

Decarbonization Pathways for the Italian Steel Sector: Environmental, Economic and Social Implications

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The Italian steel industry requires revamping through strong actions both in the short and medium term. It is essential that Italy meets its steel demand through domestic production, not only to reduce its dependence on imports but also for social and economic reasons. In this context, three decarbonization scenarios for the steel sector in Italy have been developed, including a Conservative pathway, a Potential scenario, and a Desirable one. The Conservative scenario envisions a short-term perspective in which corrective actions mainly involve the addition of CO₂ capture to the existing technologies. Potential scenario envisions a medium-term perspective that introduces substantial modifications to production processes (blue hydrogen-based DRI) to achieve complete decarbonization of the sector in the long term. Lastly, Desirable scenario envisions a long-term perspective in which primary steel will be produced using DRI technology based on the use of green hydrogen. Each scenario has been analysed from different viewpoint, considering the CO₂ overall emissions, the Levelized Cost of Production (LCOP) of steel and the employment repercussions. The outcomes highlight a good reduction of CO₂ for every scenario, with a substantial improvement for Potential and Desirable ones, with 68% less CO₂ emissions. From the economic viewpoint, the best results have been achieved by blue hydrogen-based DRI, followed by Conservative scenario and Desirable one. The employment rates are best for green hydrogen-based DRI, due to the relocation of workers into the renewable energy sector.

1. Introduction

Globally, steel production is steadily increasing, from 148 Mt in 1950 to 1,885 Mt in 2022. (worldsteel association, 2023), and, although at lower pace, it is expecting to further grow in the future thanks to the essential role that steel products play for numerous sectors (construction, automotive, machine and industrial equipment). In 2022, more than half of the global steel production was located in China (1,108 Mt), which was followed by India (125.3 Mt), and Japan (89.2 Mt). Italy (21.6 Mt) is at 11th position globally, representing the second biggest steel manufacturing country in Europe, which is led by Germany (36.8 Mt, 7th globally). The combination of Blast Furnace and Basic Oxygen Furnace (BF-BOF) is still the most used production technology for raw steel production globally (71.5 %), with Electric Arc Furnaces (EAF) accounting for the remaining share, although International Energy Agency (IEA) predicts that the BF-BOF proportion will drop to 59 % in 2030 (IEA - International Energy Agency, 2024). Alternative technologies such as fossil-based Direct Reduced Iron (DRI) accounts for less than 7% globally, while innovative technologies, e.g., hydrogen-based DRI, are still under development, mainly in Europe (worldsteel association, 2023). Despite significant differences between European countries, the continental overall share of raw steel produced using BF-BOF technology has remained relatively constant over time around 57.6%. Focusing on the Italian situation, the share of steel produced using BF-BOF has decreased from 38.1% in 2001 to 16% in 2022, while in terms of production volume, BF-BOF output dropped from 10.2 Mt to 3.5 Mt and EAF production increased from 16.5 Mt to 18.1 Mt (Federacciai, 2023a). Reasons for the significant decline in BF-BOF output include the shutdown of the Piombino and Trieste blast furnaces and environmental issues at the Taranto production site, which is currently the only Italian location with an active BF-BOF combination. According to Federacciai's Sustainability Report (2023b), the Italian steel sector produced 21.6 Mt of steel in 2022, resulting in an emission of about 16 MtCO₂, or 0.74 tCO₂/t_{steel}. This

value has been decreasing over time thanks to the declining share of steel produced through the integrated cycle, which is the primary source of direct emissions in the steel sector. From 2014 to 2023, employment in steel production (ATECO code 241) fell by 4.49%, while employment in transformation grew by 4.9% (ATECO 242) and 13.5% (ATECO 243), resulting in an overall increase of 1.63% driven by transformation activities, with a total workforce of approximately 68,500 employees. This reflects a decline in primary steel production and a slight rise in secondary production. Employment intensity per unit of production increased in primary steel due to fixed roles persisting despite lower output, while remaining stable in secondary steel production. Future employment needs will depend on production trends, particularly the shift from blast furnace to EAF technologies. The steel demand of a country is defined as apparent consumption, calculated as domestic production plus imports minus exports. According to Federacciai's annual report (2023a), Italy's apparent steel consumption from 2007 to 2022 was roughly 27.5 Mt on average, with peaks and troughs brought on by economic crises and following recoveries. Therefore, Italy is a net importer of raw steel, given that this value is lower than domestic production, that ought to be increased to fulfil the internal demand. Given this overview of the current state of the Italian steel sector, this paper evaluates projected potential future domestic supply for steel from various viewpoints, depending on the stakeholders' commitment towards decarbonization.

2. Methodology

The innovative technological options for decarbonization fall into two main categories: those focused on reducing emissions from current production methods and those that entirely replace traditional steel production technologies, according to Policy Department for Economic Scientific and Quality of Life Policies (2021). The first category includes measures aimed at optimizing energy efficiency in production facilities (near net shape casting, top gas recycling), or at decreasing the CO₂ emissions related to energy consumption through the installation of renewable energy systems, the replacement of fossil energy sources with biogenic alternatives, and the retrofitting of existing plants with CO₂ capture technologies (CCUS). The second category encompasses technologies that replace traditional steel production methods, such as smelting, increased use of electric arc furnaces (EAF) or the installation of new Direct Reduced Iron (DRI) facilities. Italy's steel sector, dominated by electric arc furnace (EAF) production (84%), currently benefits from low direct emissions and high scrap recycling rates. However, advancing decarbonization requires stakeholders, each with specific interests and responsibilities, to collaborate on economically sustainable and environmentally aligned actions. Non-Governmental Organizations (NGOs) focus on advocating for environmental protection and public health, often collaborating with the scientific community to promote the decarbonization agenda; labor unions represent workers in the steel industry and communities living near production sites, emphasizing the importance of job protection and social justice during the transition to low-carbon technologies; steel companies, as significant employers and economic contributors, prioritize maintaining continuous production while balancing the costs and risks associated with adopting innovative technologies; and public institutions play a regulatory and planning role, tasked with integrating diverse interests and enacting policies to support the transformation of the sector.

2.1 Decarbonization pathways for the Italian steel sector

Building on available technologies and medium- to long-term strategies, three decarbonization scenarios have been proposed, namely Conservative, Prospective, and Desirable, taking into consideration the perspectives and needs of all key stakeholders. Indeed, three indicators have been calculated for every scenario, each one focused on providing a specific answer to a particular question: overall CO₂ emissions for NGO and social community, Levelized Cost of Production (LCOP) of steel to account for business needs, and employment rate to satisfy labor unions requirements. The carbon emission indicator has been calculated summing up the CO₂ emissions generated by the production technologies involved for every scenario, which have been found in scientific literature and sector associations report (Table 1). The LCOP represents the average cost of producing one ton of steel, factoring in all costs over the production process's lifecycle. This includes direct costs like raw materials, energy, and labor, as well as indirect costs such as maintenance, plant depreciation, waste management, environmental costs, and increasingly, the costs associated with carbon reduction and sustainable practices. The LCOP has been calculated using Eq(1):

$$LCOP = \frac{(CRF)(CAPEX) + (OC_{fix}) + (CF)(OC_{var})}{(CF)(PROD)} \quad (1)$$

Where, CAPEX is the Capital Expenditure; OC_{fix} stands for fixed operating costs, such as labor costs, which do not vary with the amount of steel produced; OC_{var} represents variable operating costs, which depend on the amount of steel produced, such as materials used in production; CF is the Capacity Factor, i.e., the utilization rate of the plant, representing the intensity of its usage; PROD is the expected annual steel production at full

capacity; and CRF is the Capital Recovery Factor that converts the present value of an investment into a constant annual amount over a specified period, calculated using Eq(2).

$$CRF = \frac{i(1 - i)^n}{(1 - i)^n - 1} \quad (2)$$

Historically, real interest rates have fluctuated between 3% and 7%, therefore using an interest rate i of 6 % and a time period n of 12 years is often considered a conservative yet realistic midpoint.

Finally, the employment rate considers the total number of workers directly employed in the steel sector under each scenario, supplemented by potential new jobs created through the demand for decarbonized energy generation facilities. To estimate future employment based on production scenarios, data from 2014 to 2023 was used as a reference, as retrieved within Global Steel Plant Tracker, which is an online database that tracks steel plants worldwide, including information such as plant ownership, operational status, production method, plant capacity, annual production, workforce, and location. For steel production using EAF technology, there are on average 1.4 employees per 1,000 tons of steel produced. For traditional production, this figure increases to 2.4 employees per 1,000 tons. DRI technology facilities have an average of 0.6 employees per 1,000 tons, based on a wide range of plants in diverse contexts with varying scales, regulations, and labor markets. The significant differences in labor-intensity arise from structurally distinct industrial systems, production scales, and the outdated nature of many EAF and BF plants, which are more labor-intensive due to obsolete technology and organizational models. For scenarios integrating DRI and EAF technologies, employment impact is assumed to be higher than DRI alone, given the dual-stage production process. While there is no direct data from operational integrated DRI-EAF facilities, estimates from approximately 21 planned systems in Europe, set to begin operation around 2025-2026, suggest employment figures between 1.45 and 1.8 employees per 1,000 tons, with a median value of 1.6 employees per 1,000 tons of steel. Labor estimates for renewable energy were calculated using the methodology developed by GSE, which employs sectoral interdependence matrices to link economic and employment impacts to renewable energy deployment. Between 2013 and 2020, GSE data (GSE, 2022a) indicate 575 permanent jobs per GW of installed renewable capacity, which have been scaled to the installed capacity needed in the three decarbonization scenarios.

As previously reported, short-term actions involve integrating mitigation technologies into existing plants to minimize immediate investment needs while awaiting the consolidation of innovative solutions for achieving complete decarbonization by 2050. The analysis assumed a steady production of 25 Mt/year of steel, comprising 18 Mt (72%) of secondary steel from EAF and 7 Mt (28%) of primary steel. The secondary steel output aligns with historical Italian averages and reflects anticipated long-term scrap shortages. Primary steel production is expected to increase modestly, doubling from 2022 levels, supported by innovative technologies.

The scenarios primarily differ in the technologies employed to meet the demand for primary steel, highlighting varying degrees of innovation and decarbonization potential. These approaches address both current challenges and the growing global demand for steel, ensuring the Italian steel sector remains competitive and sustainable.

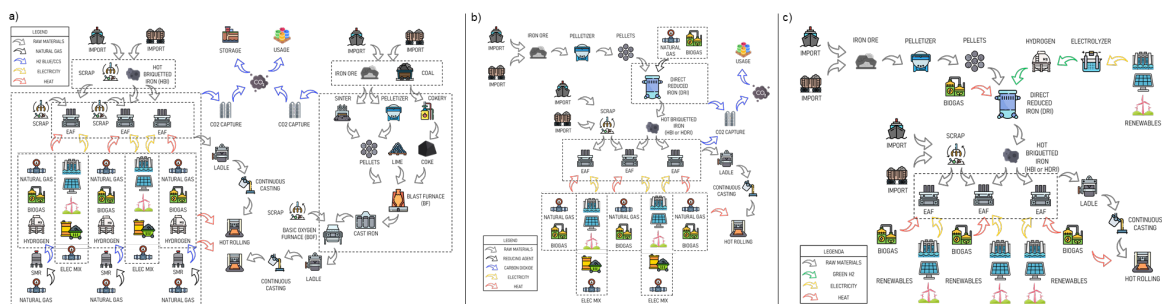


Figure 1: Schematic representation of decarbonization pathways: a) Conservative scenario; b) Prospective scenario; c) Desirable scenario

The Conservative scenario, illustrated in Figure 1a, represents a context where government bodies do not incentivize innovation in the steel or energy sectors, steel companies lack confidence in adopting innovative technologies, and NGOs and labor unions fail to effectively advocate for community interests. This scenario focuses on addressing short-term challenges without implementing technologies necessary for achieving full decarbonization in the long term. The industry would rely on importing reduced iron (Hot Briquetted Iron - HBI) or scrap metal from abroad. However, increasing global demand for steel and the decarbonization efforts of other nations would intensify competition for high-quality scrap and HBI, reducing availability and driving the use of lower-quality raw materials. This could negatively impact the quality of finished products, reducing the

competitiveness of the Italian steel sector. The Prospective scenario envisions a gradual implementation of emission reduction measures and enabling technologies, aiming for substantial greenhouse gas reductions and long-term decarbonization of Italy's steel sector. Medium-term strategies include energy integration, CO₂ capture and reuse for natural gas-based DRI and EAF processes, increased use of biogenic carbon, and small to medium-scale photovoltaic installations. EAF operators will integrate sponge iron (HBI) into production to address rising costs and declining quality of scrap. Initially, DRI will use natural gas with CO₂ capture, transitioning to biogas and green hydrogen, which will become dominant through renewable energy-powered electrolysis. Renewable energy installations will expand over time, meeting an increasing share of the energy needs for electrolysis and EAFs, while the national energy mix shifts toward renewables. CO₂ emissions will be captured and converted into value-added products or stored in reservoirs, contributing to the sector's decarbonization goals. The Desirable Scenario envisions a fully decarbonized Italian steel sector, with large green hydrogen-based DRI facilities paired with EAF sites incorporating scrap recycling. Powered entirely by renewable electricity, green hydrogen would be produced via electrolysis, supplemented by a renewable-dominated national energy mix. CO₂ emissions would originate solely from biogenic sources, reducing the need for carbon capture, though existing capture systems could further decrease net atmospheric CO₂. While current investment and technological limitations delay immediate implementation, progressive improvements through intermediate scenarios provide a viable pathway toward achieving this goal. The annual raw material requirements to sustain the Italian steel industry under these scenarios are detailed in Table 1.

Table 1: Raw materials and energy required for each potential scenario for decarbonization

Category		Primary	Primary	Primary	Secondary	Secondary	Total	Total	Total
Amount	[Mt]	7	7	7	18	18	25	25	25
Scenario*		C ¹	P ²	D ³	C, P ⁴	D ⁵	C	P	D
Sources		(Federacciai, 2021; Fishedick et al., 2014; Mio et al., 2022; Rosner et al., 2023; Wernet et al., 2016; Zecca et al., 2023)							
Iron ore	[Mt]	12.439	11.404	11.404	0	0	12.439	11.404	11.404
Coal	[Mt]	3.864	0.196	0.238	0.165	0.165	4.029	0.361	0.403
Scrap	[Mt]	1.330	0	0	19.848	19.848	21.178	19.848	19.848
Natural Gas	[GJ]*10 ⁶	10.374	79.107	0	62.784	0	73.158	141.891	0
Biomethane	[GJ]*10 ⁶	0	0	7.442		46.764			54.206
Hydrogen	[Mt]	0	0	0.469		0			0.469
Electricity	[TWh]	3.405	4.392	30.949	13.770	13.140	17.175	18.162	44.089
Lime	[Mt]	5.600	0.358	0.358	1.065	1.065	6.665	1.423	6.040

*C: Conservative; P: Prospective; D: Desirable

¹(BF+BOF+HR)+CCU = Blast Furnace + Basic Oxygen Furnace + Hot rolling + Carbon Capture and Usage

²(DRI_{NG}+EAF+HR)+CCU = natural gas-based DRI + Electric Arc Furnace+ Hot Rolling + Carbon Capture and Usage

³DRI_{H2}+EAF+HR = hydrogen-based DRI + Electric Arc Furnace+ Hot Rolling

⁴(EAF+HR)+CCU = Electric Arc Furnace + Hot Rolling + Carbon Capture and Usage (80%)

⁵EAF+HR = Electric Arc Furnace + Hot Rolling

3. Results and Discussion

A comparison of indicators under the three decarbonization scenarios by 2050 (Conservative, Prospective, and Desirable) can be made as shown in Table 2, where the CO₂ emissions in 2022 (0.74 tCO₂/t_{steel} (Federacciai, 2023b)) have been used for an annual production of 25 Mt, assuming no decarbonization technologies are introduced (Business As Usual - BAU). Long-term decarbonization of the Italian energy mix alone or with contributions from self-generated decarbonized energy might accomplish the projected emission factor for energy used in the steelmaking process in 2050 (137 gCO₂/kWh). In fact, an increase from the current 31.1 % of Italy's electricity mix to 67.6 % in 2050 would be sufficient to meet the desired target, assuming a restructured national energy mix with a greater share of renewable sources, in line with ISPRA's prediction (2023) of a 70 % renewable share in Italy's electricity mix. Otherwise, the current emission factor (291.1 gCO₂/kWh) could still drop to the required target if 53% of energy consumption were satisfied by on-site renewable sources; nonetheless, both these contributions are probably going to help the industry achieve decarbonization. All proposed scenarios reduce emissions in the steel sector compared to a BAU scenario. The Conservative scenario focuses on short-term measures, primarily adding CO₂ capture to existing BF-BOF and EAF systems. This reduces emissions to 8.753 MtCO₂ (-53.3%) but relies heavily on CO₂ storage or conversion, limiting its long-term effectiveness. The Prospective scenario introduces natural gas-based DRI and renewable energy, achieving emissions of 6.036 MtCO₂ (-67.8%) through innovative technologies, but still relying on CCU. The Desirable scenario represents the ideal long-term solution as it envisions a fully fossil-free approach with green

hydrogen DRI and a renewable energy mix, cutting emissions to 6.040 MtCO₂ (-67.8%) and offering the most sustainable path to complete decarbonization, as it can further improve thanks to a progressive decarbonization of the electricity generations sector.

Table 2: Sustainability indicators for scenarios evaluation: CO₂ emissions, LCOP and overall workforce

Scenario		Business as Usual (BAU)	Conservative	Prospective	Desirable
Heat Consumption	[GJ]*10 ⁶	73.158	73.158	141.891	54.206
Electricity Consumption	[TWh]	14.120	17.175	18.162	44.089
Direct CO ₂ emission	[Mt]	16.837	6.40	2.871	3.626 ¹
Indirect CO ₂ emissions in 2022 ²	[Mt]	1.934	5.00	5.261	12.830
Total CO ₂ emissions in 2050 ³	[Mt]	18.771	8.753	6.036	6.040
CAPEX	[M€]	-	1,478.6	1,845.5	1,387.5
LCOP	[€/t _{steel}]	-	612.76	607.28	621.61
Workforce in steel sector	[employees]	-	75,706	70,106	70,106
New workforce in energy sector	[employees]	-	4,674	4,950	12,080
Overall workforce	[employees]	-	80,380	75,056	82,186

¹Biogenic carbon emission, which have not been accounted into total CO₂ emissions

²Carbon emission factor of Italian electricity mix in 2022: 291.1 gCO₂/kWh (GSE, 2022b)

³Expected carbon emission factor of Italian electricity mix in 2050: 137 gCO₂/kWh

From the economic standpoint, the proposed decarbonization scenarios for the steel sector highlight varying levels of investment and energy demands, with specific policy measures needed to support the transition to greener production. The Conservative scenario requires annual investments of €1.478 billion on revamping traditional technology, manageable but less transformative. The Prospective scenario involves significant investment in CCU technologies, making it the most capital-intensive, but with the lowest LCOP, thanks to the usage of natural gas. The Desirable scenario, with its focus on green hydrogen and renewable energy, requires systemic efforts to meet high clean electricity demands and is still the least favourable in terms of cost of production. Direct reduction with green hydrogen has significant decarbonization potential but faces challenges in cost-competitiveness: its success depends on low electricity prices, substantial renewable energy expansion, and internalizing environmental costs through carbon pricing. Despite its current cost limitations, hydrogen-based DRI is under international industrial deployment, and advancements in technology and economies of scale are expected to reduce costs over time. Key strategies to improve Italian steel competitiveness include increasing the availability of affordable green electricity, applying the regulations such as Emission Trading System (ETS) or Carbon Border Adjustment Mechanism (CBAM), and promoting Green Procurement to drive demand for sustainable materials. Moreover, expanding high-quality steel scrap availability and improving recycling through circular economy policies are essential for supporting secondary steel route, well-established in Italy. The overall workforce in the steel sector (ATECO codes 241, 242, 243) is projected to rise to 70,106 for DRI-based scenarios and 75,706 for Conservative scenario, due to the higher labor-intensity of traditional technology, up from the current 68,526. However, the renewable energy production needed to support the transition to DRI with hydrogen would create further employment to manage and maintain the renewable energy installations required to supply the steel industry's significant energy needs. In the Prospective scenario, this demand is estimated at 4,950 jobs, increasing to 12,080 in the Desirable scenario, which demonstrates the strongest potential for employment growth and strengthening national renewable energy supply chains.

4. Conclusions

The decarbonization of Italy's steel sector is critical for achieving both sustainability goals and maintaining economic competitiveness. This study explored three distinct scenarios, namely Conservative, Prospective, and Desirable, each representing a different pathway toward reducing emissions while revamping steel production. The Conservative scenario focuses on limited short-term actions, such as adding CO₂ capture to existing BF-BOF and EAF technologies. While it achieves a moderate reduction in emissions by 2050, its reliance on storage or reuse of captured CO₂ and its limited long-term innovation make it insufficient for achieving complete decarbonization. The Prospective scenario takes a more ambitious approach by introducing technologies like natural gas-based DRI followed by CCU. It achieves a more effective emissions reduction of 67.8% by 2050 and represents a transitional phase toward full decarbonization. This scenario also relies on CO₂ capture and conversion, which is still under development at industrial scale. The Desirable scenario represents the ultimate goal of complete decarbonization. It envisions primary steel production using green hydrogen-powered DRI combined with renewable energy and biogenic carbon sources, eliminating reliance on fossil fuels. However, it requires systemic changes, large-scale investments, and substantial renewable energy capacity and biogenic carbon sources to meet its ambitious goals. All scenarios highlight the importance of expanding renewable

energy production, providing policy incentives, and fostering collaboration among stakeholders. Economically, the transition to green steel production demands significant initial investments and increase the cost of production, particularly in the Desirable Scenario, yet it offers long-term cost savings through reduced reliance on fossil fuels. The employment impacts are also significant, with new opportunities created by renewable energy integration, particularly in the Desirable Scenario. This pathway strengthens Italy's renewable energy supply chains and positions the steel sector as a driver of sustainable economic development. While challenging, the Desirable Scenario offers the most transformative pathway, aligning with global climate targets and positioning Italy as a leader in green steel production. The transition requires bold investments, technological innovation, and comprehensive policy support, but it promises substantial environmental, economic, and social benefits that will shape the future of Italy's steel industry.

Nomenclature

ATECO – Attività Economiche	BI – Hot Briquetted Iron
BAU – Business as Usual	IEA – International Energy Agency
BF – Blast Furnace	ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale
BOF – Basic Oxygen Furnace	LCOP – Levelized Cost of Production
CAPEX – Capital Expenditure	NG – Natural Gas
CCUS – Carbon Capture and Usage/Storage	NGO – Non-Governmental Organization
CF – Capacity Factor	OC_{fix} – Fixed Operating Costs
CRF – Capital Recovery Factor	OC_{var} – Variable Operating Costs
DRI – Direct Reduced Iron	PROD – expected annual Production
EAF – Electric Arc Furnace	
GSE – Gestore dei Servizi Energetici	

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