"A SUSTAINABLE VALUE CHAIN STRATEGY FOR STEEL INDUSTRY DECARBONIZATION FEATURING DANIELI AS A CASE STUDY ON GREEN STEEL TECHNOLOGIES"

Research Paper

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"Abstract"

The steel industry, responsible for approximately 7-9% of global CO2 emissions and a significant source of industrial greenhouse gases, faces an urgent need for comprehensive decarbonization efforts to align with international climate targets, as outlined in the Paris Agreement and the International Energy Agency's (IEA) Net Zero by 2050 report, to achieve long-term sustainability and global emission reduction goal. This paper discusses the solutions offered by DANIELI throughout the steel production process from beginning to end with a focus, on innovations from the upstream, to the downstream process. Key technologies include the hydrogen-based ENERGIRON Direct Reduction process, the Digimelter® EAF system, and the ECOGRAVEL® slag recycling solution, each significantly reducing emissions and energy consumption. The midstream stage features automation tools like Q-Melt for process optimization, while downstream efforts focus on emissions control with advanced filtration systems. Global collaborations, such as partnerships with Liberty Steel and Algoma Steel, illustrate Danieli's commitment to transitioning steel production towards low-carbon, efficient, and circular processes. Danieli's holistic approach sets a new standard for a sustainable, net-zero steel industry.

Keywords: Steel Industry Decarbonization, Green Technologies, Sustainable Steelmaking, Emission Reduction Strategies.

1 Introduction

The steel industry, a cornerstone of global industrial activity, is currently one of the largest contributors to human-caused greenhouse gas (GHG) emissions, accounting for around 7-9% of the total. Recent studies and industry roadmaps highlight both the significant potential and the urgent need for decarbonizing the steel sector (IEA, 2020). The transition to green steel will not only reduce emissions but also enhance the industry's resilience, ensuring it remains competitive in an increasingly carbon-conscious market. The International Energy Agency (IEA) has identified several pathways to cut emissions by at least 50% by 2050 (Molly Lempriere, 2023). Achieving green steel production on a commercial scale could require between €2 trillion and €3 trillion in capital expenditures (CAPEX), along with the development of vast renewable energy infrastructure to power these new production methods (Stamm and Naujok, 2023). To tackle these challenges effectively, it is crucial to look at the decarbonization of the steel industry through a value chain lens. This means considering every stage, from upstream activities to midstream innovations in manufacturing processes, and downstream efforts involving customer engagement and recycling. Decarbonizing the steel sector also requires a coordinated global effort and substantial investment in research, development, and the deployment of new technologies. Through the integration of renewable energy, process innovations, and circular economy principles, the steel industry has the opportunity to lead in the shift towards a sustainable, low-carbon future. By taking this holistic approach, the steel industry can better integrate decarbonization into all aspects of its operations, helping pave the way to a net-zero future. Several steel companies have made significant progress in decarbonization by leveraging innovative technologies and strategic investments, such as hydrogen-based steelmaking, carbon capture, utilization, and storage (CCUS) systems, and enhanced automation techniques. In this article, we explore these advancements by first looking at the diverse technologies and initiatives implemented by successful companies in the steel industry to decarbonize the value chain. We then shift focus to Danieli's green steel technologies, highlighting their comprehensive approach to sustainable steelmaking (UNECE, 2022). By showcasing Danieli's solutions for minimizing emissions, optimizing energy, and achieving zero-waste production, this article illustrates the broader industry efforts and the path forward for achieving a low-carbon steel future (SGRO, 2022).

2 Overview Of Porter Value Chain Model

A value chain model for the manufacturing sector was created by Michael E. Porter in 1985. It consists of five primary and four supporting activities. Due to the growth of steel plants, the value chain model is expanded to the steel production industry and is now a continuous process for their sustainability and growth (Acharyulu, Subbaiah and Rao, 2015). Due to its unique nature, the steel manufacturing business uses a modified Porter value chain model with five primary and six supporting activities (Figure 1). The value chain for the steel manufacturing sector follows Porter's model but differs in some activities and applications.

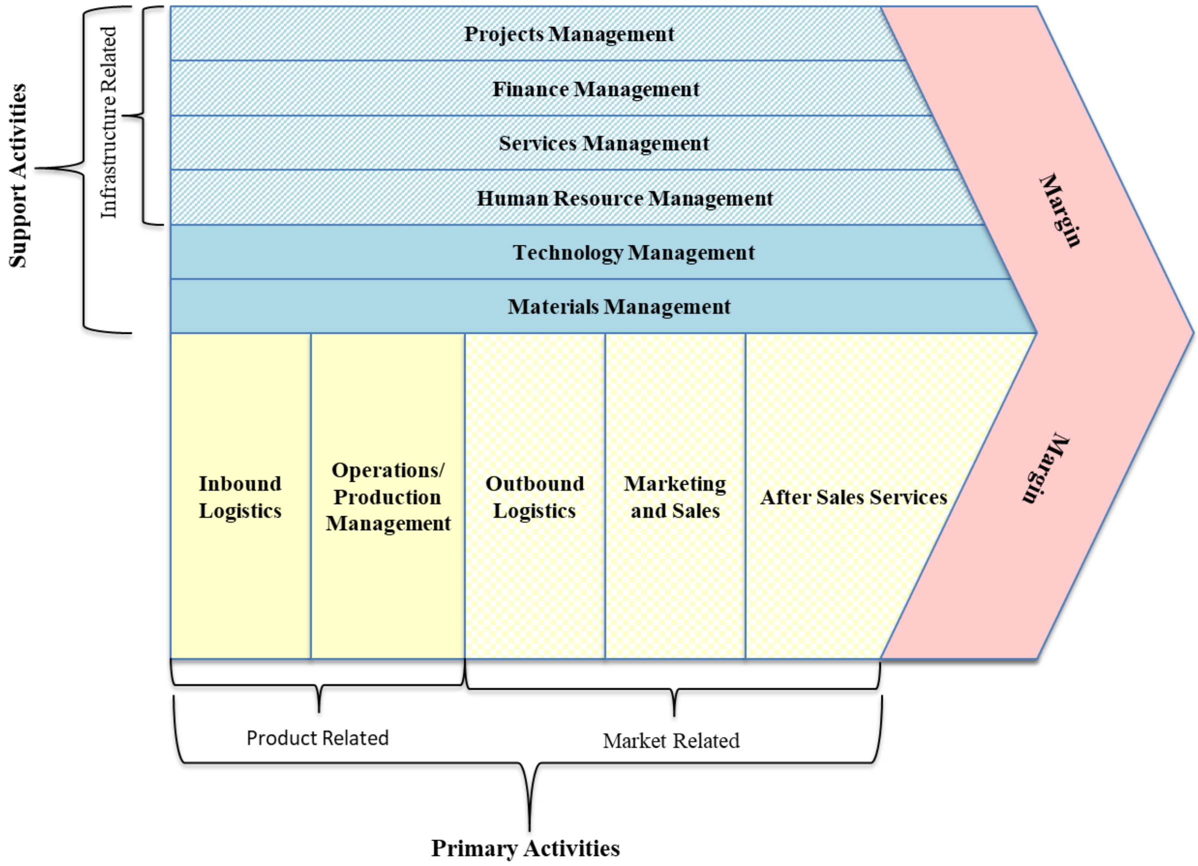

Figure 1. Porter value chain model for the steel industry (Acharyulu, Subbaiah and Rao, 2015)

In the context of decarbonization, the value chain in the steel industry comprises three main stages, as illustrated in Figure 2: upstream, midstream, and downstream processes. Each stage involves distinct primary and support activities that not only transform raw materials into final products but also strategically reduce carbon emissions and enhance sustainability at every step.

The upstream stage focuses on activities such as mining, logistics, and raw material preparation. During this stage, value is added by optimizing raw material extraction, preparation, and transportation to minimize carbon footprints through efficient energy use, improved supply chain management, and the adoption of greener mining practices.

The midstream stage, which includes iron and steel making, is a critical phase for decarbonization efforts. Here, value is created by implementing advanced technologies and innovative processes that maximize production efficiency while significantly lowering carbon emissions. This includes the adoption of low-carbon production methods such as hydrogen-based direct reduction and the use of electric arc furnaces (EAFs), which help reduce reliance on carbon-intensive blast furnace operations. Additionally, process innovations, like carbon capture, utilization, and storage (CCUS), further enhance value by reducing emissions and improving the sustainability profile of intermediate steel products. Finally, the downstream stage, involving finishing, distribution, and market application, contributes to decarbonization by tailoring products to meet stringent environmental standards, optimizing logistics for reduced emissions, and engaging with customers on sustainability practices. Value is enhanced through the development of green steel products that align with market demand for sustainable materials, ensuring compliance with environmental regulations and fostering customer loyalty by emphasizing eco-friendly production practices. This comprehensive approach to the value chain not only focuses on the efficient production of steel but also on creating value through strategic decarbonization across the entire process, from raw material sourcing to end-user application (Rechberger *et al.*, 2020; Name *et al.*, 2023).

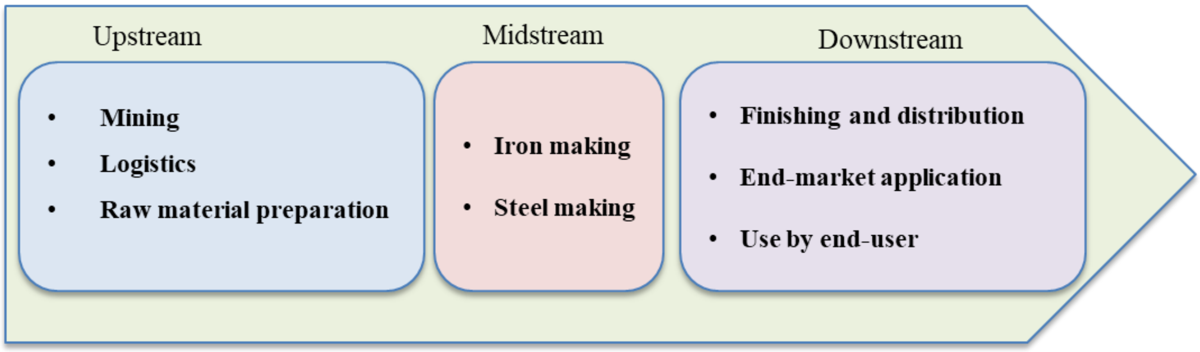

Figure 2. Various stages of the value chain

3 Decarbonizing The Steel Value Chain

The steel industry, as one of the largest contributors to global CO2 emissions, plays a crucial role in efforts to achieve decarbonization worldwide. Companies across the sector are employing a wide range of innovative strategies spanning the entire value chain, from mining and logistics to steelmaking and product distribution, to reduce their carbon footprint.

In the upstream phase, which includes mining, raw material processing, and logistics, companies such as SSAB, Tata Steel, Salzgitter, and ArcelorMittal are at the forefront of decarbonization efforts. SSAB and Salzgitter have adopted high-grade ores to reduce energy consumption during processing, while Tata Steel and SSAB are also embracing the electrification of mining machinery to lower emissions from raw material extraction. Additionally, ArcelorMittal and Voestalpine are integrating advanced digital tools like AI and IoT into their logistics systems, using electric trucks and optimized rail networks to minimize transportation-related emissions. ArcelorMittal's Smart Carbon pathway includes small-scale projects such as Steelanol (which converts CO2 into ethanol), Top Gas Recycling, and Torero, which capture and utilize waste gases, though their scalability remains limited.

In the midstream phase, groundbreaking technologies are driving decarbonization efforts in ironmaking and steelmaking. Hydrogen-based direct reduction (H2-DRI) combined with electric arc furnaces (EAF) is a major focus, with SSAB’s HYBRIT project and ArcelorMittal’s Innovative DRI system leading the way. POSCO’s HyREX technology is also a significant advancement, replacing coking coal with hydrogen in a fluidized bed system using iron ore fines, offering a near-carbon-neutral solution. Tata Steel’s HIsarna process bypasses traditional coking and sintering, reducing CO2 emissions by about 20%. Electrolysis-based steelmaking, pursued by companies like Salzgitter and Thyssenkrupp, offers another near-zero emissions option, especially when powered by renewable energy. Carbon capture, utilization, and storage (CCUS) technologies are widely employed across the industry. ArcelorMittal’s Steelanol and 3D projects, along with Thyssenkrupp’s Carbon2Chem initiative, capture CO2 emissions and repurpose them for industrial applications. Nippon Steel uses Super COURSE 50, a hydrogen injection technology for blast furnaces, which relies on CCUS for capturing residual CO2 emissions (Nocholas and Basirat, 2024). Additionally, China Baowu has partnered with ExxonMobil to explore CCUS options, both for utilization and sequestration, while ArcelorMittal's IGAR project combines natural gas with blast furnace CO2 to produce syngas for iron reduction. However, reliance on CCUS has drawn criticism, with some arguing it may serve as "greenwashing" for companies like ArcelorMittal and Nippon Steel that continue to maintain blast furnace operations instead of fully transitioning to hydrogen or other low-carbon technologies.

Further downstream, decarbonization efforts focus on finishing, distribution, and product lifecycle improvements. POSCO’s HyREX represents a shift toward green steel production, while Voestalpine and ArcelorMittal are concentrating on green logistics to reduce emissions from transportation. For example, Nippon Steel’s advanced coatings extend the lifespan of steel products, helping to reduce lifecycle emissions, particularly in large infrastructure projects. Circular economy principles are also key, with Tata Steel pioneering the recycling of by-products like slag for construction materials, which reduces waste and environmental impact. ArcelorMittal’s XCarb initiative integrates carbon credits and recycled content to offer carbon-neutral steel products.

Meanwhile, companies in developing regions are addressing decarbonization with a mix of advanced and traditional methods. China Baowu is investing in DRI technology and exploring overseas DRI facilities in Australia, while also investing in high-grade iron ore extraction in West Africa, positioning the region as a potential green steel production hub. The company is also exploring CCUS with Shell, BASF, and Sinopec. POSCO, despite focusing on hydrogen-based steelmaking, is building new blast furnaces in South Korea and Indonesia, with plans for CCUS, including a collaboration with PETROS for CO2 storage in Malaysia. JFE Steel, in collaboration with Kansai Electric Power Company (KEPCO), is exploring CCS projects for CO2 storage both domestically and internationally.

Although the steel industry is making significant strides in green hydrogen, DRI, and recycling technologies, its continued reliance on CCUS, particularly in regions where blast furnaces are dominant, highlights the complex path to full decarbonization. By integrating renewable energy, circular economy principles, and cutting-edge technologies, the sector can reduce its carbon footprint, meet global climate targets, and maintain competitiveness in an increasingly carbon-conscious market (SGRO, 2022).

4 DANIELI’s Green Steel Technologies

Danieli is a global leader in the development of green technologies for sustainable steelmaking, addressing the challenges of reducing carbon emissions, optimizing energy use, and creating zero-waste production processes. Their comprehensive approach spans every stage of steel production, upstream, midstream, and downstream, implementing cutting-edge solutions for decarbonization, energy recovery, and resource recycling. These technologies and innovations are categorized as primary activities related to operation and production management and demonstrate Danieli’s commitment to transforming the steel industry toward a greener future (Danieli Environment, 2024).

4.1 Upstream technologies and initiatives

Danieli has developed several innovative technologies in the upstream stage of steel production aimed at reducing carbon emissions and optimizing resource consumption.

ECOGRAVEL® system for zinc recovery and slag recycling

The ECOGRAVEL® system focuses on the recovery and recycling of valuable by-products from EAF and Basic Oxygen Furnace (BOF) slag. Since it involves handling and processing waste materials from steel production into reusable products, it falls under operations management. The system extracts zinc for reuse and processes slag into aggregate materials suitable for construction, thereby supporting the company's circular economy approach. As a support activity, it enhances the technology development aspect of the value chain, integrating innovative systems to improve sustainability and efficiency (Danieli, 2024).

Zinc recovery from EAF dust via induction furnace

Danieli's zinc recovery process which uses an induction furnace to extract zinc from EAF dust is another primary activity. Similar to the ECOGRAVEL® process, the zinc recovery from Electric Arc Furnace (EAF) dust using an induction furnace is also directly linked to the steel production operations. This activity aims to reclaim valuable materials, thus contributing directly to the production process by minimizing waste. This process not only recovers valuable materials but also ensures that less waste is sent to landfills. By converting what would otherwise be waste into reusable resources, the zinc recovery process supports the core operations of raw material preparation and enhances overall production sustainability.

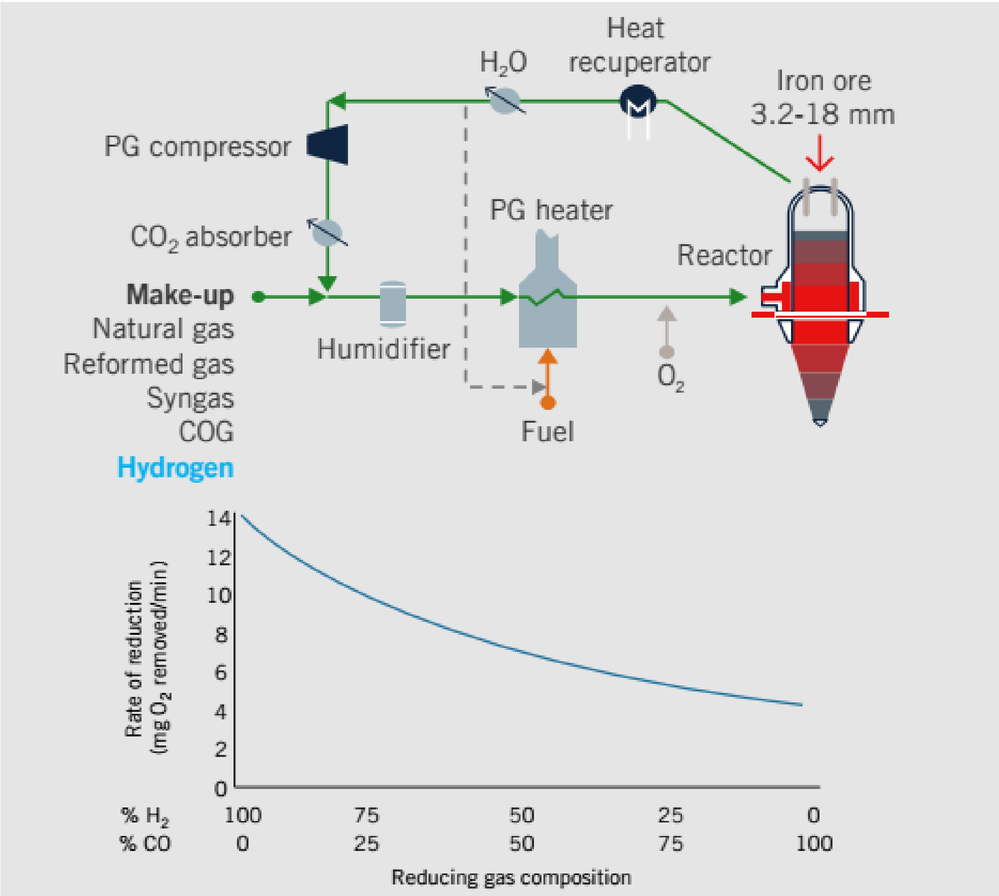

Figure 3. ENERGIRON process using various gases, including hydrogen, to produce DRI and HBI (Hertrich Giraldo, 2021)

Hydrogen-based ENERGIRON direct reduction process

This technology, developed in collaboration with Tenova, is a key primary activity related to the steel production stage, in Danieli's upstream operations. The ENERGIRON DR process enables the flexible production of Direct Reduced Iron (DRI) using various reducing gases such as hydrogen, natural gas, and syngas. It is designed to produce Cold DRI, Hot DRI, and Hot Briquetted Iron (HBI), reducing CO2 emissions by up to 86% compared to traditional blast furnace routes. By transforming raw materials into DRI, this process enhances operational efficiency while complying with stringent environmental regulations. Additionally, the system incorporates carbon capture, utilization, and storage (CCUS). As shown in Figure 3, the technology offers a scalable pathway toward the use of 100% hydrogen over time, supporting the industry’s long-term decarbonization goals and offering high-quality DRI products at low operational costs (Lapasin, 2023).

4.2 Midstream technologies and initiatives

During the midstream phase which contains iron and steel making, Daniel's technologies shine by boosting energy efficiency and cutting CO2 emissions while also improving material recovery and automating processes effectively (Danieli, 2024).

Danieli Digimelter® for scrap and DRI melting: The Digimelter® is Danieli's modern solution for electric arc furnace (EAF) steelmaking. It is directly involved in the melting process, which is a core production activity in steel manufacturing. It features Q-One Power Feeder technology, which offers precise control over arc current and voltage, reducing disturbances on the power grid and enabling smooth integration of renewable energy sources. The Digimelter® is able to melt scrap and direct reduced iron(DRI) all while keeping costs low as a lower cost option compared to the traditional blast furnace methods (Burin, 2023).

Q-Melt intelligent controller: The Q Melt smart Controller is a cutting edge automation system designed to enhance the melting process, within electric arc furnaces efficiently by utilizing sensors such as Lindarc gas analyzers for continuous monitoring and adjustment of furnace operations, in real time to decrease energy usage and enhance operational stability. Moreover the Endless Charging System (ECS®) ensures a supply of scrap and DRI which not reduces the environmental footprint but also enhances energy efficiency.

The energy clean heat recovery (CHR®) system: The CHR® system directly affects the production process by recovering waste heat and converting it into electricity. This system is created by Danieli captures and utilizes waste heat from EAF emissions to generate electricity using an Organic Rankine Cycle (ORC) turbine system. With this technology the CHR® system reduces energy waste by, around 30% enhancing the energy efficiency of steel production.

Fume and noise emission control systems (Dog House & Elephant House): Daniel Industries has implemented fume and noise control solutions named the Dog House and Elephant House to lessen harm caused by steel production activities. These systems effectively capture dust and fumes, preventing pollutants from being released into the atmosphere while also minimizing noise pollution from steel production.

Induction furnace for EAF dust recovery: Danielis innovative induction furnace approach as illustrated in Figure 4., retrieves materials, like raw zinc oxide and pig iron from the leftover electric arc furnace (EAF) dust produced during steel production processes. This method cuts down on waste, and also promotes a circular economy by transforming inactive slag into usable resources, a practice that enhances the eco friendliness of midstream operations while lessening the detrimental effects of waste disposal, on the environment.

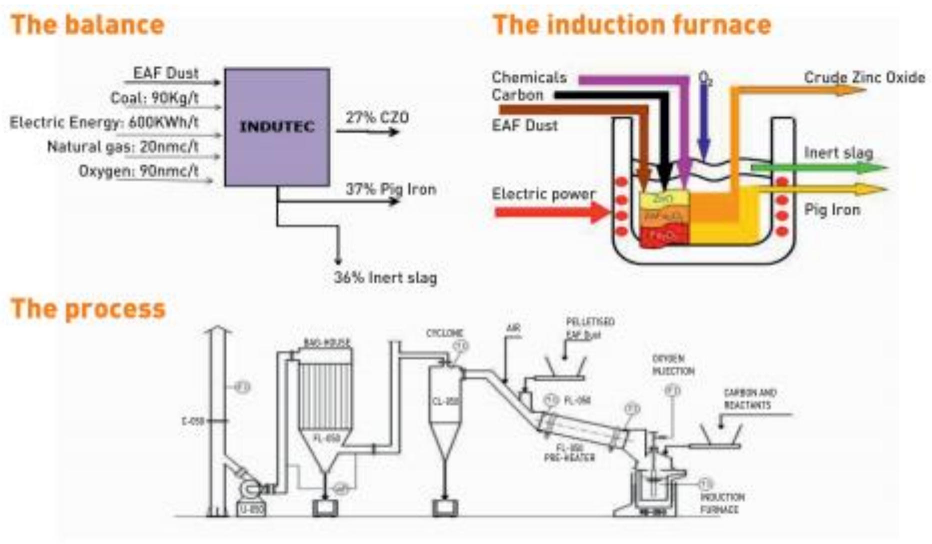

Figure 4. *Induction furnace process for recovering zinc oxide and pig iron from EAF dust*

4.3 Downstream technologies and initiatives

In the downstream phase, Danieli focuses on post-production resource recovery and further emission control to ensure minimal environmental impact.

ECOGRAVEL® slag recovery system

Extending from the upstream processes, Danieli's ECOGRAVEL® system continues to play a crucial role in the downstream by converting BOF, EAF, and ladle slag into valuable materials. This system reduces waste and promotes the reuse of slag in various industrial applications, supporting a zero-waste approach to steel production (Danieli, 2024).

Activated carbon filter for dioxin removal

The activated carbon filter is primarily used to ensure compliance with environmental standards by reducing harmful emissions. While not directly linked to core production, it supports the overall environmental performance of the steel products and the production process, contributing to after-sales environmental services and ensuring customer and regulatory satisfaction. Danieli integrates advanced filtration technologies to reduce harmful emissions. The activated carbon filter is designed to remove dioxins from the exhaust gases generated during the steelmaking process, ensuring compliance with strict environmental regulations and improving air quality.

Fume treatment plant

This technology helps in managing post-production emissions and aligns with regulatory compliance, which is crucial in providing after-sales support in terms of environmental impact mitigation. Danieli's Fume Treatment Plant (FTP) ensures that any residual pollutants from the steel production process are captured and treated before being released into the atmosphere. This technology plays a critical role in reducing air pollution and maintaining a clean, environmentally friendly production facility.

In line with these downstream decarbonization efforts, the UK's steel industry presents a practical example of how circular economy principles are implemented through efficient scrap collection, recycling, and reintroduction into the steelmaking process. As illustrated in Figure 5., the UK generates approximately 11.3 million tonnes of scrap annually, of which a significant portion is recycled, contributing to the production of 7.3 million tonnes of steel. This closed-loop system, from scrap recovery to steelmaking and post-consumer recycling, highlights the potential for resource efficiency and reduced emissions, key factors in the journey toward sustainable steel production (Danieli, 2022).

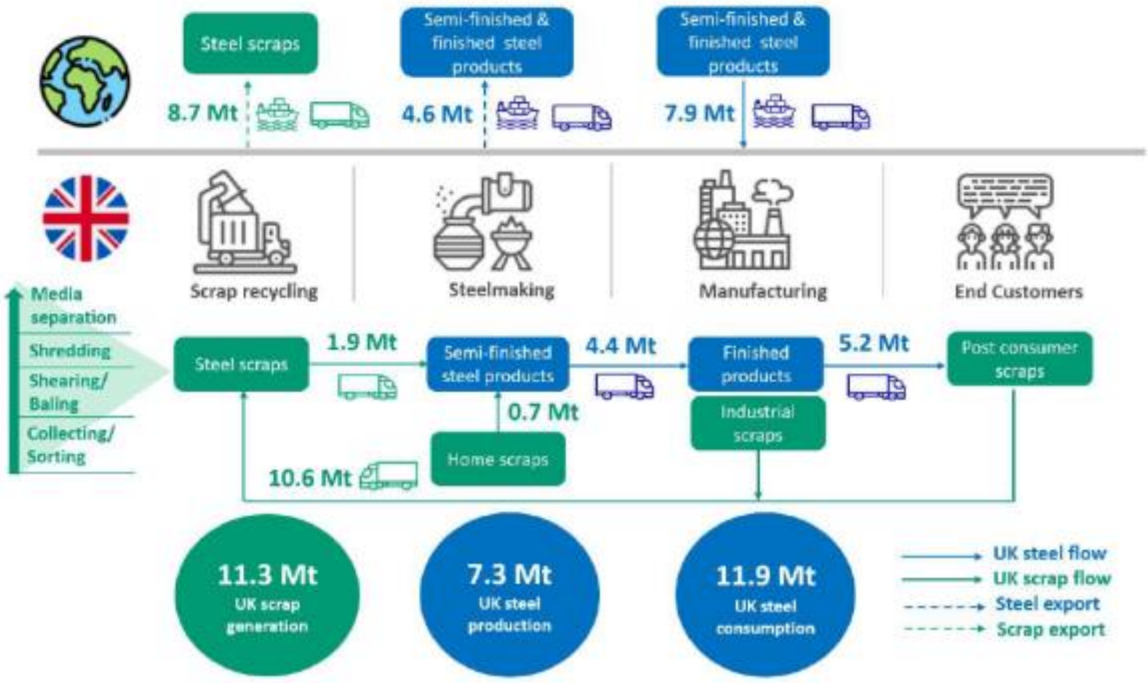

Figure 5. *UK steel scrap flow and recycling process supporting sustainable steel production (Danieli, 2022)*

4.4 Global collaborations and initiatives

Danieli's commitment to sustainable steelmaking is further evidenced by its global partnerships and projects aimed at decarbonizing steel production:

Industrial transition to EAF with liberty steel and algoma steel

Danieli has partnered with major steel producers, including Liberty Steel in Europe and Algoma Steel in Canada, to help transition from traditional blast furnace operations to electric arc furnaces. These projects aim to reduce CO2 emissions by up to 80%, with Liberty Steel aiming for carbon neutrality by 2030.

Danieli MIDA Minimills

Danielis MIDA Minimills employ the Digimelter® alongside high speed casting and direct rolling technologies, for steel production efficiency and sustainability across locations such, as India, Bangladesh and the USA.The aim is to enhance steel production while reducing energy consumption and environmental impact through advanced automation and the use of renewable energy sources.These Minimills are crafted to optimize resource utilization and minimize wastage effectively. When Digimelter® is paired with high speed casting technology it speeds up the process. Cuts down production time. Additionally direct rolling eliminates the necessity, for reheating leading to energy savings and reduced emissions. These minimills are flexible. Can be customized to manufacture steel grades meeting different market demands and supporting global initiatives, for reducing carbon footprint.

5 Conclusion

The reduction of carbon emissions, in the steel sector is essential, for meeting climate goals and securing the viability of one of the most carbon heavy industries globally. Cutting edge technologies, like hydrogen based direct reduction methods and carbon capture technology are crucial in spearheading these transformations and reducing the impact of steel manufacturing operations.The sector should prioritize creating low carbon approaches that not tackle cutting emissions but also boost effectiveness minimize resource consumption and encourage sustainability. These advancements play a role, in streamlining manufacturing procedures cutting down energy usage and staying competitive in an eco industry.

Danielis advancements, in electric arc furnace technology and innovative methods for recovering resources offer perspectives on how the steel industry can move toward an environmentally friendly approach to production and strive for carbon neutrality in the future. For success in this endeavor requires international collaboration and significant investments in research and development alongside the implementation of state of the art solutions to steer the industry toward a sustainable future, with minimal carbon footprint. To achieve these goals successfully demands teamwork among tech innovators in the field of steelmaking industry policymakers and users unit to coordinate actions and assets, towards the mission of making steel manufacturing friendly on a large scale.

References

Acharyulu, S. G., Subbaiah, K. V. and Rao, K. N. (2015) ‘Value Chain Model for Steel Manufacturing Sector: A Case Study’, *International Journal of Managing Value and Supply Chains*, 6(4), pp. 45–53. doi: 10.5121/ijmvsc.2015.6404.

Burin, P. (2023) ‘Danieli Digimelter® for sustainable, competitive, green steelmaking’, *MILLENNIUM STEEL* .

Danieli (2022) *Written evidence submitted by Danieli UK Holding Limited (GST0014)*.

Danieli (2024) *Ecogravel plants for the production of industrial aggregate from EAF slag*.

Danieli Environment (2024) *Green steel technology for a sustainable steel industry*.

Hertrich Giraldo, A. (2021) ‘Green steel production through hydrogen-based enrgiron DRI process’, *Danieli*.

IEA (2020) *Iron and Steel Technology Roadmap*. Paris. Available at: https://www.iea.org/reports/iron-and-steel-technology-roadmap (Accessed: 12 October 2024).

Lapasin, M. (2023) ‘Energiron Danieli solutions for a transition towards green steel’, *ARAB STEEL SUMMIT*.

Molly Lempriere (2023) ‘Steel industry makes “pivotal” shift towards lower-carbon production’, *Carbon Brief*, 20 July.

Name, A. *et al.* (2023) *Green Hydrogen for Low-Carbon Steelmaking Contact data*.

Nocholas, S. and Basirat, S. (2024) *Carbon Capture for Steel?*

Rechberger, K. *et al.* (2020) ‘Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking’, *steel research international*, 91(11), p. 2000110. doi: https://doi.org/10.1002/srin.202000110.

SGRO, Antonio (2022) ‘Transition technologies to Danieli ecological and quality electric steelmaking using scrap and ENERGIRON® DRI’, *2022 SEAISI Steel Mega Event & Expo*.

Stamm, H. and Naujok, N. (2023) ‘Why steel can be an unexpected leader in decarbonization’, *WORlD ECONOMIC FORUM*, 29 August.

UNECE (2022) 'Transport United Nations Special Envoy for Road Safety International Forum on Energy for Sustainable Development Road Safety Trust Fund COP27: UN report shows pathways to carbon-neutrality in "energy intensive" steel, chemicals and cement industries', *United Nations Economic Commission for Europe,* 11 November.