas and weighted via the Analytic Hierarchy Process (AHP), utilizing secondary data. Nevertheless, the quality, recency, and comprehensiveness of secondary datasets can vary, potentially impacting the reliability of KPI definitions, normalization protocols, and the framework's applicability across different national settings. Furthermore, the AHP methodology necessitates expert assessments to determine criterion weights, thereby incorporating an inherent degree of subjectivity, which is influenced by qualitative observations and the researcher's interpretive decisions.

The abductive logic used to connect the phases, revisiting qualitative constructs to ensure conceptual alignment with the KPI operationalisation, also adds interpretive complexity and increases the risk of tailoring the framework too closely to the available evidence. Importantly, this study does not operationalize the model by applying the 19 KPIs and derived weights to compute country scores or rankings; rather, it proposes the assessment formulas and a consortium-oriented, stage-based value-chain model. Full operationalisation would require additional methodological safeguards to strengthen weight validity and reliability, such as eliciting weights from a broader expert panel (e.g., Delphi), testing alternative weighting techniques (e.g., Best–Worst Method, entropy or CRITIC weighting), and benchmarking AHP-derived weights against empirical sensitivity and robustness checks before producing comparative country scores.

3.7 Ethical Assurance

The study is cautious and ethics-based when it comes to the research components to ensure high levels of integrity and fair play. Participants enlisted in the study will have a full understanding of the purpose of this research and their part in it. They will give

informed consent before taking part, after having been thoroughly briefed about their rights (including the right to withdraw at any time with no negative repercussions). Confidentiality will be of utmost importance, and any identifiers (e.g., network names or individual titles) will be anonymized so that the identities of participants and their associated organizations cannot be displayed publicly. All data collected will be stored securely and only accessible by the research team, in accordance with applicable data protection legislation.

Since the researcher will have a professional position within the steel industry, care will be taken to avoid possible conflicts of interest and maintain an objective face for all research. The reporting of the findings should be balanced and fair, accurately representing the views of different stakeholders who have been interviewed in the study, without manipulating or misleading.

Moreover, the research highlights the different socio-cultural and regional contexts in the MENA region and aims to honor these dimensions in engagement with stakeholders. As such, the study aims to engage in meaningful participation and garner insights that reflect the lived realities of the population concerned through an inclusive and thoughtful approach.

3.8 Summary

This chapter set out the methodological approach used to examine the green steel transition across the MENA steel value chain and to develop a consortium-oriented, stage-based value-chain model. The research used a sequential mixed-methods approach, guided by an abductive reasoning process. The qualitative findings were then used to

create an analytical framework, ensuring that the study's two parts were conceptually connected. The first part of the study involved conducting twenty-one semi-structured interviews. This included three interviews with leading technology suppliers, specifically Danieli, SMS Group, and Primetals Technologies. In addition, the phase included eighteen interviews with executives and technical experts from major steel companies in the MENA region. The resulting themes were organized and interpreted in relation to RQ1–RQ3, focusing on technology integration, infrastructure requirements, and transition governance.

In Phase 2, secondary data from authoritative sources were used to define 19 critical KPIs and to construct a formula-driven, stage-wise readiness assessment formulation for the proposed consortium model. The phase formalized explicit procedures for indicator definition, normalization, AHP-derived weighting, and weighted aggregation to enable future computation of stage-level readiness scores.

The chapter also documented the main methodological limitations, including representativeness constraints in the interview sample, variability in secondary-data quality, and the subjective element inherent in AHP weighting, as well as the interpretive complexity introduced by abductive integration. Finally, it specified the study's ethical safeguards, including informed consent, confidentiality and anonymisation, secure data handling, and precautions to manage potential conflicts of interest given the researcher's professional role.

CHAPTER IV:

RESULTS

4.1 Introduction

Chapter 4 reports the study findings and develops the evidence base for the proposed consortium green-steel value-chain model (Mega-Hub) for the MENA region. The chapter is organised into two connected phases. Phase 1 presents the qualitative results from 21 semi-structured interviews, including 18 steel producer company-cases across upstream, midstream, and downstream stages and 3 technology-supplier cases. The interviews were analyzed in NVivo using a hybrid deductive–inductive coding strategy, resulting in steel producer themes (SPT1–SPT5) and technology supplier themes (TST1–TST5). The findings are reported by research question to show how participants explained:

- (i) integration mechanisms across the value chain (RQ1),
- (ii) technical pathways and infrastructure configurations required for scaling (RQ2), and
- (iii) adoption drivers shaped by country conditions and external institutional pressures, including market, policy, and finance (RQ3).

Building on these qualitative results, Phase 2 translates the consolidated key messages into an operational stage-gate structure to support consortium design and country role identification. This phase introduces the three-stage consortium value-chain model, defines a KPI dictionary that links each stage-gate question to measurable

evidence requirements, and presents a transparent scoring methodology that converts KPI evidence into stage readiness scores and role-fit categories.

4.2 Phase 1: Qualitative Analysis (21 Interviews)

The qualitative findings emerged from a rigorous analysis of the data, which facilitated the identification of key themes pertinent to the research inquiries. The central objective underpinning the data gathering and subsequent analysis was to investigate the steel industry's evolution, specifically its shift from traditional, carbon-heavy production techniques to more environmentally conscious methodologies throughout the entire value chain. This investigation was conducted with the aim of formulating a contextually relevant, decision-supporting framework tailored for the MENA region.

4.2.1 Participant profile and interview logistics

This subsection summarizes the interview sample and fieldwork logistics to provide transparency about who was interviewed, how the interviews were conducted, and the contextual coverage achieved across the value-chain stages. Participant information is reported in an anonymised form (including aggregated demographic bands where available) alongside key logistics such as interview mode, timing, and roles, to support the credibility and traceability of the qualitative evidence presented in the subsequent finding's sections.

Steel Producers: Demographic Statistics and Interview Logistics

The demographic findings for 18 executives/technical experts reflected four key elements: gender, educational level, age, and years on the present positions. This section reports the interview sample as a set of company-cases. Each company was treated as a

single analytical case (n = 18) and classified using the key attribute value-chain stage (upstream, midstream, downstream). Age and years in the current role are reported in broad bands to protect participant anonymity, as the combination of country, company, and senior managerial position can make individuals identifiable in a small elite sample. The band thresholds were selected to remain analytically meaningful (consistent with common managerial career and appointment cycles) while avoiding disclosure of exact personal details.

Table 4.1. presents demographic statistics for the study steel producers' participants.

Table 4.1
Demographic Statistics for Study Steel Producers' Participants

Participant ID	Gender	Education level	Age	Years on the present position
U1	Man	Bachelor	50-60	20-30
U2	Man	Bachelor	40-50	10-20
U3	Man	Master	40-50	10-20
U4	Man	Bachelor	50-60	20-30
M1	Man	Master	40-50	10-20
M2	Man	MBA	40-50	10-20
M3	Man	Bachelor	50-60	20-30
M4	Man	University level	50-60	20-30
M5	Man	MBA	40-50	10-20
M6	Man	Master	40-50	10-20
M7	Man	MBA	40-50	10-20
M8	Man	Master	40-50	10-20
D1	Man	Master	45-55	10-20
D2	Man	Master	45-55	10-20
D3	Man	Bachelor	50-60	20-30
D4	Man	MBA	40-50	10-20
D5	Man	MBA	40-50	10-20
D6	Man	MBA	40-50	10-20

Table 4.2 presents the interview sample and company-case classification by value-chain stage, and Table 4.3 reports the interview administration records (duration, participant documentation, informed consent, and interview mode).

Table 4.2

Interview sample and case classification by value-chain stage (company-cases, n = 18)

Case ID	Country	Value-chain stage	Company	Interviewee role
U1	Bahrain	Upstream	Bahrain Steel	Executive Manager
U2	Türkiye	Upstream	OYAK Mining & Metallurgy	Operations Manager
U3	Iran	Upstream	Mobarakeh Steel Company, MSC	Development Manager
U4	Mauritania	Upstream	SNIM – Société Nationale Industrielle et Minière	General Manager
M1	United Arab Emirates	Midstream	Emirates Steel (EMSTEEL)	ESG & Sustainability Manager
M2	Türkiye	Midstream	İskenderun Demir ve Çelik A.Ş. (İsdemir)	General Manager
M3	Saudi Arabia	Midstream	Saudi Iron & Steel Company (Hadeed)	Technical Manager
M4	Oman	Midstream	Jindal Renewables LLC	Associate Vice President
M5	Iran	Midstream	Mobarakeh Steel Company, MSC	Development Manager
M6	Qatar	Midstream	Qatar Steel	Operations Manager
M7	Libya	Midstream	Tosyalı SULB Steel Industries	General Manager
M8	Oman	Midstream	Vulcan Green Steel (Jindal Steel Duqm LLC)	General Manager
D1	United Arab Emirates	Downstream	Emirates Steel (EMSTEEL)	ESG & Sustainability Manager
D2	Türkiye	Downstream	Erdemir	General Manager
D3	Saudi Arabia	Downstream	Saudi Iron & Steel Company (Hadeed)	Technical Manager
D4	Iran	Downstream	Mobarakeh Steel Company, MSC	Development Manager
D5	Qatar	Downstream	Qatar Steel	Operations Manager
D6	Algeria	Downstream	Tosyalı-Algérie	General Manager

Table 4.3

Interview administration and documentation checklist for study participants (n = 18)

Participant ID	Interview Duration (minutes)	Complete Participant Profile	Signed Informed Consent	Interview Performed
U1	60 min	Yes	Yes	Online
U2	60 min	Yes	Yes	Online
U3	60 min	Yes	Yes	Face-to-face
U4	60 min	Yes	Yes	Online
M1	60 min	Yes	Yes	Online
M2	60 min	Yes	Yes	Online
M3	60 min	Yes	Yes	Online
M4	60 min	Yes	Yes	Online
M5	60 min	Yes	Yes	Face-to-face
M6	60 min	Yes	Yes	Online
M7	60 min	Yes	Yes	Online
M8	60 min	Yes	Yes	Online
D1	60 min	Yes	Yes	Online
D2	60 min	Yes	Yes	Online
D3	60 min	Yes	Yes	Online
D4	60 min	Yes	Yes	Face-to-face
D5	60 min	Yes	Yes	Online
D6	60 min	Yes	Yes	Online

The distribution of interviews across the value chain (4 upstream, 8 midstream, and 6 downstream) was a deliberate and analytical sampling choice, not an attempt to be statistically representative. We sampled more midstream firms (n = 8) because the choices they make about primary ironmaking and steelmaking routes (for example, BF–BOF versus DRI–EAF, scrap strategy, process optimization, and energy intensity) have the most important trade-offs for reducing emissions, making CAPEX/OPEX feasible, and relying on infrastructure. This makes midstream the "bottleneck" stage for answering RQ1 and RQ2. Four upstream cases were included to show how constraints affect downstream decarbonization options, such as the availability of DRI-grade raw materials, the ability to pelletize and benefit, logistics, and energy and emissions intensity. Fewer cases were needed because there are fewer upstream actors and their strategic positions

are often more concentrated. We chose six downstream cases to make sure that the analysis includes pressures for decarbonization that come from customers and the market (like product carbon footprinting and export competitiveness under new rules) while also keeping the overall dataset balanced across stages so that we can compare cases.

The choice of countries was also deliberate: Bahrain, the UAE, Saudi Arabia, Qatar, and Oman are all examples of Gulf Cooperation Council (GCC) industrial goals, energy system features, and fresh signals for investment in hydrogen and renewables. Turkey and Iran have big, diverse steel systems that have a lot of power in their regions and various trade and sanctions policies. Mauritania, Libya, Egypt, Morocco, and Algeria bring resource endowment and institutional diversity from North and West Africa. These countries together create the most variation in key adoption conditions that are important to RQ3, such as natural resources (gas, renewables potential, iron ore), infrastructure maturity (grid reliability and captive power options), export exposure and regulatory pressure, and differences in technological readiness. This makes the thematic patterns seen across cases and value-chain stages more credible.

Technology Suppliers: Demographic Statistics and Interview Logistics

This section reports the technology-suppliers' Demographic Statistics, interview sample and the related interview administration information to ensure transparency and traceability for the qualitative analysis. Each technology supplier was treated as a single analytical case ($n = 3$) and coded as a supplier-case. Table 4.4 reported the demographic statistics for the study technology suppliers' participants.

*Table 4.4**Demographic Statistics for Study Technology Supplier's Participants*

Participant ID	Gender	Education level	Age	Years on the present position
TS1	Man	Master		
TS2	Man	Bachelor		
TS3	Man	Doctorate		

Table 4.5 summarizes the technology-supplier interview sample and case classification, and Table 4.6 documents the interview administration records for each supplier participant (duration, participant documentation, informed consent, and interview mode).

*Table 4.5**Technology supplier interview sample and case classification (supplier-case level, n = 3)*

Case ID	Company	Headquarters country	Supplier type	Interviewee role
TS1	Danieli Group	Italy, Iran	Technology supplier (ironmaking/steelmaking/rolling & automation)	Global Sales Director
TS2	SMS group	Germany	Technology supplier (metallurgy/rolling/automation)	Technology Director
TS3	Primetals Technologies	UK, Austria, Japan	Technology supplier (metallurgy/rolling/digital)	Technology Director

*Table 4.6**Interview administration records for technology supplier participants (n = 3)*

Participant ID	Interview duration (minutes)	Complete participant profile	Signed informed consent	Interview performed
TS1	60 min	Yes	Yes	Online / Face-to-face
TS2	60 min	Yes	Yes	Online
TS3	60 min	Yes	Yes	Online

The three supplier-cases, Danieli Group, SMS group, and Primetals Technologies, were selected through purposive sampling because they represent leading global suppliers of integrated steel plant equipment and automation, with extensive portfolios relevant to green-steel pathways.

4.2.2 Coding Process and Theme Derivation

A hybrid deductive–inductive coding strategy was applied to analyze the 21 semi-structured interviews with steel producers and technology suppliers. Deductive coding commenced with an initial compilation of conceptually-based codes, which were formulated based on existing literature and policy guidelines pertinent to industrial decarbonisation; these included, for instance, the logic of Scope 1–3 emissions, compliance pressures associated with the CBAM, and pathways for net-zero transition. Concurrently, inductive coding was utilized to uncover unanticipated challenges and context-specific practices that emerged directly from the participants' accounts, thus ensuring that the analysis integrated both established theoretical frameworks and the practical realities of their lived experiences.

Interview transcripts were reviewed iteratively. First, meaning units were identified and assigned initial codes. Subsequently, the codes underwent refinement via iterative comparisons of the transcripts; overlapping codes were integrated, ambiguous codes were elucidated, and under-specified codes were disaggregated as required. Following this, the refined codes were synthesized into overarching themes to facilitate a systematic synthesis of the data. NVivo was used to manage the coding process, maintain an audit trail of code definitions and revisions, and support structured retrieval of coded evidence by participant group (steel producers/ technology suppliers) and by value-chain stage. Each of the interview questions was pre-assigned to RQ1–RQ3 based on its intended construct; during analysis, responses were coded and then consolidated into themes, with findings reported by research question to maintain a transparent audit trail.

Steel producers and technology suppliers were analyzed as distinct participant groups, with separate thematic structures retained where the underlying constructs differed. To ensure the study's reliability, a written codebook was used, and the coding was checked repeatedly during the analysis. In addition, the interview data was compared with relevant secondary sources to strengthen the study's conclusions.

The detailed list of themes derived from interview with steel producers and technology suppliers and their descriptions is provided in Table 4.7 and Table 4.8.

Table 4.7
Identified Themes from Interviews with the Steel Producers

#	Theme title	Theme explanation
SPT1	Strategic Decarbonization Roadmaps and Value-Chain Positioning	Formal decarbonization intent expressed as time-bound targets, baseline years, Scope coverage, and roadmap language (e.g., net zero pathways, milestone years).
SPT2	Production-Route Decarbonization: DRI–EAF, Scrap Use and Process Optimization	The “how” of decarbonization: technology interventions, process-route choices, operational upgrades, and pilots/rollouts.
SPT3	Energy Mix and Infrastructure Transformation: Captive Power, Renewables and Grid Interfaces	Changes in electricity sourcing, renewable integration, fuel switching, and self-sufficiency infrastructure (solar, wind, I-REC clean power, captive power).
SPT4	Governance, Measurement and Value-Chain Data Infrastructure	The “proof system”: measurement, verification/assurance, standards (ISO 14001/50001/14064, ResponsibleSteel), CBAM readiness, and internal governance structures.
SPT5	Financing, Competitiveness and Collaboration for Decarbonization Investments	The “execution engine”: capex, financing instruments, technology partnerships, and named programs that enable decarbonization.

Table 4.8
Key Themes Identified in Technology Suppliers’ Interviews

#	Theme title	Theme explanation
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TST1	Flexible Green-Steel Technology Architectures	Modular/hybrid plant designs that enable phased decarbonization (e.g., NG → H ₂ blending → higher H ₂ operation) under uncertain energy availability and evolving market/regulatory conditions.
TST2	Energy & Power Stability under Renewable Constraints	Technical and digital controls that stabilize EAF/DRI performance under weak grids, variable renewables, and power-quality constraints (flicker/harmonics/reactive power).
TST3	Material-Input Versatility & Scrap Optimization	Process and digital strategies to handle variable metallic mixes (scrap/DRI/HBI/hot metal) while controlling impurities, yield losses, and cost volatility.
TST4	Environmental Control & Waste-Heat Recovery	Integrated gas cleaning/emissions abatement and waste-heat/energy recovery solutions that reduce carbon intensity, improve efficiency, and support compliance and ROI.
TST5	Deployment Feasibility & Policy Dependency	Adoption feasibility framed as conditional on policy clarity (carbon pricing/CBAM), incentives, market demand, infrastructure sequencing (power/H ₂ /logistics), and project bankability constraints.

When the main idea of the text met the theme specification, each interview extract was classified to that topic (inclusion). If the extract was mostly about anything else, it wasn't coded to that theme (exclusion). In several circumstances, one sentence or paragraph had more than one significant point. For example, a roadmap aim and a renewable energy action together. More than one theme was used in these situations. When a main topic was needed for reporting, the primary theme was chosen based on the excerpt's essential point, not just a brief mention.

Appendix D presents the qualitative codebook, including theme definitions, inclusion and exclusion criteria, and selected exemplar quotes from the interview transcripts for both steel producers and technology suppliers.

4.3 Findings: Research Question Results

To examine the transformation of the steel industry from conventional, carbon-intensive production methods to environmentally sustainable practices across the value chain, with a focus on developing a context-sensitive, decision-oriented framework for the MENA region, the following specific research questions were designed:

RQ1. How can low-carbon technologies and operational practices be integrated across the steel value chain to reduce emissions while maintaining economic feasibility and competitive advantage?

RQ2. What technical pathways and infrastructure configurations, are required to scale green-steel production in MENA?

RQ3. How do country conditions, international regulatory frameworks, economic capabilities, technological readiness, and natural resource endowments, interact with policy instruments and international collaboration mechanisms to drive adoption of green-steel innovations across MENA?

4.3.1 Findings for RQ1: Integrating Low-Carbon Technologies for Competitive Value-Chain Decarbonization

RQ1: How can low-carbon technologies and operational practices be integrated across the steel value chain to reduce emissions while maintaining economic feasibility and competitive advantage?

The first research question examines how firms combine technologies and practices across upstream–midstream–downstream activities to reduce emissions while protecting cost, productivity, and market competitiveness. In this section, the results and findings for RQ1 are reported by mapping coded interview evidence from steel producers

across the whole value chain and technology suppliers into RQ1 sub-questions, codes, and themes, supported by the related tables 4.9a and 4.9b.

Table 4.9a

From Interview Questions (by Stage) to RQ1 Sub-Questions and Themes: Steel Producers (n = 18 across stages)

Sub-questions (RQ1)	Related interview questions	Theme title (SPT)	Codes
SQ1. Operational emission hotspots and current low-carbon actions (by stage)	Upstream: Q1–Q3 Midstream: Q1–Q3 Downstream: Q1–Q3	SPT2: Production-Route Decarbonization (DRI–EAF, scrap, process optimization)	• Emission hotspots / main Scope-1 sources • Low-carbon technologies in use / piloted • Technology readiness level • Reported results/outcomes • “Quick wins” vs structural changes
SQ2. Adoption decision logic under cost and performance constraints	Upstream: Q4 Midstream: Q4 Downstream: Q4	SPT1: Strategic Decarbonization Roadmaps & Value-Chain Positioning	• Adoption criteria (payback/ROI, risk) • Compatibility with existing assets • Productivity/yield constraints • Compliance/market pressure • “Pilot-first” and phased upgrades
SQ3. Energy/fuel integration and constraints on switching	Upstream: Q5, Q7–Q9 Midstream: Q5, Q7–Q9 Downstream: Q5, Q7–Q9	SPT3: Energy Mix & Infrastructure Transformation	• Energy mix / sourcing approach • Switching drivers (cost, emissions, regulation) • Grid limits / reliability issues • Renewables availability • Hydrogen readiness • Operational constraints during switching
SQ4. Monitoring and measurement practices supporting integration and competitiveness	Upstream: Q6, Q10–Q13, Q18 Midstream: Q6, Q10–Q13, Q18	SPT4: Governance, Measurement & Value-Chain Data Infrastructure	• Energy monitoring systems • GHG measurement approach

	Downstream: Q6, Q10–Q13, Q18		• Reporting standards (ISO/GHG Protocol) • CBAM/customer drivers • Improving data accuracy • Benchmarking KPIs
SQ5. Scope-3 integration (materials/logistics) and link to value-chain claims	Upstream: Q14 Midstream: Q14 Downstream: Q14	SPT4: Governance, Measurement & Data Infrastructure	• Scope-3 tracking status • Supplier data access gaps • Boundary/method issues • MRV cost and workload • Category prioritization (what is tracked first)
SQ6. Financial and institutional conditions that make investments approvable	Upstream: Q15–Q17, Q19–Q22 Midstream: Q15–Q17, Q19–Q22 Downstream: Q15–Q17, Q19–Q22	SPT5: Financing, Competitiveness & Collaboration for Decarbonization Investments	• Support mechanisms received/needed • Networks and partnerships • Policy/institutional support • Readiness constraints • CAPEX range logic • Financing sources • Investment approval conditions (ROI, risk, strategic fit)

Table 4.9b

From Interview Questions to RQ1 Sub-Questions and Themes: Technology Suppliers (n = 3)

Sub-questions (RQ1)	Related supplier interview questions	Theme title (TST)	Codes
SQ1. How do supplier technologies reduce emissions while preserving operability and productivity?	Q5, Q6, Q9–Q10	TST1/TST4: Technology efficiency packages + environmental control & recovery	• Process efficiency beyond renewables • Automation/control for stable operation • Waste-heat recovery (WHR) • Material/by-product recovery and reuse loops • Cost–performance trade-offs
SQ2. What are the strongest OPEX levers shaping feasibility and competitiveness?	Q9–Q10	TST5: Deployment feasibility & economics	• Main OPEX cost drivers • Practical cost-reduction levers • Energy intensity / electricity cost sensitivity

			• Consumables and maintenance drivers • Productivity/yield impacts on unit cost
SQ3. What are the typical financial outcomes in modelled green-H₂ DRI-EAF projects?	Q11	TST5: Deployment feasibility & policy dependency (investment framing)	• Reported “typical” cost outcomes (as supplier estimates) • Key assumptions/conditions for feasibility • CAPEX/OPEX balance in models • Price premium / incentive dependence (if stated) • Bankability thresholds (if stated)

The RQ1 results reveal that using low-carbon technologies and operational methods throughout the steel value chain is more of an operating package than a single decarbonization lever. The coded evidence from the steel producer interviews shows that four connected elements are linked over and over again: process and route actions inside the plant (SPT2), energy and fuel-input integration (SPT3), auditable governance and performance control (SPT4), and investment and delivery arrangements that lower execution risk (SPT5). These connections are guided by roadmap sequencing and market positioning (SPT1). The descriptive NVivo outputs (case–theme matrices and stage summaries in Appendix E) demonstrate that governance and measurement content (SPT4) is the most often mentioned overall, and it is most intense in downstream situations, where there are more requirements for verification and reporting that customers can see. Conversely, process and route integration (SPT2) assumes greater significance in midstream scenarios, where participants highlighted "no-regret" operational packages—such as efficiency retrofits, automation/control enhancements, and

recovery systems—as pragmatic methods for reducing emissions intensity without compromising productivity or unit costs. Furthermore, the participants acknowledged feasibility constraints that impede more profound transitions across all stages.

For example, hydrogen was generally described as theoretically interesting but now too expensive, while solutions based on scrap were described as susceptible to changes in supply, price, and quality. Because of this, people often said that integration meant making the existing route as good as it could be while still leaving room for further changes in the future.

The interviews with technology suppliers support the same package rationale, but they mostly talk about it in terms of technical design decisions. Suppliers emphasized the importance of adaptable and upgradeable plant designs, thereby mitigating the potential for stranded assets and facilitating incremental decarbonization (TST1). Furthermore, they indicated that competitiveness is contingent upon effective operation within actual grid environments (TST2); consequently, power-quality management and rapid electrical regulation are viewed as mechanisms for enhancing productivity and minimizing expenses. Furthermore, suppliers associated cost stability with the adaptability and refinement of metallic inputs (TST3). This, in turn, required the plant's ability to handle diverse metallic compositions, including scrap, DRI/HBI, and their combinations, while simultaneously ensuring superior quality and yield; a process generally facilitated by digital stabilization technologies.

Finally, providers constantly talked about environmental performance packages (TST4) as part of the fundamental operational idea, not only as things that had to be done

to comply with the law. These packages included things like controlling emissions and recovering waste heat and energy. The RQ1 results show that companies can stay economically viable and competitive by using operational optimization, reliable energy arrangements, verifiable proof systems, and risk-managed financing and delivery structures, along with supplier designs that protect operability while allowing for progressive emissions reduction (Appendix E).

4.3.2 Findings for RQ2: Pathways and Infrastructure for Scaling Green Steel in MENA

RQ2: What technical pathways and infrastructure configurations are required to scale green-steel production in MENA?

This research question examines what must be built and coordinated, both inside the plant (process route and equipment configuration) and outside the plant (power, hydrogen, materials, logistics, and delivery ecosystems), to move from pilots and isolated projects to reliable, high-volume green-steel production across the MENA region. In this section, the results and findings for RQ2 are reported by mapping coded interview evidence from steel producers (upstream, midstream, downstream) and technology suppliers into RQ2 sub-questions, codes, and themes, supported by the related tables 4.10a and 4.10b.

Table 4.10a

From Interview Questions (by Stage) to RQ2 Sub-Questions and Themes: Steel Producers (n = 18 across stages)

Sub-Question (RQ2)	Related interview questions	Theme title (SPT)	Codes
SQ1. Which low-carbon production	Upstream:	SPT2: Production-Route Decarbonization (DRI–	• Stated “scalable route” options (DRI–EAF,

pathways are viewed as scalable in MENA, and how are they sequenced?	Q2–Q3, Q7, Q9 Midstream: Q2–Q3, Q7, Q9 Downstream: Q2–Q3, Q7, Q9	EAF, scrap, process optimization) + SPT1 (when framed as sequencing/roadmap)	higher scrap, phased transition) • Sequencing logic (pilot → expand → retrofit) • Hydrogen-ready vs current operation • Retrofit vs new build preferences
SQ2. What electricity system configuration is required for scale (grid interface, reliability, captive power, renewables integration)?	Upstream: Q5, Q8, Q19 Midstream: Q5, Q8, Q19 Downstream: Q5, Q8, Q19	SPT3: Energy Mix & Infrastructure Transformation	• Grid capacity / reliability constraints • Power quality and stability issues (as reported by firms) • Captive generation plans • Renewable sourcing mechanisms (PPAs/I-REC if mentioned) • “Throughput depends on power” framing
SQ3. What hydrogen configuration is required to move from blending to higher-H₂ operation (supply + delivery + plant integration)?	Upstream: Q7–Q9, Q19 Midstream: Q7–Q9, Q19 Downstream: Q7–Q9, Q19	SPT3 + SPT2 (when linked to plant operating envelope)	• Hydrogen availability and cost barriers • Logistics requirements (storage/transport) • Safety/control readiness in plant • Blending limits and upgrade steps • Dependence on industrial-zone coordination
SQ4. What materials/logistics prerequisites are required for scale (DR-grade inputs, scrap quality, inbound logistics)?	Upstream: Q5, Q7–Q9 Midstream: Q5, Q7–Q9 Downstream: Q5, Q7–Q9	SPT2 (materials/route operability) + SPT3 (supply constraints)	• DR-grade ore/pellet consistency • Scrap availability/quality variability • Metallics mix constraints • Bulk logistics / port dependence (if stated) • “Feedstock governs capacity” statements
SQ5. What delivery ecosystem conditions support scale (execution capability, supplier ecosystem,	Upstream: Q20–Q22–Q17	SPT5: Financing, Competitiveness & Collaboration	• Execution and integration risk (commissioning/ramp-up)

contracting, ramp-up risk control)?	Midstream: Q20–Q22– Q17 Downstream: Q20–Q22– Q17	• Dependence on experienced EPC/O&M partners • Collaboration models (consortia, MoUs) • Capacity expansion approval conditions • “Bankability depends on delivery structure” framing
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Table 4.10b

From Interview Questions to RQ2 Sub-Questions and Themes: Technology Suppliers (n = 3)

Sub-Question (RQ2)	Related supplier interview questions	Theme title (TST)	Codes
SQ1. What pathway configuration do suppliers present as scalable (and how is it staged)?	Q2, Q8, Q15, Q16	TST1: Flexible Green-Steel Technology Architectures	• Dual-feedstock / NG→H₂ blending logic • Hydrogen-ready design features • Modular upgrade paths • “Phased transition” language • Capacity ranges supported
SQ2. What electricity/grid capability is required to scale EAF/DRI reliably under renewables?	Q1	TST2: Energy & Power Stability under Renewable Constraints	• Weak-grid operability • Power-quality controls • Intermittency handling • Stability/throughput protection measures
SQ3. What hydrogen and water infrastructure constraints shape scale in MENA?	Q12, Q13, Q8	TST5: Deployment Feasibility & Policy Dependency + (TST1 when design-linked)	• Water requirements and mitigation options • Hydrogen supply readiness as a gate • Integration dependencies (storage/transport) • Feasibility conditions stated by suppliers
SQ4. What execution and delivery configuration supports scaling (regional execution	Q17, Q18, Q19	TST5	• Local capability building needs • Typical delivery structure for large projects

capacity, contracting approach)?	• Installation/commissioning constraints • Risk allocation / execution readiness
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The findings for RQ2 show that scaling green-steel production in MENA is described as a system configuration problem, not only a plant technology choice. Across the steel-producer interviews, participants linked scale mainly to

- (i) production-route configuration and sequencing (SPT2 and, when framed as staged transition plans, SPT1), and
- (ii) energy and infrastructure readiness (SPT3).

Companies did not see scale as a quick way to switch to full hydrogen operation in real life. Instead, they talked about step-by-step plans in which present operations are upgraded first and hydrogen-ready capability is built up over time through improvements and controlled transition phases (Appendix E: Tables E1–E6). Producers also kept saying that electricity is a binding barrier for scale: high-power operations need a dependable grid interface, a stable supply, and a way to integrate renewables and/or captive power, because instability directly affects throughput and operational continuity (SPT3). Also, scaling was linked to limits on inputs and logistics. Participants said that adding more DRI-based routes depends on having a steady supply of metallic inputs (DR-grade materials and/or stable scrap supply and quality) and the right logistics arrangements. This means that material availability and movement are part of the scaling configuration, not just an afterthought. Lastly, producers said that scaling is easier when the delivery environment lowers the risk of ramp-up and integration by using experienced execution

partners and organized delivery, contractual, and collaboration arrangements (SPT5). From an engineering point of view, the interviews with technology suppliers confirmed this same logic. Suppliers talked about scalable pathways as staged architectures (TST1) that were supported by grid-stability solutions for operation under renewables and weak-grid conditions (TST2). They also said that scale feasibility depended on external readiness, especially hydrogen/water constraints and delivery/execution capacity (TST5). The RQ2 research shows that in MENA, green steel needs a coordinated setup of route design, power systems, hydrogen/water preparedness, materials/logistics, and delivery ecosystem, not just one "best technology" choice (Appendix E).

4.3.3 Findings for RQ3: Country–Policy–Market Drivers of Adoption

RQ3: How do country conditions, international regulatory frameworks, economic capabilities, technological readiness, and natural resource endowments interact with policy instruments and international collaboration mechanisms to drive adoption of green-steel innovations across MENA?

This research question investigates the reasons for the variation in adoption rates among MENA nations and identifies the external factors, outside plant-level technological selections, necessary for the widespread implementation of green-steel advances. It looks at how the conditions in a country (maturity of the energy system, logistics, resource endowments, and industrial capabilities) interact with international regulatory and market frameworks (such as export-linked proof requirements), economic and financing capacity, technological readiness (installed base and implementation capability), and policy tools and collaboration mechanisms that lower risk and make

bankable projects possible. In this part, the outcomes and findings for RQ3 are shown by putting coded interview evidence from steel producers (upstream, midstream, downstream) and technology providers into RQ3 sub-questions, codes, and themes.

Tables 4.11a and 4.11b show how this was done.

Table 4.11a

From Interview Questions (by Stage) to RQ3 Sub-Questions and Themes: Steel Producers (n = 18 across stages)

Sub-questions (RQ3)	Related interview questions	Theme title (SPT)	Codes
SQ1. Which country conditions and endowments most shape adoption feasibility (energy, materials, infrastructure, water, etc.)?	Upstream: Q5, Q7–Q9 Midstream: Q5, Q7–Q9 Downstream: Q5, Q7–Q9	SPT3: Energy Mix & Infrastructure Transformation (with links to SPT2 when framed as route constraints)	• Grid reliability/connection limits • Energy price volatility • Renewables access and constraints • Hydrogen availability readiness (as a country constraint) • Feedstock/scrap market constraints linked to location
SQ2. How do international regulations and market-access pressures influence adoption (e.g., CBAM/buyer requirements/standards credibility)?	Upstream: Q11–Q13 Midstream: Q11–Q13 Downstream: Q11–Q13	SPT4: Governance, Measurement & Value-Chain Data Infrastructure	• Export exposure / buyer requirements • CBAM-type compliance readiness • Standards alignment (ISO / GHG Protocol / ResponsibleSteel) • Auditability and verification requirements • Credibility of instruments (e.g., certificates, claims acceptance)
SQ3. What domestic policy instruments and institutional arrangements enable or block adoption?	Upstream: Q17 Midstream: Q17 Downstream:	SPT5: Financing, Competitiveness & Collaboration (policy as investment enabler)	• Policy clarity and stability • Permitting and regulatory approvals

	Q17		(grid, captive power, PPAs, hydrogen) • Incentives / de-risking mechanisms • Institutional coordination capacity • Policy uncertainty as adoption barrier
SQ4. How do economic capability and finance conditions shape adoption depth and timing?	Upstream: Q15–Q16, Q20–Q22 Midstream: Q15–Q16, Q20–Q22 Downstream: Q15–Q16, Q20–Q22	SPT5: Financing, Competitiveness & Collaboration	• Access to finance / cost of capital constraints • Investment approval thresholds (ROI/payback logic) • CAPEX affordability and phasing • Risk allocation and bankability conditions • Competitiveness under cost premiums
SQ5. How do collaboration and ecosystems (partners, networks, suppliers) influence adoption speed and implementation capability?	Upstream: Q16 Midstream: Q16 Downstream: Q16	SPT5: Financing, Competitiveness & Collaboration	• Partnerships and networks • Supplier ecosystem availability • Joint studies / technology transfer • Capability building via collaboration • Execution support and shared-risk arrangements
SQ6. How is technological readiness framed (installed base readiness, retrofit limits, organizational capability)?	Upstream: Q18–Q19 Midstream: Q18–Q19 Downstream: Q18–Q19	SPT1: Strategic Roadmaps & Value-Chain Positioning (readiness framing) + SPT4 (proof capacity)	• Readiness ratings / maturity language • Retrofit constraints / installed-base limits • Capability gaps (skills, data systems) • Sequencing logic (what comes first) • Benchmarking and learning loops

Table 4.11b

From Supplier Interview Questions to RQ3 Sub-Questions and Themes: Technology Suppliers (n = 3)

Sub-questions (RQ3)	Related supplier	Theme title (TST)	Codes
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	interview questions		
SQ1. Which local country conditions most shape project feasibility (grid strength, water scarcity, local skills)?	Q1, Q12, Q13, Q19	TST2: Energy & Power Stability under Renewable Constraints + TST5 (feasibility constraints)	• Weak-grid operability and grid-code constraints • Water scarcity and water-management requirements • Local capability gaps (automation/maintenance/hydrogen systems) • • Site-condition dependency
SQ2. How do policies and incentives affect bankability and timing of adoption?	Q20, Q11	TST5: Deployment Feasibility & Policy Dependency	• Incentives and de-risking supports • Cost premium problem framing • Conditions for investor attractiveness • “Timing” logic (when scaling becomes viable)
SQ3. How is adoption enabled through collaboration and execution ecosystems in MENA?	Q17, Q18	TST5: Deployment Feasibility & Policy Dependency	• Execution strategy in-region • EPC/delivery structuring • Risk allocation and guarantees • Coordination with utilities/regulators • Supply-chain and commissioning capability
SQ4. How do resource constraints (limited hydrogen availability, local logistics) shape adoption pathways and sequencing?	Q2, (plus feasibility framing in Q17–Q18)	TST1: Flexible Green-Steel Technology Architectures + TST5	• Flexibility under hydrogen scarcity • Phased adoption sequencing • Avoiding stranded assets • Infrastructure contingency planning

The RQ3 findings show that green-steel adoption across MENA is not explained by technology availability alone; instead, adoption was reported as an interaction outcome between (i) country conditions, (ii) international market and regulatory “proof”

expectations, (iii) policy credibility and enabling rules, (iv) economic capability and bankability, and (v) collaboration and execution ecosystems. Across the steel-producer interviews, country conditions entered adoption logic mainly through energy-system constraints and input availability (SPT3), where firms described that route ambition and adoption pace are bounded by grid reliability, electricity price and access structures, renewable integration options, and the practical readiness of hydrogen supply systems. At the same time, international regimes and export-facing requirements raised the evidence threshold for adoption: participants repeatedly framed competitiveness as dependent on whether decarbonisation claims can be made auditable and acceptable to external stakeholders (SPT4), which connects adoption to MRV capacity, certification recognition, and product-footprint credibility rather than to emissions reduction actions alone. Policy instruments mattered when they reduced uncertainty and made projects investable: firms linked adoption momentum to stable rules and permissions (e.g., for captive power, long-term procurement, grid connection, and hydrogen planning) and to incentive structures that de-risk first movers (SPT5). Economic capacity manifested through limitations in financing access and approval processes (SPT5). Specifically, more extensive adoption was deemed more achievable when risk could be contractually distributed, financial arrangements could be structured, and delivery partners could ensure performance. Collaboration functioned as the principal method for practical diffusion (SPT5); in particular, partnerships, supplier ecosystems, and networks centered on capability-building were recognized as mechanisms that fostered shorter learning cycles and reduced execution risk.

Interviews with suppliers corroborated this interaction model from the vendor perspective: feasibility and timing were presented as contingent upon local factors, including grid stability, water availability, and the existing skills base (TST2/TST5), whereas policy incentives and de-risking strategies were characterized as critical factors in determining investment readiness (TST5). Furthermore, suppliers highlighted that adoption is expedited when projects are organized within regional execution ecosystems (TST5) and when plant designs are adaptable to uncertain infrastructure development (TST1). In summary, RQ3 suggests that adoption accelerates when system conditions and institutions are in alignment (energy + proof + policy + finance + collaboration), and conversely, it decelerates when a single external constraint becomes a binding factor beyond the firm's control.

4.4 Phase 2: Consortium Value Chain Model (Mega-Hub), and KPI operationalization.

Phase 2 translates the qualitative findings from Phase 1 into practical application, thereby constructing a framework for consortium design and the assignment of country-specific roles within the MENA green-steel sector. This phase, informed by the thematic analysis of 21 semi-structured interviews, organizes the identified patterns and synthesizes the core messages into a phased value-chain model, which includes clearly delineated stage gates.

This phase is structured into three principal sections. The initial section introduces the consortium's value-chain model, outlining its three phases—upstream, midstream, and downstream. It also explains how roles are specialized among the participating

countries and specifies the conditions that determine when each stage is ready. Following this, the KPI operationalization section (KPI dictionary) is presented. The subsequent section delineates and elucidates the indicators pertinent to each phase, encompassing precise definitions, measurement units, preferred data sources, and boundary assumptions to facilitate a uniform comprehension. Following this, the scoring methodology is described, detailing the normalization procedures and weighting factors used to convert Key Performance Indicator (KPI) data into stage readiness scores and role-fit classifications. This approach promotes transparency and facilitates the verification of results.

Table 4.12 summarizes the model’s key messages by stage gate.

Table 4.12

Key messages of the three-stage MENA green-steel consortium value-chain model

#	Consolidated key message	What it means in practice	Main stage gate
1	Consortium logic (system-level, not site-level): green steel feasibility is a value-chain configuration problem requiring role specialization.	Country readiness is interpreted by role-fit rather than one national score; roles are positioned as feedstock anchors, power/H ₂ + DRI/EAF hubs, and market/finance gateways.	Cross-cutting (applies to all stages)
2	Upstream gatekeeper: DR-grade feedstock access and supply security are binding constraints.	Without reliable DR-grade inputs (and stable inbound supply routes), midstream pathways become fragile and the upstream Scope 3 foundation (materials + inbound logistics) is difficult to defend.	Stage 1
3	Midstream feasibility is integrated: scalable pathways require coordinated power → H ₂ → DRI/HBI → EAF readiness.	Feasibility depends on sequencing and integration of infrastructure and operations; fragmented projects increase cost and operational risk because the route requires system coordination, not only equipment purchase.	Stage 2
4	Scope 2 integrity is decisive: electricity emissions and credibility can determine whether output is “green.”	If grid emissions are high or low-carbon electricity is not credible (including additionality where relevant), Scope 2 can dominate the footprint, especially for EAF	Stage 2

		and electrolysis-based hydrogen pathways.	
5	Scope 1 reductions are route-specific: decarbonization requires pathway-specific operating packages.	Emissions reduction depends on the selected route and its operating package (e.g., DRI fuel switching and H ₂ substitution; EAF charge strategy and controls; efficiency/yield improvements), not generic best-practice claims.	Stage 2
6	Market/proof gate: adoption requires auditable footprint proof and Scope 3 governance aligned with buyer and regulatory requirements.	Market access increasingly depends on MRV/EPD/product-passport readiness and transparent cradle-to-gate accounting, including Scope 3 governance using AD×EF logic under CBAM-like pressures.	Stage 3
7	Economics and bankability gate: bankable structures determine whether projects scale beyond pilots.	Scale-up requires credible cost and risk allocation (CAPEX/OPEX drivers, offtake strength, risk-sharing); financing conditions bridge pilots to corridor deployment and shape investment sequencing.	Stage 3 (primary), Stage 2 (feasibility constraint)

Note: Scope 1 refers to direct process emissions, Scope 2 to electricity-related emissions, and Scope 3 to supply-chain emissions. MRV/EPD refers to audited footprint reporting and Environmental Product Declarations; AD*EF refers to activity data and emission factors used in Scope 3 accounting.

4.4.1 MENA Consortium Value-Chain Model (Mega-Hub): Three Stages, Role Specialization, and Stage-Gate Readiness Logic

This part explains the suggested three-stage consortium value-chain model for green steel in MENA. The model is made based on the combined messages from the qualitative findings, which is supported by the content analysis. The main idea is that the transition to green steel in the region must be seen as a value-chain system, and not just as a change in technology at the site level. In the interviews, decarbonization was often described as a complete package. This package includes choices about production routes and operating practices (Scope 1), integration and credibility of electricity and hydrogen

(Scope 2), and governance of traceability and supply chain (Scope 3). Moreover, the practical application of this depends on several factors, such as how well it can be delivered, the existing rules, and the available financial resources.

Therefore, the model uses a stage-gate structure. Each stage has a set of important criteria that affect the project's feasibility and its potential for growth.

A “gate” in this thesis refers to a binding constraint. If the gate is weak, then the consortium pathway becomes high-risk, high-cost, or not credible for market adoption. The stage-gate logic also helps the consortium idea, because countries in MENA have different strengths like resources, power systems, industrial base, logistics, and export exposure. So, the model uses role specialization, where countries can give their contribution to the system in different roles instead of being judged by one overall score.

Stage 1 (Upstream Gate): Can the corridor secure DRI-compatible feedstock reliably?

Stage 1 is about preparing upstream, especially for DR-grade feedstock access, quality, and making sure the supply is secure. The interviews often showed this upstream condition as an important factor for scaling hydrogen-DRI/EAF. The idea is that if we cannot get reliable DR-grade materials or have good access to them through trade and logistics at a large scale, then the consortium will not be able to stabilize the midstream route. Also, the upstream part, especially the materials and inbound logistics part of Scope 3, will stay weak and hard to defend.

In practical way, Stage 1 is asking if a country can be a feedstock anchor. This can be done directly by using resources and processing, or by having secure trade and

logistics position. This does not mean that countries which do not have strong upstream conditions are not included in the consortium. Instead, it means their contribution is more probably in other roles (for example, as production hubs that depend on imported feedstock through corridors, or as downstream gateways), while the consortium creates the corridor logic to handle supply risk.

Stage 2 (Midstream Gate): Can the system produce at scale with credible low-carbon energy and stable operations?

Stage 2 checks if low-carbon steelmaking can be used and grown with an integrated midstream setup. The model sees feasibility like a connected chain of readiness. This includes low-carbon electricity, hydrogen support and logistics, DRI/HBI capacity and storage, and EAF readiness. A important message from the interviews is that projects which are fragmented or isolated can increase cost and operational risk, because the success of the route relies on system integration, not just on the equipment itself.

A main part of Stage 2 is Scope 2 integrity, because pathways that use a lot of electricity (like EAF operations and hydrogen production through electrolysis) are very sensitive to emissions from the grid. If the electricity supply is high in carbon or if low-carbon electricity is not reliable, Scope 2 can have a big impact on the footprint and lessen the benefits of other improvements. So, the model puts electricity emissions and renewable credibility as important factors in midstream readiness, including the logic of additionality when it is relevant. At the same time, the model also shows that Scope 1 reductions are specific to each route, which means the operational package relies on the pathway. For example, this includes fuel switching and hydrogen substitution in DRI,

charge strategy and control improvements in EAF, and also efficiency and yield improvements.

Countries that are strong in Stage 2 are seen as energy or hydrogen and production centers in the group. The reason for this is that they can support large-scale, low-carbon production with less risk of integration.

Stage 3 (Downstream Gate): Can the product be credibly proven, accepted by buyers/regulators, and financed at scale?

Stage 3 talks about the conditions which make green steel to be credible, tradable, and scalable. Evidence from interview showed that adoption is more and more influenced by needs of external buyers and rules. So, downstream readiness needs the ability to give proof of product footprint that can be checked, like cradle-to-gate footprinting and an MRV/EPD/product-passport method. Also, it needs clear management of Scope 3 using an activity-data*emission-factor (AD*EF) logic. Without these proof systems, it is hard to make “green” claims into business, and the consortium cannot easily reach premium or regulated markets.

Stage 3 also includes the conditions for scaling that connect pilots to industrial deployment, especially in terms of economics and bankability. The model conceptualizes financeability as a critical determinant, functioning as a threshold for projects aspiring to progress beyond the demonstration phase. This encompasses pragmatic considerations, including the reliability of off-take agreements, the frameworks for risk distribution, and the prerequisites for securing financing, such as indicators of capital costs and susceptibility to country-specific risks. Nations demonstrating robust capabilities in Stage

3 can serve as facilitators and enablers, thereby bolstering market access, establishing credibility, and assisting in the financial structuring of consortium-led initiatives.

In essence, the model’s perspective transcends a singular national performance metric when assessing readiness. Instead, the process uses gates at each stage to evaluate the suitability of a role within a consortium. These gates are: feedstock anchors in Stage 1, energy or hydrogen and production hubs in Stage 2, and market, credibility, and bankability gateways in Stage 3.

4.4.2 KPI Operationalization and Role in the Mega-Hub (KPI Dictionary)

The three-stage consortium value-chain model is functional because of a Key Performance Indicator (KPI) dictionary. This dictionary clearly defines the specific indicators used to assess readiness at each stage gate.

The KPI dictionary changes the stage-gate questions from Section 4.5.1 into requirements that can be measured as evidence. It also makes standard how each indicator is used in the model by writing down its purpose, preferred unit, and measurement intention. So, the KPI dictionary works like a common way to measure for evaluating: Stage 1 readiness to get DRI-compatible feedstock, Stage 2 feasibility to produce at large scale with reliable low-carbon energy and stable operations, and Stage 3 readiness to prove, commercialize, and finance green steel at large scale. Table 4.13 summarizes the KPI set and the preferred units used in this study.

Table 4.13

KPI Dictionary Overview: Purpose in the Model and Preferred Unit

Code	KPI	Short definition / goal in the model	Preferred unit
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K1	Iron ore reserves	Long-term domestic feedstock base supporting upstream supply security	Mt
K2	DR-grade pellet access / pelletizing capacity	Secure access to DRI-compatible feedstock (capacity or reliable access)	Mt/year
K3	Natural gas reserves (bcm)	Transition-energy security proxy supporting early DRI baseload pathways	bcm
K4	LCOE for renewables supplying corridor	Cost competitiveness of renewable electricity for the corridor	USD/MWh
K5	Renewable electricity share	Proxy for low-carbon electricity availability in the national mix	% of generation
K6	Electricity price for steel & iron industry (USD/kWh)	Industrial electricity tariff affecting EAF and electrolysis economics	USD/kWh
K7	Delivered green hydrogen cost (to DRI gate)	Hydrogen cost at the DRI system boundary (delivered)	USD/kg H ₂
K8	Hydrogen logistics readiness (ports/pipelines/storage availability)	Infrastructure readiness to deliver and store hydrogen at scale	Index (0–100) or tier (A/B/C)
K9	HBI buffer storage-days (intermittency stabilizer)	Buffer capacity to stabilize operations under intermittency	Days
K10	EAF electricity intensity	Electricity required per tonne of steel (Scope 2 exposure driver)	kWh/t steel
K11	Specific CO ₂ emissions intensity of steel	System emissions signal reflecting route mix and electricity conditions	tCO ₂ /tcs
K12	Production method mix (BOF/EAF/others %)	Baseline route structure shaping transition complexity	% share
K13	DRI production (Mt/year)	Existing DRI base indicating industrial scaling foundation	Mt/year
K14	Water stress level (baseline scarcity constraint)	Structural scarcity constraint influencing scaling feasibility	Category (e.g., WRI Aqueduct)
K15	Inbound logistics emissions intensity (inputs to plant)	Carbon intensity of inbound corridors for key inputs	kgCO ₂ e/t delivered <i>(or)</i> kgCO ₂ e/t·km
K16	Downstream logistics emissions intensity (export corridors)	Carbon intensity of export corridors to target markets	kgCO ₂ e/t delivered <i>(or)</i> kgCO ₂ e/t·km
K17	CBAM alignment (MRV/EPD compliance readiness)	Readiness for audited footprint reporting required by regulated markets	Tier/score (0–100)

K18	Weighted Average Cost of Capital (WACC) for green steel projects	Bankability proxy capturing financing friction and risk premium	%
K19	Cradle-to-gate emissions intensity (Scopes 1–2–3)	Product footprint credibility for proof, acceptance, and comparability	tCO ₂ e/t steel (cradle-to-gate)

Based on the stage-gate structure in Section 4.5.1, the KPIs are organized into three stage-specific sets that provide the evidence needed to assess each gate.

- **Upstream gate (feedstock anchor and supply security):** (K1, K2, K3).
- **Midstream gate (credible low-carbon energy and stable operations):** (K4, K5, K6, K7, K8, K9, K10, K11, K12, K13, K14, K15).
- **Downstream gate (proof, market access, and financeability):** (K16, K17, K18, K19).

Together, the KPI dictionary provides the measurement foundation for the scoring methodology section, where the stage-specific KPI sets are normalized and combined into stage readiness scores and role-fit categories consistent with the consortium model.

4.4.3 Scoring Methodology: From KPI Evidence to Stage Readiness and Role-Fit

This section presents the proposed scoring methodology that translates KPI evidence into stage readiness results for the three stage gates defined in Section 4.5.1. Scoring is required because the consortium model is structured as a stage-gate system, and each gate needs an operational and consistent way to assess whether the necessary conditions are achieved. Building on the KPI dictionary in Section 4.5.2 and the KPI list and units summarized in Table 4.13, the method converts KPI values into comparable scores through normalization, applies stage-specific weights, and incorporates gate

constraints for binding conditions. The output of the method is three separate readiness scores for each country, Stage 1 (upstream), Stage 2 (midstream), and Stage 3 (downstream), rather than one single national score. These stage scores are then interpreted to assign role-fit categories within the consortium, such as feedstock anchor, energy/hydrogen and production hub, and downstream gateway/enabler. Overall, the scoring methodology provides a transparent and auditable bridge between the qualitative model logic and the KPI-based readiness assessment used in this phase.

The scoring methodology is implemented through the following procedure:

- **KPI evidence collection:** For each country (c), KPI values $x_i(c)$ are compiled using the definitions and preferred units specified in Table 4.13.
- **Stage KPI assignment:** KPI values are organized into three stage-specific sets k_U, k_M, k_D , consistent with the stage-gate logic in Section 4.5.1.
- **Normalization setup (reference points and mapping rules):** For each KPI_i , normalization parameters are specified before scoring. For Numeric KPIs, two reference points are defined: a benchmark (target) value and a weak (floor) value. For KPIs reported as categories or rubric-based ratings (e.g., readiness levels or water-stress classes), a predefined scoring rule is applied to convert each category into a standardized value on the $[0,1]$ scale.

For numeric KPIs, two reference points are defined: a benchmark (target) value B_i and a weak (floor) value W_i . The KPI direction is handled through these reference points: for benefit-type KPIs, B_i is set as the higher “good” value and W_i as the lower “weak” value; for cost-type KPIs, B_i is set as the lower “good” value and

W_i as the higher “weak” value. Numeric KPI values are then converted into a

standardized score as: $n_i(c) = \frac{x_i(c) - W_i}{B_i - W_i}$.

For rubric- or category-based KPIs, the observed value $x_i(c)$ is a class/level rather than a continuous number, so it is converted to the 0–1 scale using a predefined scoring rule. Each level is assigned a fixed score using a small number of ordered intervals (e.g., 1.00/0.75/0.50/0.25 or 1.00/0.67/0.33), so the same rule can be applied consistently across countries and combined with numeric KPIs in the stage scoring.

- **Stage-weighting:** Within each stage (g), normalized KPI scores are combined using stage-specific weights $w_{g,i}$, where $w_{g,i} \geq 0$ and $\sum_{i \in k_g} w_{g,i} = 1$
- **Gate constraints:** A gate factor $G_g(c) \in [0,1]$, is applied to represent binding conditions that can reduce readiness when critical constraints are weak.
- **Stage score calculation:** Stage readiness scores $S_U(c), S_M(c), S_D(c)$, are computed and reported on a 0–100 scale.
- **Role-fit interpretation:** The three stage scores are interpreted jointly to assign role-fit categories within the consortium configuration (e.g., feedstock anchor, energy/hydrogen and production hub, and downstream gateway/enabler).

Table 4.14 summarizes the notation, parameters, and illustrative examples used in the proposed scoring methodology.

Table 4.14

Notation and Parameters Used in the Scoring Methodology (Illustrative Examples)

Factor name/ Symbol	Short definition (in this thesis)	Example (illustrative)
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Country (c)	Country being assessed	$c = Iran$
Stage gate (g)	Model stage: Upstream (U), Midstream (M), Downstream (D)	$g = M$
KPI index (i)	KPI identifier from Table 4.13 (K1...K19)	$i = K7$
KPI direction (δ_i)	Indicates whether “higher is better” (benefit) or “lower is better” (cost) for KPI(i)	$(\delta_i) = cost$
KPI value $x_i(c)$	Raw KPI evidence for KPI(i) in country (c)	$x_{K7}(Iran) = 3.5^{USD/Kg(H_2)}$
Benchmark (target) value B_i	“Good/target” reference point for KPI(i) used in normalization	$B_{K7} = 2.0^{USD/Kg(H_2)}$
Floor (weak) value W_i	“Weak/floor” reference point for KPI(i) used in normalization	$W_i = 6.0^{USD/Kg(H_2)}$
Normalized score KPI (Numeric) $n_i(c)$	Normalized KPI score in ([0,1]) based on B_i , and W_i	$n_{K7}(Iran) = \frac{6.0 - 3.5}{6.0 - 2.0} = 0.625$
Stage KPI sets k_U, k_M, k_D	KPI sets for the three stage gates	$k_U = \{K1, K2, K3\}$
stage-specific weights $w_{g,i}$	Importance weight of KPI(i) within stage(g)	$w_{M,K7} = 0.15$
gate factor $G_g(c)$	Stage constraint factor in ([0,1]) capturing binding conditions	$G_U(Iran) = g_{K2}(Iran)$
Stage readiness scores $S_U(c), S_M(c), S_D(c)$	Final readiness score for stage(g) on 0–100 scale	$S_M(Iran) = 72$ (illustrative output)
Role-fit category $R(c)$	Role inferred from the pattern of S_U, S_M, S_D	High $S_M \rightarrow$ production hub

These definitions and symbols are used consistently in the following subsections to specify the normalization rules, weighting logic, and stage scoring formulas.

4.4.4 Stage scoring formulas

This section specifies the stage scoring equations used to compute readiness scores for the three gates defined in Section 4.5.1. Each stage score $S_g(c)$, combines

- (i) normalized KPI scores $s_i(c) \in [0,1]$
- (ii) stage-specific weights $w_{g,i}$, and
- (iii) a gate factor $G_g(c) \in [0,1]$ that represents binding conditions.

The KPI sets for each stage follow the KPI dictionary in Table 4.13.

Stage 1 scoring model (Upstream readiness score SUS_USU)

$S_U(c)$ measures upstream readiness to secure DRI-compatible feedstock reliably and support supply security for the corridor.

KPI set used: $k_U = \{K1, K2, K3\}$.

$$S_U(c) = 100 \times G_U(c) \times \sum_{i \in k_U} w_{U,i} n_i(c) \quad (1)$$

$$G_U(c) = g_{K2}(c) \quad (2)$$

where $g_{K2}(c) \in [0,1]$, is a gatekeeper function derived from the feedstock-security condition represented by K2 (DR-grade pellet access / pelletizing capacity), using the documented mapping/threshold rule.

Stage 2 scoring model (Midstream readiness score SMS_MSM)

$S_M(c)$ measures midstream readiness to produce at scale through integrated power-hydrogen-route capability under credible low-carbon energy and stable operations.

KPI set used: $k_M = \{K4, K5, K6, K7, K8, K9, K10, K11, K12, K13, K14, K15\}$

$$S_M(c) = 100 \times G_M(c) \times \sum_{i \in k_M} w_{M,i} n_i(c) \quad (3)$$

$$G_M(c) = g_{K8}(c) \times g_{K14}(c) \quad (4)$$

where $g_{K8}(c) \in [0,1]$, reflects the binding condition of K8 (hydrogen logistics readiness) and $g_{K14}(c) \in [0,1]$, reflects the binding condition of K14 (water stress constraint).

Stage 3 scoring model (Downstream readiness score SDS_DSD)

$S_D(c)$ measures downstream readiness to credibly prove, commercialize, and finance green steel at scale under market and bankability requirements.

KPI set used: $k_D = \{K16, K17, K18, K19\}$

$$S_D(c) = 100 \times G_D(c) \times \sum_{i \in k_D} w_{D,i} n_i(c) \quad (5)$$

$$G_D(c) = g_{K17}(c) \times g_{K18}(c) \quad (6)$$

where $g_{K17}(c) \in [0, 1]$, represents the proof/credibility gate based on **K17 (CBAM alignment / MRV readiness)**, and $g_{K18}(c) \in [0, 1]$, represents the bankability gate based on **K18 (WACC)**.

This scoring methodology operationalizes the stage-gate logic of the consortium model by providing a consistent procedure to translate KPI evidence into stage readiness results. The method is applied at the stage level to support role identification across upstream, midstream, and downstream functions, rather than relying on a single aggregated national score.

4.4.5 Worked Example KPI to Role-Fit (A–C)

This example used Countries A, B, and C to show how the scoring method changes KPI evidence into normalized scores, applies gate factors, and gives stage readiness outputs. To make the example clear and simple to understand, some inputs, especially rubric- and proxy-based KPIs (like K8, K9, K15, K16, K17, K18, K19), are not considered as fully verified national statistics in this case. Instead, they are built within reasonable benchmark ranges so the reader can clearly understand the scoring mechanics and get interpretable results under Equations (1)–(6).

Table 4.15 first shows the example KPI inputs for Countries A to C. With these inputs and the benchmark or floor reference points, Table 4.16 shows the gate factors and stage readiness scores that result. These scores are then explained to show what each country's likely role is in the consortium model.

Table 4.15

Input KPI Values Used in the Worked Example (Illustrative)

KPI	WEAKEST	BEST	Country A	Country B	Country C
K1	10	3800	3000	800	150
K2	0.3	40	30	12	2
K3	50	34000	1200	25000	120
K4	75	15	26	32	22
K5	1	25	15	8	21
K6	0.2	0.03	0.08	0.05	0.12
K7	10	2	4.5	3.5	5.5
K8	1	3	2	2	3
K9	2	30	10	20	16
K10	600	360	510	450	390
K11	2.4	0.7	1.5	1.35	0.95
K12	90	0	25	15	8
K13	0.2	34.1	2.6	6.5	0.9
K14	Extremely High	Medium-High	High	Extremely High	Medium-High
K15	70	10	50	25	15
K16	100	15	70	40	25
K17	1	3	2	2	3
K18	18	7	12	8.5	10
K19	3.2	1	2.3	1.9	1.3

Table 4.16

Stage-Gate Outputs (Scores) for the Worked Example

Output (0–100 unless noted)	Country A	Country B	Country C
Gate factor $G_U = g_{K2} (0 - 1)$	1.00	1.00	0.60
Stage 1 score S_U	52.4	41.3	1.6
Gate factor $G_M = g_{K8} \times g_{K14} (0 - 1)$	0.45	0.30	0.80
Stage 2 score S_M	23.5	18.4	56.6
Gate factor $G_D = g_{K17} \times g_{K18} (0 - 1)$	0.60	0.68	0.90
Stage 3 score S_D	29.7	47.8	78.1

The results in Table 4.16 give summary of three stage scores and gate factors for Countries A to C. Because the model is stage-gated, a country can show good performance in some KPIs but still get a lower stage score when a binding condition (gate factor) is not strong. This pattern helps to understand the role-fit in the consortium instead of pushing for one national ranking only.

Country A records the strongest upstream readiness ($S_U = 52.4$, $G_U = 1$), mainly because feedstock-related capacity is relatively strong (K1 and K2 closer to benchmark levels). However, its midstream readiness is limited ($S_M = 23.5$) due to a constrained integration gate ($G_M = 0.45$), and downstream readiness is also low ($S_D = 29.7$, $G_D = 0.60$). This profile fits Country A best as a feedstock anchor / supply-security contributor, while relying on other members for scalable production and market/finance enablement.

Country B. Country B passes the upstream gate score ($S_U = 41.3$, $G_U = 1$), indicating acceptable upstream access in this illustration. The main weakness is Stage 2, ($S_M = 18.4$), driven by a low midstream gate factor ($G_M = 0.30$), which signals that system-integration conditions remain restrictive. In contrast, Stage 3 is moderate ($S_D = 47.8$, $G_D = 0.68$), implying relatively better positioning for market-facing requirements and financial structuring than for hosting large-scale production. Therefore, Country B is more suitable as a downstream/structuring support participant unless targeted investments reduce the Stage 2 constraints.

Country C has a weak upstream position score ($S_U = 1.6$, $G_U = 0.60$), so it is not a feedstock anchor in this example. Its strength is concentrated in Stage 2 and Stage 3 ($S_M = 56.6$, $G_M = 0.8$; $S_D = 78.1$, $G_D = 0.90$), reflecting stronger readiness for

integrated low-carbon operations and for proof/market/finance conditions. This is consistent with a production hub and downstream gateway role, but it requires reliable feedstock corridors from upstream-strong partners.

Taken together, these profiles demonstrate how the stage-gate structure converts KPI evidence into differentiated consortium roles, upstream anchors, midstream production hubs, and downstream market/finance gateways, rather than a single national readiness score.

4.5 Summary

Chapter 4 presents the study findings and develops the basis for the proposed MENA green-steel consortium value-chain model (Mega-Hub). It first reports the qualitative results from 21 semi-structured interviews with steel producers across upstream, midstream, and downstream activities and with three technology suppliers, analyzed in NVivo using a hybrid deductive–inductive coding approach. The findings are organised by research question to show how participants described

- (i) integration of low-carbon technologies and operating practices across the value chain (RQ1),
- (ii) the system and infrastructure configuration required to scale green steel in MENA (RQ2), and
- (iii) the adoption conditions shaped by country context, market and regulatory pressures, policy credibility, financing, and collaboration ecosystems (RQ3).

Building on these consolidated messages, the chapter then translates the qualitative evidence into an operational stage-gate consortium framework. It defines three readiness gates (upstream feedstock security, midstream feasibility and Scope 2 integrity, and downstream credibility and scaling enablers), specifies the stage-linked KPI dictionary used to represent these gate conditions, and presents the scoring methodology that normalises KPI evidence, applies stage-specific weights, and incorporates gate constraints to generate stage readiness scores and role-fit categories. Overall, the chapter links interview-based findings to a structured model and a transparent KPI operationalisation approach that supports the thesis model development in the next chapter.

CHAPTER V: DISCUSSION, IMPLICATIONS, RECOMMENDATIONS, AND CONCLUSION

5.1 Introduction

This study addresses the green-steel transition in the MENA region as a value-chain integration and coordination problem, rather than a single-technology substitution, shaped by uneven infrastructure readiness, fragmented market and policy signals, and feasibility constraints including CAPEX intensity, energy-system reliability, and the credibility requirements of low-carbon claims. Accordingly, the transition toward green steel as net-zero steel is framed as a step-by-step, stage-specific decarbonization pathway in which each value-chain segment deploys the most feasible technologies, such as energy-efficiency and digital optimization in the near term, expanded electrification and circular-material use (e.g., scrap) as enabling conditions improve, and deeper abatement options including hydrogen-based DRI, renewable-powered EAF, and CCUS (carbon capture, utilisation, and storage) where technically and economically justified, scaled through a stage-gated consortium model once readiness thresholds are met, while embedding sustainability principles through life-cycle thinking, Scope 1–3 integrity, and transparent ESG-aligned governance of impacts and trade-offs. The purpose of the research was to develop and operationalize a consortium-based transition model supported by a KPI-driven stage-readiness framework that can guide sequenced decarbonization planning and coordination across actors.

A sequential mixed-methods approach was utilized. Initially, semi-structured interviews were conducted with stakeholders across the steel value chain, including both industry participants and technology vendors. The objective was to identify the key factors, obstacles, and integration requirements inherent at each stage of the process: upstream, midstream, and downstream.

In Phase 2, these insights were transformed into a three-stage collaboration model and a structured KPI and weighting logic designed to facilitate transparent, evidence-based readiness assessment and decision-making.

The study has limitations regarding sample representativeness, incomplete or inconsistent secondary data for specific KPIs, and the intrinsic subjectivity of expert-based weighting methodologies; therefore, the framework is presented as a decision-support architecture rather than a definitive country-ranking result. Ethical considerations encompassed informed permission, participant anonymity, secure data management, and vigilance over potential conflicts of interest due to the researcher's professional affiliation with the sector.

This chapter begins by analyzing the findings for each research question in relation to the literature from Chapter 2. It then outlines succinct theoretical and practical implications, including the consortium's contribution, offers recommendations for application and future research, and concludes with a summary of the study's key contributions.

5.2 Discussion of Findings

Section 5.2 presents the results pertaining to each research question (RQ1–RQ3) and elucidates their implications for the viability and expansion of green steel pathways within the MENA steel value chain. The following analysis interprets the study's results, focusing on the main research question and goals. It assesses how well the findings support, add to, or refine the existing research discussed in Chapter 2.

The primary focus of this section is to clarify the significance of the findings and their connection to the study's conceptual framework. The wider theoretical and practical ramifications of these findings are subsequently addressed in Section 5.3.

5.2.1 Discussion of Findings for RQ1

RQ1. How can low-carbon technologies and operational practices be integrated across the steel value chain to reduce emissions while maintaining economic feasibility and competitive advantage?

The results for RQ1 indicate that participants do not perceive decarbonization in MENA as merely a substitution of one manufacturing technique for another. Instead, they define integration as a coordinated value-chain operational package in which emissions reduction must occur without compromising throughput, unit cost, or market acceptance. This approach aligns with literature that conceptualizes steelmaking as an integrated upstream–midstream–downstream system, employing a value-chain framework where competitive performance hinges on the coherence of various activities rather than on discrete process selections (Acharyulu, Subbaiah and Rao, 2015; Conejo, Birat and Dutta, 2020b; Knopp, 2022; Mallett and Pal, 2022; Dixon, 2023). It also supports the three-phase transition narrative of optimization, transition, and achieving green steel, which

implies staged integration rather than immediate route replacement (Bataille *et al.*, 2018; IEA, 2020a, 2020b, 2022; Fleischanderl, 2023).

For steel producers, the research indicates that integration is associated with five interconnected mechanisms: the roadmap's sequencing, plant-level actions concerning processes and routes, the integration of energy and fuel inputs, auditable governance and performance control, and investment and delivery plans designed to mitigate execution risk. These combined approaches demonstrate that integration transcends a purely technological concern within the plant.

It is also a challenge of coordinating organizations and economies that is affected by the quality of the infrastructure, the risk of costs, the ability to verify, and the bankability of projects. This finding supports earlier research on the importance of sustainability, regulatory compliance, and cost considerations in the steel industry's transition processes. Moreover, it adds to the existing literature by showing that companies view these factors as interconnected, rather than as separate issues (Conejo, Birat and Dutta, 2020c; Knopp, 2022; Tolettini and Di Maria, 2023; Fan and Friedmann, 2021; Hall, Zhang and Li, 2021; Carvalho, 2024).

The cross-stage pattern simplifies the understanding of integration logic. Midstream respondents prioritize efficiency retrofits, automation enhancements, and recovery systems, as the emissions-cost trade-offs are primarily evident in primary production. Conversely, downstream respondents emphasize governance, reporting precision, and robust product claims, given that competitiveness hinges on consumer

confidence and market standing at this stage. This distinction is significant, demonstrating that integration strategies are not uniform throughout the value chain.

Instead, it changes shape at each level dependent on the key technological and business pressures. The results also explain why people typically say that integration happens in stages rather than all at once. From a technical point of view, hydrogen-based reduction is quite attractive. However, the high prices and lack of infrastructure make corporations focus on upgrading the routes they already have while leaving their choices open for the future (Pimm, Cockerill and Gale, 2021; Lopez *et al.*, 2023; Basirat, 2024b). Similarly, scrap-based decarbonization is treated as important but limited by availability, quality, and price volatility, which is consistent with literature showing structural constraints in collection, sorting, and processing systems (Bataille *et al.*, 2018; Hall, Zhang and Li, 2021). In this respect, the findings qualify strands of the literature that imply that pathway availability by itself is enough to support rapid adoption. In the MENA context, pathway feasibility is filtered through operating conditions and risk exposure.

Technology suppliers reinforce the same logic through engineering and delivery choices. The findings indicate that suppliers support integration through flexible and upgradeable architectures, grid-operability solutions for high-power operations, metallics flexibility across scrap and DRI blends, and environmental packages embedded in plant design rather than appended later. This aligns with literature showing that electrification readiness, power-system conditions, and digital capability increasingly shape competitiveness in steel decarbonization (Datta and Bhattacharjee, 2020; Hall, Zhang and

Li, 2021; Rangelov *et al.*, 2021; Andrioli *et al.*, 2023; Tolettini and Di Maria, 2023a, 2023b).

In light of the theoretical frameworks discussed in Chapter 2, the process of integration appears to be both dependent on existing capabilities and shaped by practical limitations. The Resource-Based View (RBV) is particularly relevant here, as companies need strong operational, governance, and coordination capabilities to successfully integrate low-carbon strategies in a competitive environment (Andersén, 2021; Hofstetter *et al.*, 2021). Furthermore, Stakeholder Theory and Corporate Social Responsibility (CSR) help us understand how external expectations are increasingly shaping acceptable performance standards and the justification of claims (Agrawal *et al.*, 2023; Sharma, Anand and Sharma, 2023; Salih, 2024). Ecological Modernization Theory is reflected in the emphasis on technological and organizational upgrading as a route to environmental improvement without abandoning competitiveness (Lahti, Wincent and Parida, 2018; Hofstetter *et al.*, 2021). At the same time, the logic of the circular economy remains relevant in areas such as scrap use, recovery, and resource efficiency. In contrast, the findings suggest that these opportunities are limited by real constraints on inputs, rather than being available without limits (Bataille *et al.*, 2018; Nechifor *et al.*, 2020; Hall, Zhang and Li, 2021).

Overall, the discussion of RQ1 shows that successful integration in MENA depends on whether firms can coordinate process changes, infrastructure conditions, governance capability, and investment sequencing across the value chain. In this sense,

decarbonization is not simply a separate technical option. It is a coordinated industrial process that must take account of both operational and business constraints.

5.2.2 Discussion of Findings for RQ2

RQ2. What technical pathways and infrastructure configurations, are required to scale green-steel production in MENA?

The findings pertaining to RQ2 indicate that the expansion of low-carbon technologies within the MENA region is less contingent upon their theoretical feasibility and more dependent on the practical conditions necessary for their effective implementation. This interpretation aligns with existing scholarship concerning the increasing significance of climate governance, the imperative for industries to mitigate carbon emissions, and the evolving expectations of the market. Furthermore, it suggests that the diffusion of technology is influenced not only by its technical sophistication but also by the preparedness of the existing infrastructure and the ease of its deployment.

The evidence demonstrates three primary causes for scale in all cases. The increasing significance of governance and regulation constitutes the initial consideration. This evolution engenders heightened urgency, subsequently shaping investment strategies by transforming climate objectives and industrial policies into tangible incentives and constraints (United Nations, 2015; Vogl, Åhman and Nilsson, 2020). The second is market pull, especially when low-carbon steel may generate money by having a product that is different from others in a way that can be trusted and checked (Datta and Bhattacharjee, 2020; Rangelov *et al.*, 2021; Tolettini and Di Maria, 2023a). The final point is about how mature and upgradeable technology is. This approach simplifies

deployment, as pathways can be incrementally integrated with pre-existing resources, thereby avoiding the need for a complete system overhaul (Bataille *et al.*, 2018; Fleischanderl, 2023). These considerations collectively demonstrate that scaling transcends the mere transition from pilot projects to expansive implementations.

It depends on whether technical pathways can handle the reality of business and infrastructure. The results also reveal that scaling is generally limited by a few feasibility constraints that behave like system limits. It is very important to know about the electricity system because the reliability of the grid, the quality of the power, the intensity of the emissions, and the structures of the tariffs all affect the environment and the competitiveness of costs in pathways that led to electrification (Hall, Zhang and Li, 2021; Andrioli *et al.*, 2023). A second key problem is the cost of hydrogen and the lack of confidence about infrastructure. People think that hydrogen-based reduction is an excellent idea from a technological point of view, but it is now constrained by costs, availability, logistics, and contract uncertainty (Pimm, Cockerill and Gale, 2021; IEA, 2023; Lopez *et al.*, 2023; Basirat, 2024b). A further constraint stems from the accessibility of scrap materials, their inherent quality, and the volatility of their market prices. This observation aligns with existing scholarship indicating that the efficacy of collection, sorting, and processing infrastructures diminishes under conditions of escalating demand (Bataille *et al.*, 2018; Liu *et al.*, 2021). A subsequent limitation pertains to the financial risks and operational complexities associated with project implementation. Substantial capital investments, the cost of capital, and uncertainties regarding the pace of scaling impede financial institutions' willingness to provide

funding, thereby hindering the transition from pilot projects to widespread deployment (Fan and Friedmann, 2021; Carvalho, 2024). Moreover, these findings contribute to a more nuanced understanding of how supportive systems can help transform isolated adoption into a more widely accepted and credible practice.

A lot of the time, people argued that measurement, traceability, and auditable verification are more than just extra reporting responsibilities; they are like business infrastructure. It's hard to get into key markets without convincing proof of emissions at the product level, and it's not apparent how much money is worth investing in the transition (Datta and Bhattacharjee, 2020; Rangelov *et al.*, 2021; Tolettini and Di Maria, 2023a, 2023b). At the same time, supplier capabilities help to improve scale when modernization methods include being ready for electrification, being compatible with hydrogen, and having digital reporting systems from the start instead of considering them as things to add later (Vogl, Åhman and Nilsson, 2018, 2021; Bataille, 2020). This makes it apparent which parts of the book are about technology. It indicates that the choice of equipment doesn't just determine scalability; it also depends on how well the surrounding operating and proof environment is set up.

From the theoretical perspective of the study, these patterns indicate that size is shaped by external demands for legitimacy and the development of internal competencies. Understanding Stakeholder Theory and CSR can help you understand why evidence requirements and market credibility are becoming more and more crucial when making investment decisions. RBV helps us understand why organizations who are better at managing energy, controlling operations, and running their businesses are better able to

turn pressure to be more sustainable into a competitive advantage. Ecological Modernization Theory is still significant since the data show that scaling depends on improving technology and organization, but it doesn't go easily. People also embrace Circular Economy thinking, especially when circular inputs are seen as part of transition paths. The results show, however, that material circularity is limited by actual supply conditions and not just assumed (Lahti, Wincent and Parida, 2018; Andersén, 2021; Hofstetter et al., 2021; Wen-yi, 2005; United Nations, 2015; Vogl, Åhman and Nilsson, 2020; Nechifor et al., 2020; Liu et al., 2021; S. Agrawal et al., 2023; Sharma, Anand and Sharma, 2023; Salih, 2024).

In conclusion, the talk about RQ2 shows that the green-steel scale in MENA should be thought of as a challenge of feasibility because of the limitations of infrastructure, input, financing, and proof systems. It's not simply a matter of which technologies are available; it's also a matter of which paths can flourish well in real-world situations.

5.2.3 Discussion of Findings for RQ3

RQ3. How do country conditions, international regulatory frameworks, economic capabilities, technological readiness, and natural resource endowments, interact with policy instruments and international collaboration mechanisms to drive adoption of green-steel innovations across MENA?

The findings for RQ3 indicate that green-steel adoption in MENA is best explained as an interaction problem rather than as a single-factor choice. Participants consistently described feasibility as the result of whether several conditions align at the

same time, including natural resource endowments, enabling infrastructure, technology integration capability, governance and proof systems, and financing capacity under CAPEX-intensive transition options. This interpretation is consistent with transition literature that treats industrial decarbonization as a staged and constraint-driven process in which adoption accelerates only when multiple binding conditions are addressed together rather than separately (Hall, Zhang and Li, 2021; Bataille et al., 2018; IEA, 2022).

A first interaction mechanism concerns the relationship between natural resource endowments and industrial infrastructure. Renewable potential or gas availability becomes relevant to green-steel adoption only when electricity reliability, power quality, and integration capability are strong enough to support high-power operations and electrification economics. Likewise, hydrogen pathways are strategically appealing, but their structural limitations remain unless supply, logistics, and contractual arrangements develop together on a large scale (Hall, Zhang and Li, 2021; Pimm, Cockerill and Gale, 2021; Voraberger *et al.*, 2022; Lopez *et al.*, 2023). This means that resource abundance alone does not create adoption readiness; it must be translated into usable industrial capability.

A second interaction mechanism involves the relationship between international regulatory frameworks, market access, and governance capability. Respondents emphasized that the commercial value of low-carbon steel increasingly depends on the ability to produce auditable product-level emissions evidence and traceability across the value chain. In this context, regulatory pressure and customer requirements act not simply

as general drivers, but as selection mechanisms that favor regions and firms capable of proving performance and disadvantage those that cannot. This interpretation extends the literature by showing that regulatory alignment is not only a compliance matter. It increasingly shapes commercial inclusion in low-carbon markets (Datta and Bhattacharjee, 2020; Rangelov *et al.*, 2021; Tolettini and Di Maria, 2023a, 2023b).

A third interaction concerns economic capability, policy design, and execution risk. Even when technology is technically available, how quickly it's adopted is strongly influenced by how much capital is needed, the cost of financing, and the uncertainty during the initial stages. The findings suggest that policies are most effective when they directly reduce these obstacles. This can be done by lowering the cost of capital, sharing the risks of early investments, or stabilizing the costs of energy and other inputs, rather than just showing ambition. This view is supported by existing research, which shows that decisions about transitions are shaped by both the economics of investment and the costs within the energy system (Fan and Friedmann, 2021; Carvalho, 2024).

Finally, the findings highlight international collaboration mechanisms as an important way of relaxing constraints in a region marked by heterogeneous strengths and weaknesses. Several adoption-critical conditions, such as DR-grade feedstock optionality, hydrogen corridors, shared verification standards, and financing structures, are difficult to secure efficiently through isolated firm-level or single-country initiatives. In this respect, the findings diverge from transition approaches that remain largely national in framing. In the MENA context, feasibility is partly regional because complementary strengths are distributed unevenly across countries. The consortium model developed in this thesis is

therefore analytically important because it provides a coordination logic for combining those complementary roles and reducing corridor-level risk.

Viewed through the theoretical lenses of the study, the discussion of RQ3 shows that green-steel adoption in MENA depends on the interaction between resources, institutions, market governance, and coordination capability. RBV remains relevant, but the findings suggest that advantage cannot be understood only at the firm level because several enabling conditions are distributed across the wider value chain and regional environment. Stakeholder Theory and CSR help explain why international market rules and legitimacy pressures shape adoption, while Ecological Modernization Theory helps explain why policy, technology, and organizational upgrading must progress together. The findings also extend Circular Economy thinking by showing that material efficiency and circular input use matter, but only within a broader system of energy, infrastructure, and governance conditions.

Overall, the discussion of RQ3 shows that regional adoption in MENA is not determined by whether one country possesses a single superior condition. It depends on how different conditions interact and whether these can be coordinated into a credible transition pathway. In this sense, regional heterogeneity is not only a source of fragmentation; when properly organized, it can also become a source of complementarity.

5.3 Implications of the Findings

The findings of this study have important implications for both the theoretical understanding and the practical use of green-steel transition strategies in the MENA region.

This section will explore the broader impacts of these results on conceptual understanding, strategic planning, and the design of practical implementations, whereas section 5.2 specifically addressed the relationship between the findings, the research questions, and the existing body of literature. The implications are presented, beginning with a theoretical overview and then addressing each research question individually.

5.3.1 Theoretical Implications

This study contributes to existing scholarship by illustrating that the green-steel transition within the MENA region is best understood as a complex, staged value-chain coordination challenge, rather than simply a process of technological adoption at either the firm or national level. The findings indicate that the successful advancement and expansion of this transition are contingent upon the concurrent harmonization of several critical elements.

These conditions include operational capacity, enabling infrastructure, governance credibility, and financial feasibility across upstream, midstream, and downstream activities. A key theoretical implication is that the significance of various elements is secondary to the alignment of these elements, which is the main factor determining the feasibility of transition in this specific geographical area. Moreover, the findings improve the theoretical frameworks used in this study.

From a Resource-Based View (RBV) perspective, the competitive advantage inherent in green steel production stems not solely from proprietary technologies or internal operational efficiencies. It also derives from the ability to coordinate effectively, maintain route flexibility, uphold auditable systems, and execute transitions

systematically. In addition, the findings, based on Stakeholder Theory and Corporate Social Responsibility (CSR) principles, suggest that external pressures go beyond just following regulations or using simple public relations strategies.

They are becoming market forces that determine the credibility of different strategies and product claims. Moreover, the results support Ecological Modernization Theory, which suggests that environmental improvement and industrial competitiveness can coexist. However, they also show that this is only possible if the infrastructure is ready, the institutions are credible, and the sequencing capacity is there. The core principles of the Circular Economy remain important, especially in waste management, material recovery, and using resources efficiently.

However, the results show that circularity in steel is limited by factors like supply, quality, and pricing. These findings together endorse a more cohesive theoretical framework wherein the transition to green steel is elucidated through the interplay of capabilities, constraints, and coordinating mechanisms. Consequently, the thesis contributes a meso-level perspective to the literature by demonstrating that, in heterogeneous regions like MENA, decarbonization cannot be sufficiently understood by firm-level analysis or macro-level policy framing alone. The main challenge, however, is creating these corridors. The division of responsibilities, the preparation needed at each stage, and the benefits of international cooperation all play a role in this.

5.3.2 Implications for RQ1

RQ1's implications indicate that integration ought to be approached as a system-design and sequencing challenge, rather than as a collection of discrete technology

projects. In real life, judgments on investments and operations should be based on whole-system limits including electricity reliability and price exposure, metallics flexibility, ramp-up risk, and the trustworthiness of environmental claims. This means that the best way to protect the future is not to replace the entire route right away, but to use no-regret packages in a disciplined way. These packages include things like efficiency improvements, automation, recovery systems, and flexible plant designs. These features help reduce emissions while also maintaining productivity.

Another important point is that decarbonization isn't just a technical issue. Competitive integration is becoming more reliant on the capacity to facilitate process change through reliable reporting and verification mechanisms, since market acceptance is influenced not only by the methods of steel production but also by the demonstration of performance. Another implication is that the conditions needed for competitive integration, such as a reliable supply of low-carbon electricity, shared infrastructure, and consistent verification standards, cannot be guaranteed by organizations acting independently. Therefore, coordinated implementation strategies across the entire value chain are more likely to be effective.

5.3.3 Implications for RQ2

The results of RQ2 suggest that plans to increase green-steel production in MENA should focus on what is possible within strict limits, not on what technology is available in general. The research points to the fact that the magnitude of a project depends on whether it can still be financed and run in real-world situations where the power grid is exposed, hydrogen costs are high, infrastructure is unclear, the scrap market is volatile,

and funding is tight. So, while choosing a project, cost-and-risk robustness should come before pathway prestige.

The findings further indicate that modular and upgradeable configurations are preferable, as they preserve flexibility in the face of evolving hydrogen and power system technologies. Simultaneously, the requirements for scaling extend beyond mere technical preparedness. Product-level emissions evidence and consistent assurance systems work as commercial infrastructure since scale without credible proof doesn't guarantee long-term access to the market. So, the policy implication is not just to encourage green technology. It is also to make enabling systems less uncertain by making power frameworks, hydrogen infrastructure, and offtake conditions more reliable, developing the circular input market, and standardizing assurance standards.

5.3.4 Implications for RQ3

Research Question 3 has broader and more strategic implications because it examines the combined effects of national circumstances, policy tools, market governance, and collaborative methods. The results suggest that efforts for adopting green steel in MENA should focus on how different factors interact with each other instead of just one aspect that is better than the others. Natural resources, technical availability, and policy ambition are individually insufficient on their own; adoption becomes more possible when funding conditions, infrastructural preparedness, governance competence, and market-facing proof systems align at the same time.

This means that we should measure how well a policy works less by how ambitious its goals are and more by how well it can lower bankability frictions, execution

risk, and uncertainty in energy and input systems. The results further support the idea that MRV and EPD preparedness should be seen as infrastructure for accessing the market, not only as instruments for following the rules. The findings suggests that geographical variability should not solely be seen as an obstacle. When organized through job specialization, stage-based coordination, and KPI-based gate proof, such heterogeneity can become a source of complementarity within a scalable regional transition pathway.

5.4 MENA Consortium Value-Chain Model (Mega-Hub) & Porter Alignment, Technology Enablement, and Implementation Logic

This section positions the consortium value-chain model developed in Chapter 4 of this study, as a central implication of the study by showing how the stage-gate readiness logic converts the qualitative findings into a deployable coordination approach for the MENA green steel transition. While literature review section in Chapter 2 mapped the technology options, policy drivers, and enabling roles of technology suppliers and digitalization, it did not operationalize a decision architecture for

- (i) assigning complementary roles across countries with heterogeneous strengths or
- (ii) determining when a pathway is feasible, credible, and scalable under binding constraints.

The thesis contribution is to operationalize coordination through a three-stage gate structure, upstream feedstock security, midstream low-carbon energy and stable operations, and downstream proof/market acceptance and financeability, combined with role specialization and a KPI-based scoring method that translates evidence into stage

readiness and role-fit outcomes. As a result, transition planning is reframed from isolated site-level adoption decisions to a value-chain system design that links competitiveness and Scope 1–3 integrity to measurable readiness conditions and bankability.

5.3.1 Porter-Aligned Stage-Gate Mapping

To align the proposed consortium stage-gate model with Porter’s value-chain logic, this thesis interprets green steel competitiveness as the outcome of coordinated primary activities (inbound logistics, operations, outbound logistics, marketing & sales, and service) supported by enabling activities (firm infrastructure/governance, procurement, technology development, and human resource management). This adapted reading is consistent with steel-focused uses of Porter’s framework where value creation depends on cross-activity integration rather than isolated process choices, and where sustainability and compliance capabilities increasingly shape competitive performance (Acharyulu, Subbaiah and Rao, 2015; Mallett and Pal, 2022). Figure 5.1 shows that the proposed MENA Mega-Hub consortium model is aligned with Porter’s value-chain logic by structuring the three stage-gates as coordinated constraints on both primary activities (inbound logistics, operations, outbound logistics, marketing & sales, and service) and supporting activities (firm infrastructure/governance, procurement, technology development, and human resource management), thereby linking stepwise decarbonization progress to cross-activity integration rather than isolated technology choices.

However, Porter’s framework is not, by itself, a readiness or sequencing tool. The consortium model extends the Porter lens by treating stage conditions as binding

constraints (“gates”): if a gate is weak, costs rise, execution risk increases, or product credibility becomes indefensible, even when individual sites adopt low-carbon technologies. This is particularly salient in MENA because key enablers (DR-grade feedstock access, low-carbon electricity and hydrogen logistics, and auditable proof systems) are unevenly distributed and often exceed the control of single firms or single-country initiatives.

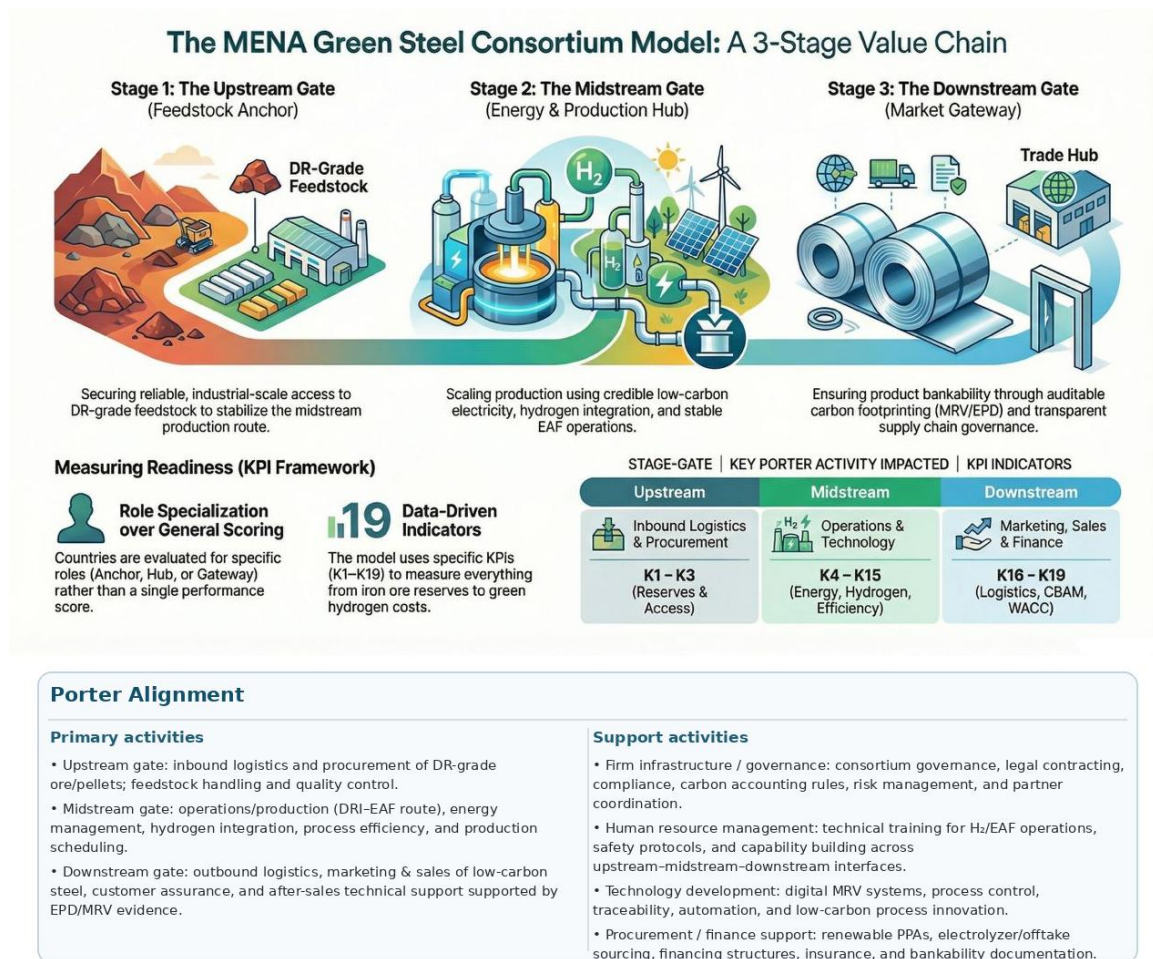


*Figure 5.1
Porter-aligned stage-gate mapping of the MENA Mega-Hub consortium model (designed by author, with Google LM support)*

Table 5.1 therefore maps each gate to the Porter activity set it most constrains, shows how the gate is operationalized through the KPI clusters defined in Table 4.13, and indicates the resulting role-fit positions within the consortium.

*Table 5.1
Porter-aligned stage-gate mapping for the consortium model*

	Stage 1: Upstream Gate	Stage 2: Midstream Gate	Stage 3: Downstream Gate
Gate question (binding constraint)	Can the corridor secure DRI-compatible feedstock reliably?	Can the system produce at scale with credible low-carbon energy and stable operations?	Can the product be proven (MRV/EPD), accepted by markets/regulators, and financed at scale?
Porter primary activities most affected	Inbound logistics (inputs flow, corridor reliability)	Operations (DRI/EAF readiness, stability, yield)	Outbound logistics, Marketing & sales, Service (verified value + ongoing transparency)
Porter support activities most enabling	Procurement, Firm infrastructure, Technology development	Firm infrastructure, Procurement, Technology development, HRM	Firm infrastructure/governance, Technology development, Procurement, Finance structuring
KPI clusters (Table 4.13)	K1–K3 (<i>K2 gatekeeper</i>)	K4–K15 (<i>K8 & K14 gatekeepers</i>)	K16–K19 (<i>K17 & K18 gatekeepers</i>)
Consortium role-fit output	Feedstock anchor	Energy/hydrogen & production hub	Downstream gateway/enabler

5.3.2 What does Mega-Hub add beyond a standard Porter mapping

The added value of the consortium (Mega-Hub) model relative to a conventional Porter value-chain map is that it converts an activity-based competitiveness logic into an implementable, gate-based transition architecture. As illustrated in Figure 5.2, the model operationalizes the transition through three binding stage-gates, an Upstream Feedstock Anchor gate, a Midstream Energy & Production Hub gate, and a Downstream Market & Finance Gateway gate, each of which must be “passed” before decarbonization can credibly scale.

First, the stage-gate structure makes feasibility explicit by treating critical conditions (e.g., DR-grade feedstock access, low-carbon electricity and hydrogen readiness, and auditable MRV/EPD proof) as constraints that determine whether a pathway can expand at acceptable cost and risk, rather than assuming performance will follow automatically from adopting “best practice” activities.

Second, role specialization replaces a single-country “overall score” with role-fit positions (anchor/hub/gateway), so countries contribute where comparative advantage is strongest while the consortium manages cross-border interdependencies along the corridor.

Third, KPI-based scoring translates qualitative integration logic into auditable evidence requirements for sequencing decisions, strengthening defensibility for Scope 1–3 integrity, low-carbon claims, and bankability.

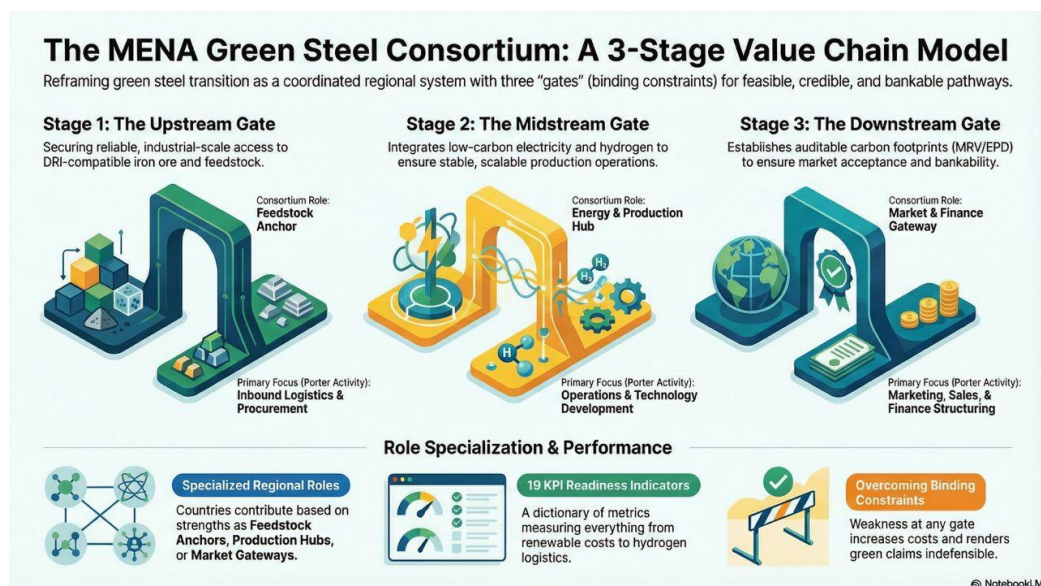


Figure 5.2
Three-stage gate structure of the MENA Green Steel Mega-Hub consortium model
(designed by author, with Google LM support)

In this way, the model extends Porter by making the gates the practical mechanism that links coordination, readiness, and stepwise scaling toward net-zero steel.

5.3.3 Technology enablement by gate: supplier solution packages

The MENA consortium model treats “technology” as gate-specific implementation packages, not as a single equipment choice, because each stage-gate represents a different binding constraint in the Mega-Hub pathway (feedstock security → energy/operations stability → proof/market/financeability). This logic is consistent with the Porter-aligned gate mapping already defined in Table 5.1, where each gate constrains different primary and support activities and is operationalized through the stage KPI clusters.

Table 5.2 therefore provides an illustrative “technology-by-gate” mapping using the three supplier portfolios, grouped by four labels used consistently in this study: Green-core, CCUS (built-in option), CCUS-ready, and Enablers/Transitional. The aim is not to rank vendors, but to show how supplier options can be assembled as stage-appropriate bundles that help a country/corridor pass the gate at acceptable cost, risk, and credibility.

*Table 5.2
Stage-based mapping of representative decarbonization technologies from technology suppliers*

Upstream Stage	
DANIELI Group	ENERGIRON®  CCUS  Green-core (H ₂ -DRI route; CO ₂ removal system for CCU/CCS) Hytemp®  Enabler (hot-DRI handling to EAF) Danieli Corus low-CO₂ BF/BOF packages  Transitional (BF/BOF decarb retrofits)

	Prothal® DH ☼Enabler (electric process gas heating) (SGRO, 2022; Lapasin, 2023; Danieli, 2024)
SMS Group	MIDREX® (NG™/Flex/H₂) ✓ CCUS ✓ Green-core (DRI; carbon capture options on MIDREX plants) Blue Blast Furnace ◇CCUS-ready ∪Transitional (BF modernization; capture can be applied as an add-on “last mile”) DRP–OBF route ∪Transitional / next-gen ironmaking-to-melt route EASyMelt ∪Transitional (smelting concept) (Salemi, Torabi and Haghparast, 2022; Key and Manager, 2023; Midrex, 2023; SMS, 2026)
Primetals Technologies	MIDREX® ✓ CCUS ✓ Green-core (DRI; capture options documented in Primetals MIDREX portfolio) HYFOR® ✓ Green-core (H ₂ -based fine-ore DR route) HyREX ✓ Green-core (H ₂ -based reduction + smelting route) FINEX® ∪Transitional (smelting-reduction route; “green” only with major abatement/add-ons) ESF (Electric Smelting Furnace) ✓ Green-core <i>if powered by low-carbon electricity</i> (Fleischanderl <i>et al.</i> , 2021; Lorraine, 2024)
Midstream Stage	
DANIELI Group	Digimelter® ✓ Green-core (EAF steelmaking) Q-One® / Q-Melt™ ☼Enabler (EAF electrical + automation backbone) DSTM (Scrap-to-Melt) ☼Enabler (scrap preparation/charge optimization) CHR / Q-Steam ☼Enabler (EAF off-gas heat recovery / utilities) (Ometto, 2022; Burin, 2023; DANIELI, 2024)
SMS Group	EDGE DC EAF ✓ Green-core (EAF steelmaking) X-Pact® AURA / SynReg / EAFXpert ☼Enabler (automation + power/process optimization) Allcharge / Condoor® ☼Enabler (charging/continuous charging concepts)

	Viridis ☼Enabler (energy/emissions monitoring suite) (SMS, 2023, 2025)
Primetals Technologies	EAF Ultimate / EAF Quantum ✓ Green-core (EAF steelmaking) EAF Optimizer / Steelmaking Process Assistant ☼Enabler (optimization/decision support) Arvedi ESP ☼Enabler (endless casting+rolling integration that cuts energy/CO ₂ intensity) (Arvedi <i>et al.</i> , 2011; Mikrukow and Schillinger, 2024; WEBWIRE, 2024; Masolini and Hein, 2025)
Downstream	
DANIELI Group	QSP-DUE / MIDA-QLP ☼Enabler (endless casting & rolling; fewer reheats/energy) Q-Heat® ☼Enabler (electrified/induction heating) Hydro Series burners (RAD/MAB/TFB) ☼Enabler (H ₂ -ready reheating/thermal processing) Q3-DEMS / Q-Water ☼Enabler (energy/water management) (Ichikawa <i>et al.</i> , 2017; Benedetti and Moggridge, 2023)
SMS Group	ECOFlame+ / ZEROFlame (HY²/Dual/Regenerative) ☼Enabler (low-CO ₂ / H ₂ -ready reheating burners) X-Pact® DigiMod Control / Prometheus ☼Enabler (combustion + furnace control/optimization) SMS Elotherm ☼Enabler (induction heating / electrified reheating) (Carsen, Dappen and Schibisch, 2009; Cascino <i>et al.</i> , 2023)
Primetals Technologies	PLTCM / UC-MILL ☼Enabler (cold rolling route; energy/productivity improvements) CWC (Coating Weight Control) ☼Enabler (coating line efficiency/quality control) UHT-Thermo Jet® ☼Enabler (process heating; impact depends on energy source) (Guelton and Lerouge, 2010; Zhen <i>et al.</i> , 2021)

Legend:

- ✓ CCUS = CO₂ capture/removal is an explicit built-in option;
- ✓ Green-core = directly produces low-carbon iron/steel in a green route (H₂-DRI / EAF / electrified smelting);
- ♦ CCUS-ready = typically paired with external capture (not itself the capture unit).
- ☼ Enabler = reduces energy/emissions but doesn't define the "green" route;

- **UTransitional** = decarbonizes conventional BF/BOF pathways (often not “green steel” by itself).

5.4 Recommendation

The recommendations in this section follow from the thesis’s main finding that the MENA green-steel transition is constrained less by the availability of individual technologies than by whether value-chain conditions allow those technologies to scale credibly, at acceptable cost, and with manageable risk. In this study, the Mega-Hub model translates that challenge into three binding stage-gates: upstream feedstock anchoring, midstream energy and production readiness, and downstream market and finance access. The recommendations are therefore organized into two areas: practical applications for transition delivery and future research priorities for improving and validating the readiness model.

5.4.1 Recommendations for Practical Applications

The results show that the green-steel transition in MENA should be controlled through coordinated stage-gate execution instead of separate projects or national initiatives that work on their own.

The most important thing for politicians and regional planners to do is to make sure that the three gates can be passed in order. This involves making cooperation at the corridor level stronger, making industrial power more reliable, allowing legitimate low-carbon electricity claims, supporting hydrogen logistics and water-management infrastructure, and making verification capacity and finance conditions stronger. These actions are especially significant because some of the most important problems are above the level of a single company and can't be fixed effectively by that company alone.

The results show that for consortium members and steel companies, managing decarbonization as a tiered investment and operating roadmap directly related to the three gates makes implementation more believable. Companies should not view decarbonization as a series of isolated technical improvements. Instead, they should ensure that their initiatives align with feedstock security, energy and operational readiness, and downstream proof and bankability prerequisites. Furthermore, the findings suggest that role-fit specialization, encompassing anchor, hub, or gateway roles, is more feasible than complete value-chain internalization in a context where skills and constraints are unevenly distributed.

on this strategy, investing early on auditable data capture, traceability, and Scope 1–3 integrity is important not only for environmental performance, but also for market credibility and defensible low-carbon claims.

The results imply that technology suppliers can create the most value when they sell technologies as gate-enabling solution packages instead of as separate pieces of equipment. Therefore, suppliers should structure their offerings around integrated bundles. These bundles should include feedstock interfaces, stable DRI/EAF integration for power, hydrogen readiness, automation, and built-in monitoring and reporting systems. In the MENA region, modular designs and staggered upgrading plans are especially important. This is because factors like hydrogen availability, water scarcity, and energy reliability are not developing evenly across different countries and areas.

Environmental sustainability should not be seen as a separate goal, but rather as a limitation on how the architecture can be used. In particular, water stress, exposure to the

local environment, and the integrity of the life cycle should all be taken into account when designing corridors and choosing technologies. This way, emissions reductions won't come at the expense of other environmental areas.

5.4.2 Recommendations for Future Research

The first thing that needs to be done for future research is to make the readiness model's methods more reliable and defensible outside of the study. Since the suggested framework is meant to help with decision-making, more work needs to be done to make the KPI inclusion criteria more clear, the system-boundary rules clearer, and the consistency between numeric and rubric indicators better. More research is also needed to see if the suggested gatekeepers, especially K2, K8, K14, K17, and K18, really do act as binding restraints in different countries and corridors. Expert triangulation, inter-rater consistency tests, sensitivity analysis, and clearer reporting of weighting stability would all help make this stronger.

The second aim is to make the model better at telling the difference between things without making it less disciplined. If any new indicators follow the same standards for relevance, measurability, comparability, update frequency, and resistance to manipulation, future studies could add to the KPI vocabulary when it makes sense to do so. This is especially true for role-fit evaluation and comparative preparedness analysis. This is significant because uncontrolled growth of indicators would make them less useful and raise the possibility of KPI inflation or gaming.

The third aim is to improve the quality of the evidence and the range of the environment. Using an evidence register containing confirmed, estimated, and assumed

tags, as well as remarks on source quality, year, and uncertainty, would make the model more transparent and better for comparing across MENA. Future research should also add more environmental indicators to the framework, such as how to manage waste and by-products, land-use constraints, and biodiversity exposure, as long as it doesn't change the core principles of life-cycle thinking and Scope 1–3 integrity.

5.5 Conclusion

In conclusion, this research suggests that the shift to green steel production in the MENA region is primarily a challenge of integrating and coordinating the entire value chain, rather than just replacing existing technologies.

The challenges of achieving net-zero steel production stem from several factors. These include differences in infrastructure readiness, inconsistent policy and market signals, the high costs of capital, the need for a reliable energy system, and the growing importance of credible claims about low-carbon practices.

Phase 1 used a sequential mixed-methods design to combine evidence from stakeholders and technology providers about what drives adoption, what limits it, and what needs to be done to integrate it. Phase 2 then turned these findings into a Mega-Hub consortium transition architecture with three binding stage-gates: upstream feedstock anchoring, midstream energy and production readiness, and downstream market and finance access. This was done using a KPI-based readiness and weighting logic.

The study shows that how well a company competes and how effectively it reduces carbon emissions depend on coordinating activities and using corridor-level resources. These resources are often outside the control of individual companies.

This is done by aligning the stage-gates with Porter's primary and support activities. The main contribution is an auditable decision-support framework that connects decarbonization choices to Scope 1–3 integrity, claim credibility (MRV/EPD), and bankability, rather than making a final country ranking. This framework allows for stage-gated sequencing and role-fit specialization (anchor/hub/gateway).

Simultaneously, constraints concerning sample representativeness, the completeness of secondary data for certain KPIs, and the subjectivity inherent in expert-based weighting suggest that forthcoming research should enhance the model by developing more comprehensive KPI dictionaries when warranted, conducting empirical assessments of gatekeeper behavior, and establishing transparent evidence registers that record data quality and uncertainty for external utilization.

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APPENDIX A:

LARGEST STEEL PRODUCTION COMPANIES IN MENA

Table A1

Largest Steel Production Companies in MENA

#	Company (linked)	Country	Value Chain Stages
1	Mobarakeh Steel Company (MSC) https://www.msc.ir/en/	Iran	Integrated
2	Sangan Steel Mining Industries Company (Foolad Sangan / SMIC) https://www.sanganco.ir/	Iran	Upstream
3	Khouzestan Steel Company (KSC) https://www.ksc.ir	Iran	Midstream
4	Esfahan Steel Company (ESCO) https://en.stic.ir/esfahan_steel_company/	Iran	Midstream - Downstream
5	Khorasan Steel Complex (KSCCO) https://kscco.ir/en/at-a-glance	Iran	Integrated
6	Hormozgan Steel Company (HOSCO) (MSC Group) https://hormozgansteel.ir/	Iran	Midstream
7	Gol-e-Gohar Steel Complex https://www.golghar.ir/	Iran	Upstream - Midstream
8	Erdemir (OYAK Mining & Metallurgy) https://www.erdemir.com.tr/en	Türkiye	Integrated
9	Tosyali Holding (Turkey operations) https://www.tosyaliholding.com.tr/en	Türkiye	Midstream - Downstream
10	Kardemir https://www.kardemir.com.tr/	Türkiye	Integrated
11	Colakoglu Metalurji https://www.colakoglu.com.tr	Türkiye	Midstream - Downstream
12	Icdas Celik https://www.icdas.com.tr/	Türkiye	Midstream - Downstream
13	National Steel Company (SNS)	Saudi Arabia	Midstream - Downstream
14	Saudi Iron & Steel Co. (Hadeed) https://hadeed.sabic.com/	Saudi Arabia	Midstream - Downstream
15	Al-Ittefaq Steel Products Company (ISPC) https://www.ispc.com.sa/	Saudi Arabia	Midstream - Downstream
16	Al Jazeera Steel Products https://www.aljazeerasteel.com/	Oman	Midstream - Downstream
17	Jindal Shadeed Iron & Steel https://www.jindalshadeed.com/	Oman	Midstream - Downstream
18	Moon Iron & Steel Company (MISCO) https://miscooman.com	Oman	Midstream - Downstream

19	Sohar Steel (incl. Sharq Sohar Steel Rolling Mills) http://sohar-steel.com/Home.aspx	Oman	Midstream - Downstream
20	Vale Oman Pelletizing Company (VOPC) https://vale.com/oman	Oman	Upstream
21	Bahrain Steel (GIIC / Bahrain Steel BSCC E.C.) https://www.bahrainsteel.com.bh/#!/home	Bahrain	Upstream
21	Emirates Steel LLC https://www.emiratessteel.com	UAE	Midstream - Downstream
23	Emirates Steel Arkan (ESG) https://www.emiratessteelarkan.com	UAE	Midstream - Downstream
24	Union Iron & Steel (UIS) https://www.uis-uae.com	UAE	Midstream - Downstream
25	Ezz Steel (EZZ) https://www.ezzsteel.com/	Egypt	Midstream - Downstream
26	Egyptian Steel Group https://egyptian-steel.com/en/	Egypt	Midstream-Downstream (limited)
27	Suez Steel https://www.suezsteel.com/	Egypt	Midstream - Downstream
28	Beshay Steel https://www.beshaysteel.com/	Egypt	Midstream - Downstream
29	Tosyali-Algerie https://www.tosyali-algerie.com	Algeria	Integrated
30	SIDER El Hadjar http://www.sider-elhadjar.dz	Algeria	Midstream - Downstream
31	AQS - Algerian Qatari Steel (Bellara) https://www.aqs.dz	Algeria	Midstream-Downstream (limited)
32	Qatar Steel Company (QASCO) https://www.qatarsteel.com.qa/	Qatar	Midstream-Downstream
33	Libyan Iron and Steel Company (LISCO) https://libyansteel.com/en/	Libya	Midstream-Downstream
34	Tosyali SULB https://www.tosyaliholding.com.tr/en	Libya	Midstream
35	LISCO - Libyan Iron & Steel Co. https://www.lisco.ly	Libya	Midstream-Downstream
36	SNIM – Société Nationale Industrielle et Minière https://www.snim.com/en	Mauritania	Upstream

APPENDIX B

INTERVIEW GUIDE FOR TECHNOLOGY SUPPLIERS

This research investigates the decarbonization of the steel industry in the Middle East and North Africa (MENA) region, with a focus on low-carbon technologies and green innovation. The study is part of a doctoral thesis (DBA) and seeks to understand how technology suppliers contribute to the integration of sustainable practices and infrastructure in steelmaking. Insights gathered will inform strategic roadmaps and investment frameworks for green steel deployment in MENA.

Participant Information:

- **Interview Type:** Semi-structured, expert interview
- **Estimated Duration:** 60–90 minutes
- **Participants:** Senior representatives from technology solution providers involved in steel decarbonization projects
- **Anonymity:** Responses will be anonymized in the final report unless explicit permission is given
- **Data Usage:** Responses will be used solely for academic purposes

Demographic and Background Questions:

1. Full name (optional for anonymized analysis):
2. Company name and headquarters:
3. Current job title:
4. Years of experience in steel technology or energy systems:
5. Country or region of primary operations:

Q0. Can you briefly describe your role in green steel projects and the scope of your company's offerings (e.g., technology supplier, EPC, R&D, or advisory)?

Q1. How does your organization manage power intermittency in EAF or DRI systems when operating with variable renewable energy sources?

- Q2.** In projects where hydrogen availability is limited, how does your H₂-DRI system manage dual-feedstock operation using both natural gas and hydrogen?
- Q3.** What kinds of input materials can your EAF handle while still making good-quality steel? How do you deal with changes in scrap quality, especially in places where high-grade scrap is hard to find?
- Q4.** How does your EAF technology handle environmental challenges when processing contaminated or low-quality scrap?
- Q5.** Besides using renewable energy, how does your technology help reduce a plant's overall carbon footprint through operational efficiency?
- Q6.** How does your technology support the recovery and reuse of waste materials or energy streams in steel plants?
- Q7.** In your experience, what is the smallest production capacity at which your low-carbon steelmaking technologies (e.g., EAF, DRI with green hydrogen) become commercially viable?
- Q8.** How is your company's hydrogen-ready direct reduction technology prepared for flexible operation with hydrogen and natural gas mixtures, and what technical features make it suitable for a cost-effective transition to hydrogen-based steelmaking?
- Q9:** What technologies and solutions do your company provide to help reduce operating costs (OPEX) in hydrogen-ready DRI and EAF steel plants?
- Q10.** From your experience in MENA projects or studies, which OPEX items offer the best opportunities to reduce costs?
- Q11.** In your recent or modeled green steel projects in the MENA region (using 100% green hydrogen in DRI + EAF), what were the typical financial results?
- Q12.** How does your hydrogen production technology address water requirements in water-scarce regions such as MENA?
- Q13.** How does your company address water management challenges in steel plants located in water-scarce regions such as MENA, especially when those plants plan to operate DRI and EAF processes using hydrogen as the reducing agent?
- Q14.** Have you worked on carbon capture (CCUS) projects for existing steel plants, and how do these compare technically and economically to building new green steel facilities?
- Q15.** Has your company supported any step-by-step (phased) decarbonization strategies to reduce emissions from existing BF/BOF steel plants?
- Q16.** For each of your main green steel technologies, what plant capacity ranges are supported by your company designs?
- Q17.** What is your company's approach to supporting regional execution of green steel projects in MENA?
- Q18.** In your recent projects, how does your company typically structure the delivery and installation of a 1 million ton/year DRI + EAF steel plant?
- Q19.** In MENA or other similar regions, local expertise in green hydrogen or digital automation is still developing. Has your company done anything to help build local skills and operational capacity?
- Q20.** In your experience, which government policies or incentives have helped the most in making green steel projects attractive for investors?

APPENDIX C

INTERVIEW GUIDE FOR STEEL PRODUCERS

This research investigates the decarbonization of the steel industry in the Middle East and North Africa (MENA) region, with a focus on low-carbon technologies and green innovation. The study is part of a doctoral thesis (DBA) and seeks to understand how steel producers across three stages of steel industry value chain, upstream, midstream and downstream, contribute to the integration of sustainable practices and infrastructure in steelmaking. Insights gathered will inform strategic roadmaps and investment frameworks for green steel deployment in MENA.

Participant Information:

- **Interview Type:** Semi-structured, expert interview
- **Estimated Duration:** 60–90 minutes
- **Participants:** Representatives from steel-producing companies, including roles such as plant managers, sustainability officers, operations directors, R&D engineers, energy transition leads, and corporate strategy advisors.
- **Anonymity:** Responses will be anonymized in the final report unless explicit permission is given
- **Data Usage:** Responses will be used solely for academic purposes

Demographic and Background Questions:

6. Full name (optional for anonymized analysis):
7. Company name and headquarters:
8. Current job title:
9. Years of experience in steel technology or energy systems:
10. Country or region of primary operations:

Upstream Steel Decarbonization Interview Questions

1. Which unit operations contribute most to direct (Scope 1) emissions?

- ☐ Mining fuel/diesel
- ☐ Coke ovens
- ☐ Pelletizing furnaces
- ☐ Shaft kiln
- ☐ Rotary kiln
- ☐ Raw material drying
- ☐ Transport/logistics
- ☐ Other: _____

2. What low-carbon technologies are active or piloted at your site?

- ☐ Electrified beneficiation
- ☐ Waste heat recovery
- ☐ Electrified mining trucks
- ☐ Digital energy dashboards
- ☐ None)

3. Rate the operational readiness of sustainable upstream technologies in your facility: (1 = Awareness only, 2 = Initial studies/feasibility, 3 = Pilot testing, 4 = Limited deployment, 5 = Fully deployed at scale)

- Waste heat recovery from pelletizing kilns and induration furnaces (1200-1350°C operations)
- Energy recovery from cooling systems and exhaust gases
- Process optimization for reduced fuel consumption in pellet formation
- Environmental emission control and dust management systems
- Energy-efficient grinding and concentration processes
- Integration of renewable energy sources for facility operations

→ Please elaborate on the highest-scoring technology with specific operational metrics, energy savings achieved, and deployment timeline.

4. How does your organization decide whether to implement new low-emission technologies?

- ☐ Financial return (payback period, cost savings)
- ☐ Corporate decarbonization targets
- ☐ Customer or investor pressure
- ☐ Compliance with regulations or carbon pricing

- ☐ Operational performance (efficiency, yield)
- ☐ Technical compatibility with existing systems
- ☐ No formal method used yet
- Please share an example, if available.

5. What types of energy and feedstock do you currently use in your production processes?

- ☐ Coal/coke (for BF)
- ☐ Natural gas
- ☐ Hydrogen (grey, blue, or green)
- ☐ Scrap (post-consumer or industrial)
- ☐ Electricity from national grid
- ☐ Renewable energy (solar, wind, hydropower)
- ☐ Other: _____
- Which is your main energy input? Are changes planned?

6. Do you monitor your plant's energy use regularly?

- ☐ Yes – with digital or automated systems
- ☐ Partially – some manual tracking or audits
- ☐ No – we don't track it consistently

7. What factors do you consider when trying to reduce energy use or shift energy types?

- ☐ Time of day (e.g., off-peak grid rates)
- ☐ Equipment/process energy intensity
- ☐ Weather/season (for RE availability)
- ☐ Production planning
- ☐ Energy price fluctuations
- ☐ Other: _____

8. Have you experienced technical or operational challenges when switching energy sources or feedstock (e.g., from NG to H₂, or scrap mix changes)?

→ Please describe briefly (e.g., furnace performance, quality variation, infrastructure limits).

9. What factors would most influence your decision to shift to lower-emission energy sources?

- ☐ Lower cost of alternatives
- ☐ Stable energy supply
- ☐ Government regulation or incentives

- ☐ Customer/market pressure
- ☐ Ease of integration into current systems
- ☐ Support for infrastructure (grid, hydrogen, etc.)
- ☐ Other: _____

10. Do you measure your GHG emissions? If so, how?

- ☐ By process stage (e.g., DRI, EAF, reheating)
- ☐ Per ton of steel output
- ☐ Real-time digital sensors
- ☐ Manual calculations or periodic audits
- ☐ No measurement yet
- ☐ Planning to measure soon

11. Do you follow any standards or frameworks for reporting emissions?

- ☐ GHG Protocol
- ☐ ISO 14064
- ☐ WSA or regional steel-specific reporting
- ☐ National/MENA environmental guidelines
- ☐ Internal company benchmarks
- ☐ None

12. What is driving your need to measure emissions?

- ☐ EU CBAM (Carbon Border Adjustment Mechanism)
- ☐ LCA or EPD requests from customers
- ☐ Investor/ESG requirements
- ☐ Government regulations
- ☐ Voluntary internal goals
- ☐ No current external pressure

13. What would help improve the accuracy or ease of emissions tracking at your plant?

→ E.g., sensors, automated data platforms, training, external audits

14. Do you monitor Scope 3 emissions (e.g., purchased raw materials, logistics)?

- ☐ Yes – in detail
 - ☐ Some categories only
 - ☐ Not yet, but planning to
 - ☐ No – not tracked
- If not, what's the biggest challenge (e.g., data access, cost, unclear methods)?

15. Have you received any kind of support to help reduce emissions or improve efficiency?

- ☐ National grants
- ☐ Tax benefits
- ☐ International partnerships (e.g., UNIDO, IEA)
- ☐ Local R&D or pilot project support
- ☐ No support received

16. Are you part of any industrial networks focused on decarbonizing steel or improving efficiency?

- ☐ Yes – active involvement
 - ☐ Occasionally engage
 - ☐ Not involved
- If yes, which have been most helpful and why?

17. What kind of policy or government support would help your company move forward with decarbonization?

→ E.g., affordable energy tariffs, retrofit funding, RE access, staff training programs

18. Do you benchmark your energy or emissions performance against other steel plants?

- ☐ Yes – regular KPI tracking
 - ☐ Occasionally
 - ☐ No benchmarking
- If yes, what indicators do you use (e.g., kg CO₂/t liquid steel, MWh/t slab)?

19. How ready is your current production infrastructure to adopt emission-reduction technologies?

- ☐ Ready for minor upgrades (e.g., digital tools, scrap preheating)
- ☐ Can support moderate retrofits (e.g., off-gas recovery, burners)
- ☐ Needs major overhauls (e.g., furnace replacement, full DRI switch)
- ☐ Not suitable for low-emission upgrades yet

20. Has your company estimated the cost (CAPEX) for decarbonizing production?

- ☐ <\$50 million
- ☐ \$50–500 million
- ☐ \$500 million–2 billion
- ☐ >\$2 billion
- ☐ Not yet assessed

21. How are such projects usually financed in your company?

- ☐ Company funds
- ☐ Bank/commercial loans
- ☐ Public-private partnerships
- ☐ Sustainability-linked finance (green bonds, ESG funds)
- ☐ No financing available yet

22. What conditions must be met for you to approve investments in emission-reduction projects?

- ☐ ROI above 10%
- ☐ Payback period under 5 years
- ☐ CO₂ reduction impact justifies cost
- ☐ Strategic alignment or compliance preparation
- ☐ Other – please specify: _____

Midstream Steel Decarbonization Interview Questions

1. Which operations in your plant contribute most to direct (Scope 1) emissions?

- ☐ Natural gas or hydrogen used in DRI units
- ☐ Coke ovens or blast furnaces (BF)
- ☐ Electric arc furnaces (EAF)
- ☐ Reheating furnaces
- ☐ Casting operations
- ☐ Internal transport/logistics
- ☐ Other – Please specify: _____

2. What low-carbon technologies are currently used or piloted at your site?

- ☐ Hydrogen-based DRI
- ☐ Scrap preheating in EAF
- ☐ Carbon injection optimization
- ☐ Off-gas recovery and reuse
- ☐ CCUS (carbon capture, utilization, or storage)
- ☐ Digital monitoring of furnace energy/emissions
- ☐ None in place yet

3. How would you rate the readiness of these technologies at your plant? (1 = Only studied, 5 = Fully deployed)

→ Please mention the technology with the highest readiness and explain its performance or results.

- Hydrogen-based DRI
- EAF off-gas recovery and reuse
- Scrap preheating for EAF
- Low-NO_x or oxy-fuel burners in reheating furnaces
- Carbon injection optimization in BF/BOF
- Digital energy or emissions monitoring tools

4. How does your organization decide whether to implement new low-emission technologies?

- ☐ Financial return (payback period, cost savings)
- ☐ Corporate decarbonization targets
- ☐ Customer or investor pressure
- ☐ Compliance with regulations or carbon pricing
- ☐ Operational performance (efficiency, yield)
- ☐ Technical compatibility with existing systems

- ☐ No formal method used yet
- Please share an example, if available.

5. What types of energy and feedstock do you currently use in your production processes?

- ☐ Coal/coke (for BF)
- ☐ Natural gas
- ☐ Hydrogen (grey, blue, or green)
- ☐ Scrap (post-consumer or industrial)
- ☐ Electricity from national grid
- ☐ Renewable energy (solar, wind, hydropower)
- ☐ Other: _____
- Which is your main energy input? Are changes planned?

6. Do you monitor your plant's energy use regularly?

- ☐ Yes – with digital or automated systems
- ☐ Partially – some manual tracking or audits
- ☐ No – we don't track it consistently

7. What factors do you consider when trying to reduce energy use or shift energy types?

- ☐ Time of day (e.g., off-peak grid rates)
- ☐ Equipment/process energy intensity
- ☐ Weather/season (for RE availability)
- ☐ Production planning
- ☐ Energy price fluctuations
- ☐ Other: _____

8. Have you experienced technical or operational challenges when switching energy sources or feedstock (e.g., from NG to H₂, or scrap mix changes)?

→ Please describe briefly (e.g., furnace performance, quality variation, infrastructure limits).

9. What factors would most influence your decision to shift to lower-emission energy sources?

- ☐ Lower cost of alternatives
- ☐ Stable energy supply
- ☐ Government regulation or incentives
- ☐ Customer/market pressure
- ☐ Ease of integration into current systems

- ☐ Support for infrastructure (grid, hydrogen, etc.)
- ☐ Other: _____

10. Do you measure your GHG emissions? If so, how?

- ☐ By process stage (e.g., DRI, EAF, reheating)
- ☐ Per ton of steel output
- ☐ Real-time digital sensors
- ☐ Manual calculations or periodic audits
- ☐ No measurement yet
- ☐ Planning to measure soon

11. Do you follow any standards or frameworks for reporting emissions?

- ☐ GHG Protocol
- ☐ ISO 14064
- ☐ WSA or regional steel-specific reporting
- ☐ National/MENA environmental guidelines
- ☐ Internal company benchmarks
- ☐ None

12. What is driving your need to measure emissions?

- ☐ EU CBAM (Carbon Border Adjustment Mechanism)
- ☐ LCA or EPD requests from customers
- ☐ Investor/ESG requirements
- ☐ Government regulations
- ☐ Voluntary internal goals
- ☐ No current external pressure

13. What would help improve the accuracy or ease of emissions tracking at your plant?

→ E.g., sensors, automated data platforms, training, external audits

14. Do you monitor Scope 3 emissions (e.g., purchased raw materials, logistics)?

- ☐ Yes – in detail
- ☐ Some categories only
- ☐ Not yet, but planning to
- ☐ No – not tracked

→ If not, what's the biggest challenge (e.g., data access, cost, unclear methods)?

15. Have you received any kind of support to help reduce emissions or improve efficiency?

- ☐ National grants
- ☐ Tax benefits
- ☐ International partnerships (e.g., UNIDO, IEA)
- ☐ Local R&D or pilot project support
- ☐ No support received

16. Are you part of any industrial networks focused on decarbonizing steel or improving efficiency?

- ☐ Yes – active involvement
 - ☐ Occasionally engage
 - ☐ Not involved
- If yes, which have been most helpful and why?

17. What kind of policy or government support would help your company move forward with decarbonization?

→ E.g., affordable energy tariffs, retrofit funding, RE access, staff training programs

18. Do you benchmark your energy or emissions performance against other steel plants?

- ☐ Yes – regular KPI tracking
 - ☐ Occasionally
 - ☐ No benchmarking
- If yes, what indicators do you use (e.g., kg CO₂/t liquid steel, MWh/t slab)?

19. How ready is your current production infrastructure to adopt emission-reduction technologies?

- ☐ Ready for minor upgrades (e.g., digital tools, scrap preheating)
- ☐ Can support moderate retrofits (e.g., off-gas recovery, burners)
- ☐ Needs major overhauls (e.g., furnace replacement, full DRI switch)
- ☐ Not suitable for low-emission upgrades yet

20. Has your company estimated the cost (CAPEX) for decarbonizing production?

- ☐ <\$50 million
- ☐ \$50–500 million
- ☐ \$500 million–2 billion
- ☐ >\$2 billion
- ☐ Not yet assessed

21. How are such projects usually financed in your company?

- ☐ Company funds
- ☐ Bank/commercial loans
- ☐ Public-private partnerships
- ☐ Sustainability-linked finance (green bonds, ESG funds)
- ☐ No financing available yet

22. What conditions must be met for you to approve investments in emission-reduction projects?

- ☐ ROI above 10%
- ☐ Payback period under 5 years
- ☐ CO₂ reduction impact justifies cost
- ☐ Strategic alignment or compliance preparation
- ☐ Other – please specify: _____

Downstream Steel Decarbonization Interview Questions

1. Which operations in your plant contribute most to direct (Scope 1) emissions?

- ☐ Hot/cold rolling
- ☐ Coating
- ☐ Heat treatment
- ☐ Reheating furnaces
- ☐ Logistics
- ☐ Scrap processing
- ☐ Other – Please specify: _____

2. What low-carbon technologies are currently used or piloted at your site?

- ☐ Electrified heating
 - ☐ Smart automation
 - ☐ Renewable electricity
 - ☐ Low-emission coatings
 - ☐ None in place yet
- Which had the most significant impact on cost or emissions?

3. How would you rate the readiness of these technologies at your plant? (1 = Only studied, 5 = Fully deployed)

→ Please mention the technology with the highest readiness and explain its performance or results.

- Electrification of reheating/annealing furnaces
- Waste heat recovery from rolling or finishing lines
- High-efficiency motors and drives
- Smart energy monitoring platforms
- Use of renewable electricity
- Low-emission coatings and treatments
- Material-efficient design or lightweighting

4. How does your organization decide whether to implement new low-emission technologies?

- ☐ Financial return (payback period, cost savings)
- ☐ Corporate decarbonization targets
- ☐ Customer or investor pressure
- ☐ Compliance with regulations or carbon pricing
- ☐ Operational performance (efficiency, yield)
- ☐ Technical compatibility with existing systems

- ☐ No formal method used yet
- Please share an example, if available.

5. What types of energy and feedstock do you currently use in your production processes?

- ☐ Coal/coke (for BF)
- ☐ Natural gas
- ☐ Hydrogen (grey, blue, or green)
- ☐ Scrap (post-consumer or industrial)
- ☐ Electricity from national grid
- ☐ Renewable energy (solar, wind, hydropower)
- ☐ Other: _____
- Which is your main energy input? Are changes planned?

6. Do you monitor your plant's energy use regularly?

- ☐ Yes – with digital or automated systems
- ☐ Partially – some manual tracking or audits
- ☐ No – we don't track it consistently

7. What factors do you consider when trying to reduce energy use or shift energy types?

- ☐ Time of day (e.g., off-peak grid rates)
- ☐ Equipment/process energy intensity
- ☐ Weather/season (for RE availability)
- ☐ Production planning
- ☐ Energy price fluctuations
- ☐ Other: _____

8. Have you experienced technical or operational challenges when switching energy sources or feedstock (e.g., from NG to H₂, or scrap mix changes)?

→ Please describe briefly (e.g., furnace performance, quality variation, infrastructure limits).

9. What factors would most influence your decision to shift to lower-emission energy sources?

- ☐ Lower cost of alternatives
- ☐ Stable energy supply
- ☐ Government regulation or incentives
- ☐ Customer/market pressure
- ☐ Ease of integration into current systems

- ☐ Support for infrastructure (grid, hydrogen, etc.)
- ☐ Other: _____

10. Do you measure your GHG emissions? If so, how?

- ☐ By process stage (e.g., DRI, EAF, reheating)
- ☐ Per ton of steel output
- ☐ Real-time digital sensors
- ☐ Manual calculations or periodic audits
- ☐ No measurement yet
- ☐ Planning to measure soon

11. Do you follow any standards or frameworks for reporting emissions?

- ☐ GHG Protocol
- ☐ ISO 14064
- ☐ WSA or regional steel-specific reporting
- ☐ National/MENA environmental guidelines
- ☐ Internal company benchmarks
- ☐ None

12. What is driving your need to measure emissions?

- ☐ EU CBAM (Carbon Border Adjustment Mechanism)
- ☐ LCA or EPD requests from customers
- ☐ Investor/ESG requirements
- ☐ Government regulations
- ☐ Voluntary internal goals
- ☐ No current external pressure

13. What would help improve the accuracy or ease of emissions tracking at your plant?

→ E.g., sensors, automated data platforms, training, external audits

14. Do you monitor Scope 3 emissions (e.g., purchased raw materials, logistics)?

- ☐ Yes – in detail
 - ☐ Some categories only
 - ☐ Not yet, but planning to
 - ☐ No – not tracked
- If not, what's the biggest challenge (e.g., data access, cost, unclear methods)?

15. Have you received any kind of support to help reduce emissions or improve efficiency?

- ☐ National grants
- ☐ Tax benefits
- ☐ International partnerships (e.g., UNIDO, IEA)
- ☐ Local R&D or pilot project support
- ☐ No support received

16. Are you part of any industrial networks focused on decarbonizing steel or improving efficiency?

- ☐ Yes – active involvement
 - ☐ Occasionally engage
 - ☐ Not involved
- If yes, which have been most helpful and why?

17. What kind of policy or government support would help your company move forward with decarbonization?

→ E.g., affordable energy tariffs, retrofit funding, RE access, staff training programs

18. Do you benchmark your energy or emissions performance against other steel plants?

- ☐ Yes – regular KPI tracking
 - ☐ Occasionally
 - ☐ No benchmarking
- If yes, what indicators do you use (e.g., kg CO₂/t liquid steel, MWh/t slab)?

19. How ready is your current production infrastructure to adopt emission-reduction technologies?

- ☐ Ready for minor upgrades (e.g., digital tools, scrap preheating)
- ☐ Can support moderate retrofits (e.g., off-gas recovery, burners)
- ☐ Needs major overhauls (e.g., furnace replacement, full DRI switch)
- ☐ Not suitable for low-emission upgrades yet

20. Has your company estimated the cost (CAPEX) for decarbonizing production?

- ☐ <\$50 million
- ☐ \$50–500 million
- ☐ \$500 million–2 billion
- ☐ >\$2 billion
- ☐ Not yet assessed

21. How are such projects usually financed in your company?

- ☐ Company funds
- ☐ Bank/commercial loans
- ☐ Public-private partnerships
- ☐ Sustainability-linked finance (green bonds, ESG funds)
- ☐ No financing available yet

22. What conditions must be met for you to approve investments in emission-reduction projects?

- ☐ ROI above 10%
- ☐ Payback period under 5 years
- ☐ CO₂ reduction impact justifies cost
- ☐ Strategic alignment or compliance preparation
- ☐ Other – please specify: _____

APPENDIX D

QUALITATIVE CODEBOOK AND THEME DEFINITIONS

D1: Steel Producers Qualitative Codebook

Theme definitions, inclusion and exclusion criteria, and selected exemplar quotes for steel producers.

SPT1: Strategic Decarbonization Roadmaps and Value-Chain Positioning

This theme captures how firms frame decarbonization as a corporate strategic direction, including formal roadmaps, long-term targets (e.g., 2030/2040/2050), Scope framing, and market/value-chain positioning (e.g., “low-carbon/green steel”). SPT1 may co-occur with SPT3 (energy transition) and SPT5 (finance), but it is coded as primary when the dominant message is strategic intent and direction (“where the company is going”), rather than energy sourcing or financing mechanisms.

Inclusion (code as SPT1): The excerpt includes at least one of:

- explicit strategy/roadmap language (strategy, roadmap, net-zero pathway)
- quantified targets with a time horizon (e.g., “X% by 2030”, “net zero by 2050”)
- positioning in low-carbon markets/value chains (e.g., “low-carbon steel products”)
- corporate-level statements linking decarbonization to overall direction, governance, or identity.

Exclusion (do not code as SPT1): The excerpt focuses mainly on:

production-route/process measures without strategic framing (SPT2)

- energy sourcing, renewables, captive power, or grid interface (SPT3)
- MRV, reporting systems, standards, footprints, or verification (SPT4)
- financing instruments, loan structures, investment conditions, or competitiveness framing (SPT5)

Exemplar Quotes

Bahrain Steel (Upstream, Bahrain): “These projects ‘are financed by a sustainability-linked loan from the regional banks’ and that they ‘will mark a significant milestone in the Kingdom’s pursuit of renewable energy and contribute to achieving its 2060 net-zero goals.’”

EMSTEEL (Downstream, UAE): “EMSTEEL’s downstream operations form a critical part of the company’s integrated Decarbonization Roadmap, which targets a 40% reduction in Scope 1 and 2 emissions by 2030 (baseline 2019) and full Net Zero alignment by 2050.”

Erdemir / OYAK Mining & Metallurgy (Group, Türkiye): “Targets & scope: OYAK Mining & Metallurgy (Erdemir & İsdemir) announced a Net Zero Roadmap to reduce CO₂ per ton by ≥25% by 2030, 40% by 2040, and reach net-zero by 2050...”

Hadeed / SABIC (Downstream, Saudi Arabia): “By 2030 – We will reduce our direct and indirect greenhouse gas (Scope 1 & 2) emissions by 20% from a 2018 baseline... By 2050 – We will fully decarbonize our operations in line with the goals of the Paris Agreement.”

Jindal Steel (Integrated, Oman, Duqm): “The group has net-Zero target in 2045.”

SNIM (Upstream, Mauritania): “*SNIM has adopted a quantified climate objective to ‘reduce our greenhouse gas emissions by 7.25% by 2030’ compared with 2020...*”

Mobarakeh Steel Company / MSC (Integrated, Iran): “*Internal strategic goals: MSC has established a carbon-management ... and has a carbon-neutral roadmap and carbon committee.*”

Qatar Steel (Downstream, Qatar): “*committed to reducing its GHG emission intensity ... by 10% by 2035, using 2022 as the baseline year...*”

Tosyali (Group, Algeria): “*Tosyali sets group-wide environmental targets: We aim to have the infrastructure in place for 100% hydrogen use in all our facilities by 2026*”

“Our SPP investment will produce 50% of our electricity’ by 2025...”

Vulcan / Jindal Steel Duqm (Project, Oman): “*Year 2045 – Target to become Carbon net-zero.*”

SPT2: Production-Route Decarbonization (DRI–EAF, Scrap Use, Process optimization)

This theme captures decarbonization actions implemented within the production route and operating processes. It includes route shifts (e.g., BF/BOF → DRI–EAF), higher or more flexible scrap/metallics use, equipment and practice upgrades, and process optimization initiatives that reduce energy use and emissions across ironmaking/steelmaking, casting, reheating, and rolling. SPT2 may co-occur with SPT1 (strategic roadmaps) and SPT3 (energy system transition); however, it is coded as

primary when the excerpt's dominant focus is what is changed inside the plant and how it improves performance/emissions, rather than strategic targets or external energy sourcing/infrastructure.

Inclusion (code as SPT2): Code the excerpt to SPT2 when it primarily describes one or more of the following:

- production-route change or flexibility (e.g., DRI–EAF adoption, scrap ratio increase, mixed-metallics practice)
- process and operational optimization (e.g., specific energy reduction, yield improvement, off-gas recovery, heat recovery tied to process operation, digital/process control used to optimize the route)
- equipment or practice upgrades that directly reduce operational emissions (e.g., EAF/DRI modernization, improved charging, control logic, or retrofit measures with operational impact).

Exclusion (do not code as SPT2): Do not code as SPT2 when the excerpt is mainly about:

- targets/roadmaps/corporate direction without operational detail (SPT1)
- energy sourcing and enabling infrastructure as the main topic (renewables share, captive power, grid reliability, PPAs/I-RECs, hydrogen supply/logistics) (SPT3)
- measurement, reporting, and verification/data systems (MRV, standards, footprints, LCA/EPD, Scope 3 mapping) (SPT4)
- financing, investment conditions, competitiveness or partnership structures as the core message (SPT5)

- If process changes are mentioned only as dependent on electricity/hydrogen availability (without describing the process intervention itself), code SPT3/SPT5 as primary, and use SPT2 only if the process intervention is substantively described.

Exemplar Quotes

Bahrain Steel (Upstream, Bahrain): “These iron-ore pellets, produced to uniform size with high-quality property characteristics in Bahrain Steel’s pelletising plants, are then sold on to steelmakers. ... An official Bahrain Steel press release adds that the company’s pellets are used for steelmaking via either the Direct Reduced/Electric Arc Furnace route or the Blast Furnace/Basic Oxygen Furnace route.”

EMSTEEL (Downstream/ Midstream, UAE): “AI-based furnace temperature control and Level 2 process automation, optimizing fuel-air ratios and reducing natural gas consumption.”

“Scope 1 – Direct Emissions: Reduction efforts focus on improving energy efficiency in Direct Reduction (DRP) and Electric Arc Furnace (EAF) operations.”

“The DRP plants have achieved measurable efficiency gains through natural gas optimisation, off-gas recovery, and digital monitoring.”

Erdemir / OYAK Mining & Metallurgy (Group, Türkiye): “Hydrogen: Two-day hydrogen injection pilot at BF#1 completed in Oct-2024.”

“Waste heat recovery from pelletizing kilns and induration furnaces (1200-1350°C operations)”

Mobarakeh Steel Company, MSC (Integrated, Iran): “Planned changes: MSC has started studies to use hydrogen instead... process and is phasing in its 600 MW solar program.”

Qatar Steel (Downstream, Qatar): “Waste-heat recovery (regenerative heat transfer): In operation (5/5) — Company brochure states the plant ‘utilizes [the] principle of Regenerative Heat Transfer for heat recovery from the waste gas.’”

Hadeed / SABIC (Downstream, Saudi Arabia): “Flue-gas jet blowers were installed in the direct reduction ... resulting in reduced natural gas consumption by 4%, and increased the recycling of fuel gas by 15.3%.”

Jindal (Group, Oman): “The DRI plant is licensed by Midrex, and is the only plant in the world with HOTLINK technology, where hot DRI is directly fed through gravity at 650+ Degree C lowering the power consumption in EAF, carbon emissions and product carbon foot print (PCF) substantially.”

SNIM / Mauritania (Upstream, Mauritania): “ArcelorMittal – SNIM and ArcelorMittal signed a non-binding memorandum of understanding to assess the opportunity to jointly develop two pellet and DRI plants in Mauritania, supplied with ores produced by SNIM. ... [to] leverage Mauritania’s potential in terms of renewable energy and green hydrogen production, with metal produced from green hydrogen described as an important step in the transition of the steel industry towards zero carbon.”

Tosyali (Group, Algeria): “A new DRI Plant with an annual capacity of 2.7 million tonnes became operational in 2024. This plant is one of the best practices in the

global steel industry for carbon-free green steel production, particularly due to its capability to operate with 100% hydrogen.”

***Vulcan / Jindal Steel Duqm (Project, Oman):** “ENERGIRON® Technology: A hydrogen-ready process system that enables seamless transition from natural gas to green hydrogen.”*

SPT3: Energy Mix and Infrastructure Transformation (Captive Power, Renewables, Grid Interfaces)

This theme captures changes in the energy system that supports decarbonization, especially electricity and fuel infrastructure. It includes renewable electricity adoption, captive generation, grid interface problems, electrification moves, and energy-supply strategies that shape emissions outcomes. SPT3 overlaps with SPT5 because many energy projects are described together with loans or capex. The decision rule was: when the paragraph is mainly about how the energy is secured or transformed (renewables share, certificates, grid interface, captive power), SPT3 is primary. When it is mainly about how the energy project is financed (loan structure, sustainability-linked KPIs, investment program framing), SPT5 is primary and SPT3 becomes secondary. SPT3 can also overlap with SPT2 when fuel/electricity affects processes; here, SPT3 is primary if the emphasis is supply and infrastructure, and SPT2 is primary if the emphasis is operational process change. So, to operationalize SPT3 consistently, the following inclusion and exclusion criteria were used.

Inclusion criteria: Content was coded to SPT3 when it focuses on (a) renewable electricity use and sourcing mechanisms (renewables share, clean electricity, PPAs,

certificates like I-REC, nuclear/solar integration through grid), (b) captive power and self-generation investments, (c) grid reliability and supply constraints (shortages, instability, redundancy needs), or (d) energy infrastructure planning connected to decarbonization (energy security, electrification readiness, and similar supply-side transitions).

Exclusion criteria: Do not code SPT3 when the text is mainly about (a) long-term targets and strategic roadmap language without energy-system detail (SPT1), (b) process-level production route adjustments (scrap ratio, DRI/EAF optimization) without focus on energy sourcing (SPT2), (c) measurement, reporting, verification, footprints, EPD/LCA, supplier mapping, and data systems (SPT4), or (d) investment financing terms and competitiveness arguments where energy is mentioned only as a project being funded (SPT5).

Exemplar Quotes

Bahrain Steel (Upstream, Bahrain): “The associated solar project is described as ‘the Kingdom’s largest solar project at 100 MW’, featuring a ‘42MW roof-top solar installation ... making it the world’s largest roof-top solar project.’ And ‘the solar plant will offset 24% of Bahrain Steel’s total power demand and reduce 17.3% of the company’s overall carbon emissions,’ with the solar project ‘strategically deployed across seven distinct zones within its facilities.’”

EMSTEEL (Midstream, UAE): “Scope 2 – Indirect Emissions from Electricity: EMSTEEL sources 86% of its total electricity from clean and renewable energy through the I-REC certification system, integrating both solar and nuclear power from

the national grid, with the remaining 14% from conventional grid supply, and is exploring long-term Power Purchase Agreements (PPAs) to further reduce its carbon footprint across midstream operations.”

Erdemir / OYAK Mining & Metallurgy (Group, Türkiye): *“Other – by-product gases reused for energy: The No.6 steam boiler uses blast furnace/steel plant/coke gases to generate steam & electricity (commissioned/in operation).”*

Mobarakeh Steel Company, MSC (Integrated, Iran): *“Highlighted Technology: Energy Recovery from Exhaust Gases (HRSG),*

Technology: Heat Recovery Steam Generator (HRSG)

Location: MSC’s 914 MW combined-cycle gas power plant

Operational Metrics:

Exhaust temperature drop: from 600 °C to 40 °C

Fuel savings: 43% less fuel per MW generated

CO₂ reduction: 15% decrease

Deployment Timeline: Commissioned in 2024

Recognition: Registered under UNFCCC CDM for verified emissions reduction

This project exemplifies MSC’s strategic integration of energy efficiency, emissions control, and climate-aligned investment.”

Hadeed / SABIC (Integrated, Saudi Arabia): *“This Roadmap is operationalized along five pathways: ‘Reliability, Energy Efficiency and Improvements; Renewable Energy; Electrification; Carbon Capture; and Green / Blue Hydrogen.”*

Jindal (Group, Oman): *“The company has prioritized the substitution of NG based grid electricity with renewable energy as immediate measure and NG with green hydrogen when it becomes technically and economically viable.”*

SNIM (Upstream, Mauritania): *“The integration of renewable energies into SNIM’s energy mix is a strategic direction, with a 4.4 MW wind farm in Nouadhibou and a 3 MW solar park in Zouerate. The report gives the 2022 energy balance as 96 % thermal and 4 % renewable, noting that in 2022 these plants supplied 11,750 MWh of renewable energy out of 328,894 MWh of total energy produced.”*

Qatar Steel (Midstream, Qatar): *“Electricity from national grid, The main source of energy consumed at Qatar Steel is electricity, supplied from Qatar’s energy grid.”*

Tosyalı (Group, Algeria): *“Tosyalı signed an agreement for the first 120 MWp part’ of a 1.2 GW self-consumption solar power plant (GES) project.... [and] the first 120 MWp phase is planned to be commissioned in 2025, that ‘the completion of this 1.2 GW project worldwide is targeted for 2027, and that construction has already started in Osmaniye for the first 120 MW part.”*

Vulcan / Jindal Steel Duqm (Project, Oman): *“a future 5 Mt/a DRI/HBI ‘hydrogen-ready’ facility using ENERGIRON® technology and refers to ‘Phase-wise Decarbonization: Includes future upgrades like renewable-powered”*

SPT4: Governance, Measurement, and Value-Chain Data Infrastructure

This theme captures how companies measure, manage, and govern decarbonization through data and systems. It includes GHG accounting (Scopes 1–3),

ISO-related measurement frameworks, CBAM/MRV readiness, product carbon footprint tools (LCA/EPD), supplier ESG assessment, and digital platforms used to track KPIs.

SPT4 overlaps strongly with SPT1 because roadmaps often mention targets, and targets often require measurement. The decision rule was: when the core content is about how emissions are measured, verified, and governed (systems, standards, tools, supplier mapping, EPD/LCA), SPT4 is primary, and SPT1 is secondary if targets appear. SPT4 also overlaps with SPT5 in sustainability-linked finance because KPI tracking is part of financing; in that case, SPT5 is primary when the loan/investment mechanism is the main point, while SPT4 is primary only when the text focuses on the MRV/KPI system itself rather than the financing. In line with the decision rule above, SPT4 was coded using the following inclusion and exclusion criteria.

Inclusion criteria: Content was coded to SPT4 when it includes (a) emissions measurement and reporting systems (MRV, verified emission reports, Scope 1/2/3 disclosures), (b) formal standards and certifications used for carbon data (e.g., ISO 14064/14067, ResponsibleSteel references where they are used for reporting/assessment), (c) product-level footprinting and customer-facing proof systems (LCA, EPDs), (d) supplier and value-chain data programs (Scope 3 mapping, supplier ESG assessments), or (e) digital tools and governance structures for KPI tracking (balanced scorecards, dedicated ESG teams that track metrics, named software platforms).

Exclusion criteria: Do not code SPT4 if the text is mainly (a) a roadmap/target statement without measurement detail (SPT1), (b) an operational route/process change without focus on measurement/verification (SPT2), (c) energy sourcing and infrastructure

description without MRV/data emphasis (SPT3), or (d) financing structures and investment conditions, even if KPIs are mentioned only as part of loan terms (SPT5).

Exemplar Quotes

Bahrain Steel (Upstream, Bahrain): “the facility will be tracked against a set of relevant KPIs and ambitious”

EMSTEEL (Midstream, UAE): “Responsible oversight is embedded within the ESG & Sustainability Team, supported by the ESG Center of Excellence (CoE), which tracks decarbonization KPIs through a Balanced Scorecard (BSC) and IBM Envizi digital Carbon measuring and reporting.”

Erdemir / OYAK Mining & Metallurgy (Group, Türkiye): “Selected: Per ton of steel output; Manual calculations or periodic audits (selected for the periodic verification aspect; calculation modality not stated).”

“Yes – regular KPI tracking. We benchmark Specific Energy Consuming program to compare efficiency with the best-performing facilities.”

Mobarakeh Steel Company, MSC (Integrated, Iran): “MSC reports its emissions using ISO 14064-1 for organizational GHG management, ISO 14067 for product-level carbon footprint, Worldsteel Climate Action participation, and GRI Standards for sustainability disclosures.”

Hadeed / SABIC (Downstream, Saudi Arabia): “Our Scope 3 emissions are measured “in accordance with the GHG Protocol.”

SPT5: Financing, Competitiveness, and Collaboration for Decarbonization

Investments

This theme captures the economic side of decarbonization: how firms fund it, justify it, and manage external constraints and partnerships. It includes investment programs, sustainability-linked loans, financing conditions, carbon cost exposure (e.g., CBAM discussions when framed as competitiveness), and collaboration models such as MoUs and joint studies. SPT5 overlaps with almost all themes because finance touches everything. The decision rule was: code SPT5 as primary when the paragraph's "main story" is money and enabling conditions, how projects are financed, what investment scale is involved, what KPIs are tied to financing, what collaboration is used to share cost or reduce risk, or how competitiveness/market access is affected. If the same paragraph also mentions targets (SPT1), energy projects (SPT3), or MRV systems (SPT4), those themes are coded secondarily unless they are clearly the central focus. In short: financing/competitiveness first = SPT5 primary; strategy first = SPT1; energy system first = SPT3; measurement system first = SPT4; process technology first = SPT2.

Inclusion criteria: Content was coded to SPT5 when it discusses (a) decarbonization-related capex/opex or investment packages, (b) financing instruments (sustainability-linked loans, green finance, external financing references, KPI-linked loan tracking), (c) competitiveness and market-access pressures tied to decarbonization economics (carbon pricing, CBAM impacts when framed as cost/market risk), or (d) cooperation and partnerships aimed at enabling decarbonization (MoUs, joint feasibility studies, cost-sharing, consortium-style initiatives).

Exclusion criteria: Do not code SPT5 when the text is mainly (a) corporate targets and roadmaps without financing content (SPT1), (b) technical process and production-route

measures without economic/financing focus (SPT2), (c) energy sourcing and infrastructure discussions without a financing/competitiveness framing (SPT3), or (d) measurement and reporting systems unless the main message is financing terms rather than MRV design (SPT4).

Exemplar Quotes

Bahrain Steel (Upstream, Bahrain): “Bahrain Steel has ‘inked an agreement with a consortium of banks for a US\$450 million Sustainability-Linked Loan (SLL)’ and that ‘the proceeds from this loan will be directed towards CAPEX for constructing the world’s largest stockyard shed with rooftop solar panels, in addition to fulfilling working capital requirements.’”

EMSTEEL (Downstream/ Midstream, UAE): “Each collaboration is structured through clear performance guarantees under EPC (Engineering, Procurement, and Construction) or O&M (Operation & Maintenance) contracts, ensuring measurable improvements in energy performance and emissions reduction.”

“EMSTEEL collaborates with a network of leading global and regional technology providers across its midstream operations, particularly within the Direct Reduction Plants (DRP), Electric Arc Furnaces (EAF), and associated auxiliary systems—to enhance performance and support decarbonization, including both performance guarantees and long-term technology transfer.”

Erdemir / OYAK Mining & Metallurgy (Group, Türkiye): “Selected: Bank/commercial loans (external borrowing).”

“Erdemir has reported raising funds through international borrowing / Eurobond issuance to support its investment program, which confirms the use of external/commercial financing for these projects. The published sources do not specify the use of PPPs, green/sustainability-linked instruments, or that internal funds are the primary source.”

“Selected: Bank/commercial loans. OYAK states the Group’s USD...50 million Eurobond issuance as part of its funding activities.”

Mobarake Steel Company, MSC (Upstream, Iran): *“MSC’s Financing Channels for Decarbonization and Efficiency Projects ...*

MSC finances its major projects through:

- Internal capital increases*
- Bank loans and facilities*
- Capital-market instruments (e.g., FX and rial Murabaha notes)*
- ... ”*

“☑ Capital-market instruments: MSC issued €200 m FX Murabaha...nd a €20 m Bank Tejarat loan for a group project company. (MSC)”

“The €305 million solar power project (Aftab Sharq), with 120 MW in its first phase, is framed as a flagship investment aiming to enhance energy self-sufficiency and emissions reduction.”

Hadeed / SABIC (Group, Saudi Arabia): *“SABIC’s Annual Report 2020 explains that the EECM team developed an overall roadmap for the energy-efficiency portfolio, which resulted in a comprehensive, consolidated target roadmap to comply with SEEC*

second cycle, which prioritized the portfolio projects list to 54 projects, carrying a cost of US\$ 1.9 billion. These are... the highest energy-saving projects for closing the gap.”

Jindal (Group, Saudi Arabia): *“Part of Net-Zero alliance group formed in the country and actively engaged with them to provide necessary industrial data and expertise in finding ways to reduce the emissions. The group is studying the possibility of deploying CCUS in the industrial zone on cost-sharing basis as one of the initiatives.”*

Mauritania SNIM (Upstream, Mauritania): *“For the dredging and extension of the ore port channel at Nouadhibou, the project, costing €110,705,411.06, was financed by SNIM, with substantial financial assistance from the European Investment Bank (EIB) and the African Development Bank (AfDB).”*

Qatar Steel (Downstream, Qatar): *“A subordinated medium-term loan facility of USD 250 million (QAR 912.5 million) signed with a syndicate of International Bank of Qatar (IBQ) and Union National Bank (UNB)...”*

“the new subordinated loan will be utilized by Qatar Steel to construct a new state-of-the-art Steel Melt Shop with a 1.1 MTA production capacity.”

Tosyali Algérie (Downstream, Algeria):

“We received the highest syndication loan granted abroad by foreign banks to a Turkish company.”

Vulcan / Jindal (Project, Duqm/Oman): *“Technology suppliers: Danieli (for Jindal Steel Sohar). Metso Outotec (for one ore-processing plant). Process technologies: Direct Hot Charging, QTB tech, BGV finishing (Sohar rolling mill). Travelling Grate Technology with “impressively low water usage of 0.03 m³ ...”*

D2: Technology Suppliers Qualitative Codebook

Theme definitions, inclusion and exclusion criteria, and selected exemplar quotes for technology suppliers.

TST1. Flexible Green-Steel Technology Architectures

TST1 captures supplier statements about modular, hybrid, and upgradeable plant architectures that enable phased decarbonization under uncertain hydrogen availability, evolving electricity mixes, and changing market requirements. The emphasis is placed on design-for-optionality (e.g., NG → H₂ blending → high-H₂ operation), rather than on policy debate or grid hardware.

Content was coded as TST1 (primary) when the passage was mainly concerned with how the plant was architected to preserve future decarbonization options (fuel-flex, modular upgrades, reversible operation). If the passage was mainly concerned with whether/when deployment was shaped by policy, infrastructure, or market conditions, TST5 was coded as primary.

Inclusion criteria: TST1 was coded when the interview content included one or more of the following:

- Hydrogen-ready or fuel-flex DRI architecture (NG/H₂ mixtures up to high-H₂).
- Phased transition logic explicitly embedded in design (upgrade paths, minimal modifications, reversible mode).
- Modularity/hybridization (units designed for staged expansion or reconfiguration).
- Engineering choices framed as “future-proofing” under uncertainty.

Exclusion criteria: Content was not coded to TST1 if the passage was mainly about:

- Grid weakness, flicker, compensation hardware, or power electronics (→ TST2).
- Scrap yard systems, impurity control, or metallic mix handling (→TST3).
- Emissions abatement hardware, WHR, or gas cleaning (→ TST4).
- Policy clarity, CBAM/carbon pricing, incentives, “only deploy if...,” or infrastructure sequencing (→ TST5).

Exemplar quotes

TS2 (SMS): *“MIDREX NG™ allows up to 30% of natural gas to be replaced with hydrogen without equipment modifications.”*

TS2 (SMS): *“MIDREX Flex™ provides the flexibility to operate on any mixture of natural gas and hydrogen (up to 100% hydrogen) with some minor modifications.”*

TS1 (Danieli): *“REVERSIBLE MODE from 100% NG to high H₂ usage.”*

TS3 (Primetals): *“MIDREX Flex is ‘designed to operate at different ratios...’”*
and highlights hydrogen-ready equipment/piping as part of the design package.

TS3 (Primetals): *“No process changes for existing plants are required... up to... about one third of the required natural gas.”* (framed as an initial blend envelope)

TST2. Energy & Power Stability under Renewable Constraints

T2 captures supplier emphasis on operability under weak/variable grids and intermittent renewables, using power electronics plus digital controls to stabilize EAF/DRI loads (flicker control, power factor improvement, fast current control) and maintain productivity/quality.

Content was coded as T2 (primary) when the passage focused on power quality, grid compliance, arc stability, or electrical control hardware/software. If the passage was mainly concerned with where electricity/hydrogen was sourced (PPAs, policy, infrastructure availability), TST5 was coded as primary.

Inclusion criteria: Content was coded to TST2 when it included:

- Weak-grid operability, flicker reduction, and IEEE 519 compliance logic.
- STATCOM/SVC substitution or elimination enabled by advanced feeders.
- Power factor improvement, fast current control, and arc-stability framing.
- Automation/control for stability under supply variability.

Exclusion criteria: Content was not coded to TST2 when the passage was mainly about:

- Plant fuel-flex/hydrogen-readiness architecture (→ TST1).
- Metallic mix/scrap variability and impurity handling (→ TST3).
- Environmental control hardware or WHR (→ TST4).
- Policy/incentives/carbon pricing or deployment prerequisites (→ TST5).

Exemplar quotes

TS1 (Danieli): *“Very low network flicker due to real time control on the arc”*
(power-quality framing).

TS1 (Danieli): *“natively ready for direct feeding of energy coming from renewable sources”* (operability with renewables).

TS2 (SMS): *“designed to achieve efficient and stable power ... including weak grids” and “0.95 minimum power factor.”*

TS2 (SMS): *“a power factor above 0.95 and 30% flicker reduction... enabling a high-power melting unit within a weak grid environment.”*

TS3 (Primetals): *“fast current control... minimizing power fluctuations... reduces flicker by a factor of 10... eliminate the need for separate compensation systems.”*

TST3. Material-Input Versatility & Scrap Optimization

TST3 captures supplier discussion of feedstock flexibility (scrap/DRI/HBI/hot metal mixes), including digital and process strategies to manage impurities, yield losses, variability, and cost—especially where scrap markets are volatile or inconsistent.

Content was coded as TST3 (primary) when the passage was mainly concerned with metallics quality/impurities/mix envelope and scrap logistics/charging optimization. If the passage was mainly concerned with grid/power stability, it was coded to TST2; if it was mainly concerned with route architecture for fuel switching, it was coded to TST1.

Inclusion criteria: Content was coded to TST3 when it included:

- Handling variable scrap grades, impurity management, yield, and quality stability.
- Continuous charging/preheating logic tied to scrap variability.
- Scrap-yard automation, sorting/cleaning, and digital material tracking.
- Operating envelopes for mixed metallic inputs (DRI/HBI + scrap; hot metal blends).

Exclusion criteria: Content was not coded to TST3 when the passage was mainly about:

- Fuel-flex/hydrogen-ready design (→ TST1).

- Grid power quality, flicker, compensators, or power electronics (→ TST2).
- Emissions abatement hardware, WHR, or gas cleaning (→ TST4).
- Policy/infrastructure prerequisites and adoption timing (→ TST5).

Exemplar quotes

TS2 (SMS): *“ready to accept all mixes of metallics, up to 60% hot metal, and 100% cold or hot DRI.”*

TS3 (Primetals): *“Melt Expert... increases process stability, and helps ... overcome scrap fluctuations.”*

TS1 (Danieli): *“continuous scrap-charging and preheating”* (used to stabilize scrap-based operation).

TS3 (Primetals): *“scrap preheating”* and performance framing (kWh/t reduction logic) tied to feed efficiency.

TS1 (Danieli): *“automatic scrap management”* (positioned as part of meltshop automation).

TST4. Environmental Control & Waste-Heat Recovery

TST4 captures supplier claims and explanations about engineering controls that reduce environmental load: fume capture, dedusting/gas cleaning, dioxin control, and waste-heat recovery systems that cut energy use and carbon intensity while supporting compliance.

Content was coded as TST4 (primary) when the passage focused on abatement hardware/system design or WHR energy recovery. If the passage focused on external reporting/EPDs/MRV governance, it was treated as part of the producer-side governance

theme, unless MRV tooling was explicitly discussed by the supplier as part of the offered system.

Inclusion criteria: Content was coded to TST4 when it included:

- Gas cleaning/dedusting systems, fume capture scope, and BAT claims.
- Quantified emissions abatement (e.g., dioxin limits).
- Waste-heat recovery (capture/convert waste heat into usable energy).
- Environmental compliance framed as a design requirement.

Exclusion criteria: Content was not coded to TST4 when the passage was mainly about:

- Fuel-flex plant architecture (→ TST1).
- Grid power quality stabilization (→ TST2).
- Metallic input variability and scrap optimization (→ TST3).
- Adoption prerequisites, carbon price/CBAM, incentives, or sequencing (→ TST5).

Exemplar quotes

TS1 (Danieli): “*capture and treat the primary fumes... and the secondary fumes...*” (system boundary framing).

TS1 (Danieli): “*controls PCDD-F dioxin emissions below 0.1 ng-TEQ/Nm³.*”

TS2 (SMS): “*the residual emission... (Dioxins) can be limited below 0.1 ng I-TEQ/Nm³, if demanded.*”

TS3 (Primetals): “*capture and convert waste heat... transforming it into valuable energy resources... enhancing plant efficiency and reducing emissions.*”

TS2 (SMS): “*almost complete interception of... varying gas volumes*” (design-for-variability in gas cleaning).

TST5. Deployment Feasibility & Policy Dependency

TST5 captures supplier statements in which green-steel deployment was framed as contingent on enabling conditions: policy clarity, carbon pricing/CBAM pressure, incentives, market demand/premiums, and sequencing with infrastructure (grid, hydrogen, logistics). This theme captures how technical options were linked to bankability and timing.

Content was coded as TST5 (primary) when the passage was mainly concerned with whether/when adoption was driven by policy, economics, infrastructure readiness, or market demand. If the passage was mainly concerned with how the plant was engineered to be flexible once deployed, TST1 was coded as primary.

Inclusion criteria: Content was coded to TST5 when it included:

- Policy dependency (carbon price, subsidies, mandates, incentives).
- CBAM/compliance as an adoption driver or constraint.
- Green-steel cost premiums and willingness-to-pay signals.
- Infrastructure prerequisites (hydrogen availability, strong grid connection, logistics readiness).
- Sequencing language (step-by-step rollout conditioned on external readiness).

Exclusion criteria: Content was not coded to TST5 when the passage was mainly about:

- Technical plant architecture for fuel switching (→ TST1).

- Electrical stability/flicker/power electronics (→ TST2).
- Metallic input flexibility and scrap systems (→ TST3).
- Abatement hardware and WHR (→ TST4).

Exemplar quotes

TS2 (SMS): *“Green steel... is currently more expensive... Customers would need subsidies, grants, or other incentives to afford it.”*

TS2 (SMS): *“without a carbon border adjustment mechanism (CBAM), companies could be tempted to relocate production...”* (policy mechanism framing).

TS2 (SMS): *“Each steel producer has to set up its own roadmap... depending on the actual state... (sustainability, regulations, market, etc.).”*

TS3 (Primetals): *“strong grid connection, optimal logistics, and stable, competitively priced low CO₂ energy”* (site feasibility conditions).

TS3 (Primetals): *“the transition to green steel production will not happen overnight... step-by-step process.”*

TS3 (Primetals): *“The current regulatory framework... effective... yet practical to reduce emissions globally... CBAM...”* (regulatory role in deployment framing).

APPENDIX E

THEME–RQ MAPPING AND NVIVO CODING MATRICES

Table E1

Themes and Research Questions Relationships (Steel Producers' Interview, n=18)

Theme title	Relationship to RQ1 (integration & economic feasibility)	Relationship to RQ2 (technical pathways & infrastructure)	Relationship to RQ3 (country conditions, policy, international regimes)
SPT1: Strategic Decarbonization Roadmaps and Value-Chain Positioning	Shows how decarbonization is integrated into corporate strategy, framing feasibility through competitiveness, market access, and risk management (not isolated projects).	Indicates the pathway direction and sequencing (milestones, retrofit priorities) that shapes subsequent technology and investment choices.	Captures how national targets, regulation (e.g., CBAM-related pressure), and investor/buyer expectations influence roadmap ambition and pace.
SPT2: Production-Route Decarbonization: DRI–EAF, Scrap Use and Process Optimization	Provides direct evidence of operational integration (route/process changes) and the trade-offs between emissions, cost, productivity, and product quality.	Specifies “what is implemented” at plant level (route choices, optimization levers), revealing which pathways are technically feasible in practice.	Links adoption feasibility to country-conditions such as gas availability, scrap supply/quality, ore/pellet suitability, and installed base constraints.
SPT3: Energy Mix and Infrastructure Transformation: Captive Power, Renewables and Grid Interfaces	Connects decarbonization to energy cost and reliability management, showing how power strategy protects margins while reducing Scope 2 exposure.	Identifies infrastructure configurations required for scale (captive power, renewables integration, grid interface capacity, firming solutions for DR/EAF loads).	Demonstrates dependence on country-specific resources, tariffs, power-market rules, and regulatory permissions for self-generation and grid connection.
SPT4: Governance, Measurement and Value-Chain Data Infrastructure	Supports feasibility and competitiveness through auditable measurement (KPIs, footprints) needed for operational control and low-carbon product claims.	Defines the enabling data/MRV backbone for designing, managing, and scaling any pathway across upstream–midstream–downstream nodes.	Shows how institutional capacity and international compliance demands (MRV, certification, buyer requirements) shape adoption and credibility of claims.

SPT5: Financing, Competitiveness and Collaboration for Decarbonization Investments	Explains when integration becomes viable: financing structures, risk-sharing, and partnerships that determine bankability and competitive outcomes.	Shows that pathway selection is constrained by finance and partner availability, what gets built depends on funding terms and delivery capability.	Highlights the interaction of national credit conditions, access to development finance, and cross-border collaboration mechanisms that enable diffusion.
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Table E2

Themes and Research Questions Relationships (Technology Suppliers' Interviews, n = 3)

Theme title	Relationship to RQ1 (integration & economic feasibility)	Relationship to RQ2 (technical pathways & infrastructure)	Relationship to RQ3 (country conditions, policy, international regimes)
TST1: Flexible Green-Steel Technology Architectures	Explains how integration is engineered through fuel-flex and modular architectures that protect operability while reducing stranded-asset risk during decarbonization.	Specifies pathway logic (NG→H ₂ blending, upgradeability, reversible operation) and the technical configuration choices required for staged scale-up.	Shows how technology design responds to external uncertainty (hydrogen availability, standards evolution, buyer requirements), shaping adoption strategies across countries.
TST2: Energy & Power Stability under Renewable Constraints	Identifies integration measures (power-quality control and automation) that protect productivity and cost under variable supply, supporting feasibility in operations.	Defines infrastructure-facing requirements for scale (weak-grid operability, grid-code compliance, flicker/harmonics control, reactive power management) for high-power EAF/DRI systems.	Connects diffusion constraints to country-specific grid conditions, connection approvals, and utility coordination capacity.
TST3: Material-Input Versatility & Scrap Optimization	Describes how integration is maintained when feedstocks vary (scrap/DRI/HBI/hot metal), including impurity/yield controls that protect product quality and cost.	Clarifies scaling constraints and operational envelopes associated with metallics availability, scrap logistics, and charging/preheating strategies.	Links feasibility to country conditions in scrap markets and DR-grade metallics access, including logistics and material governance factors.
TST4: Environmental	Shows how emissions control and WHR are integrated as combined	Specifies configuration elements that matter	Demonstrates how permitting stringency and environmental

Control & Waste-Heat Recovery	compliance-and-efficiency packages that reduce carbon intensity while improving energy performance and ROI logic.	at scale (capture boundaries, gas-cleaning sizing, BAT alignment, WHR integration) as part of plant design.	standards influence technology selection and diffusion pathways.
TST5: Deployment Feasibility & Policy Dependency	Explains when integration becomes investable (cost premiums, incentives, risk allocation) rather than only technically available.	Frames scaling as sequenced investment conditional on infrastructure readiness (grid, hydrogen, logistics) and the pacing of external system build-out.	Captures how policy clarity, carbon pricing/CBAM-type pressures, standards credibility, and collaboration/finance ecosystems shape bankability and timing.

Table E3

Case-Theme Coded References/Coverage Matrix (Steel Producers, Company-Cases n = 18)

Cases/Themes	SPT1	SPT2	SPT3	SPT4	SPT5
1 : Downstream_EMSTEEL	9	12	6	14	5
2 : Downstream_Erdemir	5	1	7	10	6
3 : Downstream_Hadeed	8	7	4	13	3
4 : Downstream_Mobarake	10	11	14	23	16
5 : Downstream_Qatar Steel	4	5	4	11	7
6 : Downstream_Tosyali	9	9	7	12	17
7 : Midstream_EMSTEEL	7	19	3	8	4
8 : Midstream_Erdemir	5	14	6	5	7
9 : Midstream_Hadeed	10	6	7	21	13
10 : Midstream_Jindal	2	10	3	6	4
11 : Midstream_Mobarake	3	8	20	9	15
12 : Midstream_Qatar Steel	13	10	7	21	12
13 : Midstream_Tosyali	14	13	12	21	13
14 : Midstream_Vulcan Green Steel	10	10	3	12	7
15 : Upstream_Bahrain Steel	12	3	6	17	14
16 : Upstream_Erdemir	9	6	4	7	6
17 : Upstream_Mauritania	14	1	12	12	11
18 : Upstream_Mobarake	8	10	8	12	7

Table E4

Theme intensity and dispersion summary across company-cases (NVivo references-based indicators, n = 18)

Theme	Total references	Average refs/case	Median refs/case	Min refs/case	Max refs/case	#cases coded
SPT1	152	8.44	9.0	2	14	18
SPT2	155	8.61	9.5	1	19	18
SPT3	133	7.39	6.5	3	20	18
SPT4	234	13	12.0	5	23	18
SPT5	167	9.28	7.0	3	17	18

Table E5

Stage Emphasis by Theme (Steel Producers, Company-Cases $n = 18$ $n=18$)

Theme	Upstream (n=4) Refs/case	Midstream (n=8) Refs/case	Downstream (n=6) Refs/case	Stage order (highest to lowest)
SPT1	10.75	8.00	7.50	Upstream → Midstream → Downstream
SPT2	5.00	11.25	7.50	Midstream → Downstream → Upstream
SPT3	7.50	7.63	7.00	Midstream → Upstream → Downstream
SPT4	12.00	12.88	13.83	Downstream → Midstream → Upstream
SPT5	9.50	9.38	9.00	Upstream → Midstream → Downstream

Table E6

Within-stage ranking of themes

Stage (N cases)	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Upstream (4)	SPT4: 48 (26.8%)	SPT1: 43 (24.0%)	SPT5: 38 (21.2%)	SPT3: 30 (16.8%)	SPT2: 20 (11.2%)
Midstream (8)	SPT4: 103 (26.2%)	SPT2: 90 (22.9%)	SPT5: 75 (19.1%)	SPT1: 64 (16.3%)	SPT3: 61 (15.5%)
Downstream (6)	SPT4: 83 (30.9%)	SPT5: 54 (20.1%)	SPT1: 45 (16.7%)	SPT2: 45 (16.7%)	SPT3: 42 (15.6%)

Table E7

Supplier Case–Theme Coded References Matrix ($n = 3$)

Supplier case	TST1	TST2	TST3	TST4	TST5
Danieli	60	10	25	25	13
SMS group	45	13	28	17	10
Primetals Technologies	63	13	24	24	15

APPENDIX F

ABBREVIATIONS AND ACRONYMS

Table F1
Abbreviations and Acronyms and their descriptions

Abbreviation / Acronym	Description
AD×EF	Activity Data × Emission Factor(s)
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
BF	Blast Furnace
BF/BOF	Blast Furnace / Basic Oxygen Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CBI	Cold Briquetted Iron
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CSR	Corporate Social Responsibility
DRI	Direct Reduced Iron
EAf	Electric Arc Furnace
EMT	Ecological Modernization Theory
EPC	Engineering, Procurement, and Construction
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
HBI	Hot Briquetted Iron
H₂-DRI	Hydrogen-Based Direct Reduced Iron
IEA	International Energy Agency
IIoT	Industrial Internet of Things
I-REC	International Renewable Energy Certificate
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MENA	Middle East and North Africa
MRV	Measurement, Reporting, and Verification
NG	Natural Gas
O&M	Operation and Maintenance
OHF	Open Hearth Furnace
OPEX	Operating Expenditure
PCR	Product Category Rules
PPA	Power Purchase Agreement
RBV	Resource-Based View
ROI	Return on Investment

SPT	Steel Producer Theme
TST	Technology Supplier Theme
UNIDO	United Nations Industrial Development Organization
USD	United States Dollar
WACC	Weighted Average Cost of Capital
WHR	Waste-Heat Recovery
WSA	World Steel Association