

Article

Techno-Economic Assessment of Hydrogen Integration for Decarbonizing the Steel Industry: A Case Study

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Abstract

The iron and steel industry is one of the largest industrial sources of greenhouse gas emissions. This paper examines the potential of green hydrogen as a reducing agent for decarbonizing primary steel production, focusing on the Taranto integrated steelworks in southern Italy. Producing about 3.5 Mt of crude steel annually, the plant is also among the country's biggest emitters, with CO₂ emissions of roughly 8 Mt per year at typical blast furnace intensity (2.2 tCO₂/t steel). The analysis quantifies the hydrogen demand required to replace fossil fuels in iron ore reduction and evaluates the techno-economic feasibility of meeting it with green hydrogen. Using DWSIM (open-source chemical process simulation software, v9.0.2) for water electrolysis powered by renewables, the study estimates both the CO₂ emission reductions and cost impacts of hydrogen-based steelmaking. Results show that integrating green hydrogen at Taranto could achieve deep decarbonization by cutting emissions by over 90%, with a base-case levelized hydrogen cost (LCOH) of 3.6 EUR/kg and green steel production cost 653 EUR/t. With optimistic assumptions (renewable electricity at 40 EUR/MWh and electrolyzer CAPEX halved to 500 EUR/kW), hydrogen cost could be reduced to 2.3 EUR/kg, making green steel cost-competitive with conventional steel and implying a breakeven carbon price of under 60 EUR/t. Sensitivity analyses highlight that falling renewable electricity prices, supportive carbon policies, and successful demonstration projects are key enablers for economic viability. The findings underscore that renewable hydrogen can be a viable decarbonization pathway for steel when coupled with continued technological improvements and policy support.

Keywords: steel industry decarbonization; hydrogen-based direct reduced iron (H₂-DRI); green hydrogen; techno-economic analysis (TEA); process simulation (DWSIM)



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1. Introduction

The efforts to mitigate the effects of climate change require urgent decarbonization of heavy industries such as iron and steel production, cement, chemicals, oil refineries, food processing, and the pulp and paper industry. The emissions of the global iron and steel sector in 2020 were around 2.6 billion tonnes of CO₂, roughly 7% of worldwide anthropogenic CO₂ emissions [1,2], Figure 1. This makes steel manufacturing one of the largest single industrial sources of greenhouse gases. Transitioning the steel industry towards low-carbon processes is therefore pivotal to achieving climate targets such as the Paris Agreement [3]. Steel production is an inherently carbon-intensive process when using conventional blast furnace–basic oxygen furnace (BF-BOF) routes, which rely on

coal-derived coke, both as a fuel and as the chemical reducing agent to convert iron ore into iron [4]. In a conventional integrated steel plant, producing one tonne of steel typically results in 1.8–2.0 tonnes of CO₂ emissions [5], primarily from blast furnaces and coke ovens. According to the IEA's Sustainable Development Scenario, achieving alignment with the Paris Agreement requires the emission intensity of crude steel to fall by about 58% relative to 2019 levels [6]. Thus, finding viable alternatives to fossil carbon in ironmaking is a key challenge in decarbonizing the steel industry. Significant interest is therefore emerging in the potential of using green hydrogen to replace carbon in reduction processes [7].

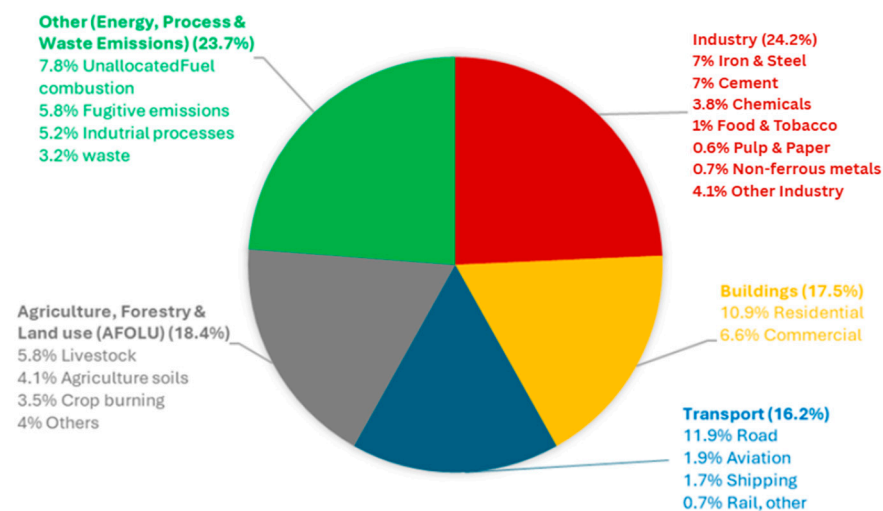


Figure 1. Global greenhouse gas emissions by sector. Adapted from Our World in Data using Climate Watch/WRI data; CC BY 4.0 [8].

1.1. Hydrogen as a Decarbonization Pathway for Steel

The decarbonization pathways for the steel industry include increased scrap recycling, efficiency improvements, carbon capture and storage, alternative fuels, and replacing fossils with hydrogen in the iron ore reducing process [9]. Among these, the use of hydrogen as a reducing agent has garnered significant attention [10]. Global crude steel production is dominated by the traditional blast furnace—basic oxygen furnace (BF-BOF) route, with alternative routes such as scrap-based electric arc furnace EAF and natural gas-based DRI-EAF playing smaller but growing roles, Figure 2. The carbon intensity of steel production varies significantly by route: BF-BOF averages 2.33 tCO₂/t steel, direct reduced iron DRI-EAF about 1.37 tCO₂/t, and scrap-based EAF just 0.68 tCO₂/t, highlighting the potential of EAF-based routes for deep decarbonization [11].

Hydrogen can be used to replace carbon (from coke or natural gas) in reducing iron ore (Fe₂O₃) to iron, yielding water (H₂O) as the by-product instead of CO₂ [10]. The most mature application of this concept is in direct reduced iron (DRI) production. DRI technology reduces iron ore using a reducing gas in a shaft furnace, traditionally a mixture of hydrogen and carbon monoxide derived from natural gas (MIDREX or ENERGIRON processes) [12]. In gas-based DRI, the reducing gas (syngas) from reformed natural gas typically contains a large fraction of hydrogen (50–60%) alongside CO [13]. By shifting to a hydrogen-rich reducing gas, and ultimately 100% green hydrogen produced from renewable energy, it is possible to largely eliminate carbon emissions from the iron reduction stage [14]. Figure 3 illustrates a hydrogen-based direct reduction of iron (H₂-DRI) route for near-zero-emission primary steel production, using renewable electricity to generate green hydrogen that replaces carbon monoxide as the reducing agent.

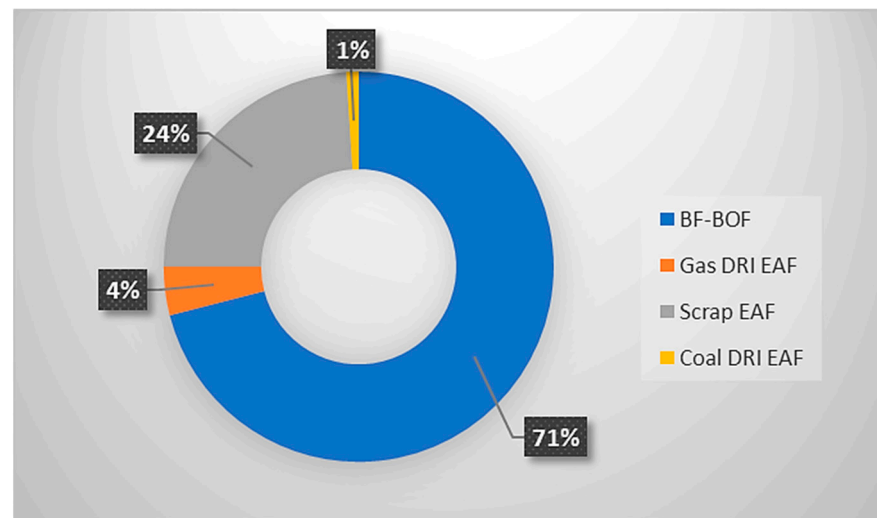


Figure 2. Global crude steel production by process route (2022). Adapted from World Steel Association, World Steel in Figures 2024; author's own visualization. Source [11].

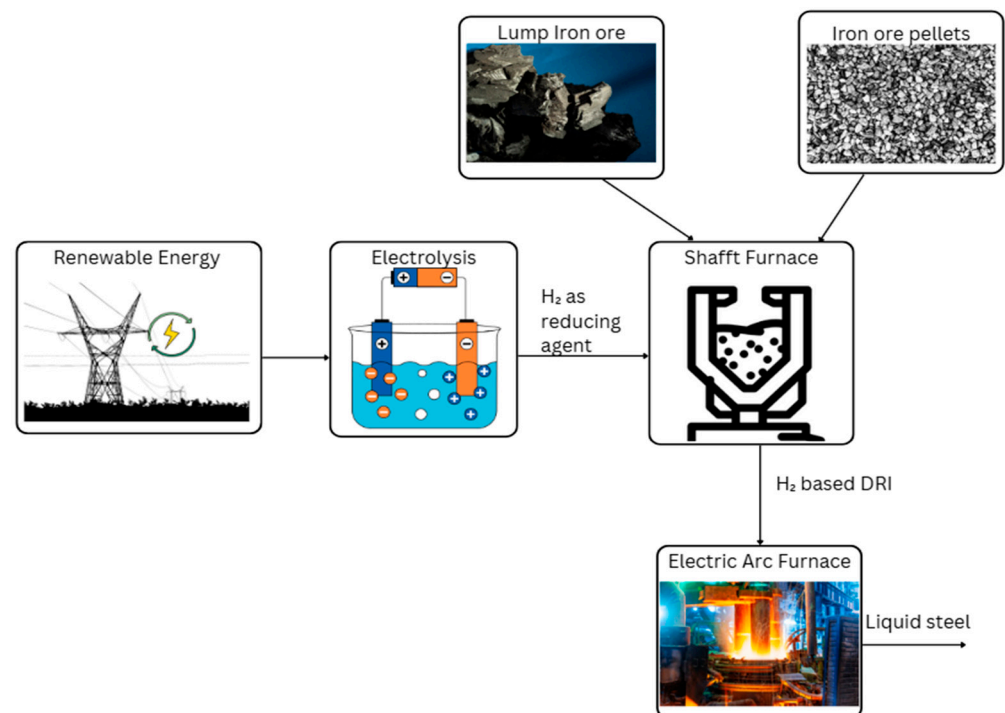


Figure 3. Schematic of hydrogen-based DRI-EAF steelmaking.

1.2. Taranto Steel Plant Case Study Context

Italy is a particularly interesting context; it is one of Europe's largest steel producers (with 21 million tonnes of crude steel in 2023, second after Germany) [15]. Italy also has a relatively low CO₂ emission intensity in its steel sector compared to many countries, due to its high share (around 85%) of EAF (scrap-based) steel production [16]. The scrap-EAF route has an emission intensity of about 0.66–0.70 tCO₂/t steel, while the global average (across all steel routes) is 1.9 tCO₂/t steel [17]. However, the remaining portion of Italy's steel production, less than 15% of output, roughly 3.5 Mt in recent years, comes from primary steel made from iron ore in an integrated BF-BOF plant [18]. Italy currently has only one integrated steelworks plant in operation using the blast furnace–basic oxygen furnace (BF-BOF) route: the Acciaierie d'Italia plant in Taranto, Puglia region, shown in Figure 4. This plant (formerly ILVA) is by far the largest steel mill in Italy and has historically been

one of the largest in Europe in terms of capacity and scale of BF-BOF operations. It was designed with a capacity of about 8 Mt per year of crude steel, though actual output has often been well below that level, around 3 to 4 million tonnes [19]. In 2023, its output was reported at just under 3 Mt due to operational downsizing [20].



Figure 4. Location of Taranto in Italy (left) and satellite view of the Acciaierie d'Italia steel plant (right).

Even at these reduced production levels, Taranto still accounted for about 14% of Italy's crude steel output in 2023, of around 21 million tonnes [10]. Also, Acciaierie d'Italia in Taranto is traditionally the country's major producer of flat steel products via the primary (BF-BOF) route. While flat steel can be produced in EAF plants, the integral cycle (Taranto) remains necessary to meet higher quality standards for certain applications, due to limitations of scrap purity and EAF-based production [15]. Therefore, the Taranto integrated steelworks presents a significant decarbonization challenge and opportunity. Being a coal-based full-cycle plant, its emissions are very high. In 2022, the Acciaierie d'Italia (Taranto) steel plant emitted about 8.5 Mt of CO₂ [21] with a production of 3.8 Mt, making it one of the largest single-point CO₂ emitters in Italy.

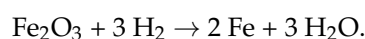
The heavy environmental impact (including local air pollution and public health issues) has also made the plant the subject of intense scrutiny and legal battles over the years [22,23]. In recent years, there has been a growing consensus that maintaining the coal-fired blast furnace route at Taranto is incompatible with long-term climate goals and local environmental priorities [24]. Thus, decarbonizing this plant is not only a matter of climate strategy but a critical step toward protecting public health, reducing local environmental burdens, and aligning the region's industrial activity with long-term sustainability goals.

Decarbonizing Taranto's steel production will center on replacing the blast furnace route with a DRI-EAF configuration by first using natural gas as a transitional fuel and later switching to green hydrogen. Natural gas-based DRI can reduce CO₂ emissions by roughly 50–60% [4] compared with BF-BOF operations by eliminating coal and using a cleaner reducing gas. This phased transition would deliver substantial emission cuts and put the plant on track to meet EU 2030 climate targets [25]. The ultimate objective, however, is to further replace natural gas with green hydrogen as the reducing agent, enabling near-zero carbon steel production when powered by renewable energy [24].

The Italian government and partner companies have initiated concrete steps on this front. For instance, a consortium led by the state's investment agency (Invitalia) under the name "DRI d'Italia" has been established to oversee the installation of DRI-EAF plants for Taranto and potentially other sites [26]. Recent developments underscore the strong commitment to fully decarbonize the Taranto plant. The plan involves phasing out the coal-fired blast furnaces and transitioning to electric furnaces fed by pre-reduced iron

(DRI/HBI), alongside exploring carbon capture for remaining emissions [27]. The European Commission has also approved funding (over 300 EUR million) for a “Puglia Green Hydrogen Valley” project, which will build about 160 MW of electrolyzer capacity in the region to supply green hydrogen, which is intended to contribute to decarbonizing the Taranto steelworks and other local industries, with operations expected in around 2028 [28].

A critical aspect of integrating hydrogen into steelmaking is the sheer quantity of hydrogen needed. Iron ore reduction is a chemical process that requires a significant amount of reductant. When using hydrogen, the reaction is roughly as follows:



In hydrogen-DRI-EAF processes, studies suggest that roughly 60 kg of hydrogen (0.06 tonnes) is required per tonne of steel produced under typical assumptions [29]. This estimate includes the iron reduction stage and assumes some efficiency losses. For a steel plant producing, say, 8 Mt of steel per year (the anticipated full capacity target for Taranto), the hydrogen required would be around 0.48 Mt per year. This equates to a continuous hydrogen production rate of about 55 tonnes of H_2 per hour to keep the DRI furnaces in steady operation. To produce such quantities of hydrogen by water electrolysis, a significant renewable electricity supply is needed. With current electrolysis technology (52–55 kWh per kg H_2 [9]), roughly 52 MWh of electricity is required to produce 1 tonne of H_2 ; around 25 TWh/year for 8 Mt steel. In addition, transitioning a large integrated steel plant to hydrogen-based production demands major capital investments in new DRI furnaces, EAFs, electrolyzers, hydrogen storage, and renewable power capacity. Nevertheless, the long-term strategy among industry and policymakers is increasingly clear: coal-fired steelmaking is being phased out, and green hydrogen is emerging as one of the few viable pathways for fully decarbonizing primary steel production.

1.3. Research Gap and Objectives

This paper uses the Acciaierie d'Italia steel plant (from here on referred to as the Taranto plant) in southern Italy as a concrete case study to explore hydrogen integration for decarbonization, examining the hydrogen demand, the expected CO_2 emissions reduction, and the techno-economic feasibility of a green hydrogen supply for such a project. While many studies have analyzed hydrogen-based DRI steelmaking, most use generic or national-level models. Few provide plant-specific, process-simulated assessments for an integrated steelworks in southern Europe. For instance, prior works often examine idealized cases or pilot-scale examples, leaving a gap in understanding how hydrogen integration would play out at an existing site like Taranto. Moreover, the integration of EU climate policies (e.g., the Emissions Trading System and Carbon Border Adjustment Mechanism) into project economics is often not explicit. This study addresses that gap by developing a detailed DWSIM process model for hydrogen integration at Taranto and linking the hydrogen production cost (LCOH) to the steel production cost and carbon costs at the site level. We explicitly quantify the required infrastructure (electrolyzer size, renewable needs) and evaluate scenarios reflecting future cost reductions. The key objectives are to determine the hydrogen demand, potential CO_2 emissions reduction, and the breakeven carbon price or policy support needed for economic viability. By focusing on a real-world plant with site-specific data, the analysis provides grounded insights for industrial stakeholders and policymakers on deploying green hydrogen in the steel sector.

In the following sections, a state-of-the-art review of the relevant literature and existing projects on hydrogen-based steelmaking is provided to contextualize the current state of technology and research (Section 2). This includes examples of pilot projects and studies on the economics and challenges of H_2 -DRI. Subsequently, the study quantifies hydrogen

demand and production for the selected case study using a DWSIM process simulation of green hydrogen generation via water electrolysis powered by renewable energy (Section 3). The simulation results provide data on hydrogen demand, levelized cost of hydrogen (LCOH), steel production cost, and CO₂ reduction, which are then used to evaluate the techno-economic feasibility and potential CO₂ abatement cost of replacing fossil fuels with green hydrogen at the steel plant (Section 4). Section 4 also discusses the economic and policy implications, including comparisons to other projects and the role of by-product oxygen and water use. Finally, Section 5 concludes with key findings, quantitative results, and recommendations for future work, including dynamic hydrogen storage modeling.

2. Literature Review

The literature consistently identifies hydrogen-based direct reduction of iron (DRI) feeding electric arc furnaces (EAFs) as the leading pathway to deep emissions cuts, alongside maximized scrap recycling. Beyond steel, broader assessments emphasize that green hydrogen is crucial across multiple hard-to-abate sectors, reinforcing its role as a cross-sectoral solution for achieving net zero emissions [30]. Several pilot projects worldwide are demonstrating the feasibility of hydrogen-based steelmaking. One of the flagship projects in this domain is the HYBRIT project in Sweden (a collaboration between SSAB, LKAB, and Vattenfall). Initiated in 2016, HYBRIT aims to replace coal with hydrogen for iron ore reduction [31]. By 2020, the project had begun test operations at a pilot plant in Luleå, Sweden, successfully producing sponge iron using green hydrogen [32]. In 2021, the first batch of “fossil-free steel” was delivered to the automaker Volvo for prototype vehicles, demonstrating the real-world application of hydrogen-DRI steel [33]. HYBRIT’s goal is to scale up to a demonstration plant by 2026 and ultimately an industrial-scale operation that could eliminate virtually all CO₂ emissions from SSAB’s steel production by around 2035.

Another notable example is ArcelorMittal’s Hamburg plant in Germany. This initiative aims to retrofit the Hamburg DRI module, initially operating with gray hydrogen to produce about 100,000 t/year of direct reduced iron (DRI), with full operations expected by the end of 2025 [34]. Similarly, Austria’s H2FUTURE project at voestalpine’s Linz steelworks commissioned a 6 MW PEM electrolyzer in 2019 to produce green hydrogen for steelmaking trials [35]. These initiatives have yielded promising pilot and demonstration data for integrating hydrogen into steelmaking. Studies show that the earliest large-scale hydrogen steel plants are likely to emerge in regions with low-cost renewable energy, high-grade iron ore, and enabling policies [14,36].

Beyond dedicated DRI, hydrogen can also be used in traditional blast furnace operations. For instance, hydrogen-rich gases can be injected into blast furnaces to partially replace pulverized coal injection (PCI) and reduce CO₂ output [37]. While this can achieve moderate emission reductions, it is fundamentally limited because the blast furnace is optimized for carbon-based chemistry. According to a study [38], hydrogen injection in BF could cut CO₂ emissions by perhaps 20% at most, whereas switching to DRI with hydrogen offers a far deeper decarbonization potential [39]. Comparative reviews, such as those by Bataille et al. [40] and Xue et al. [41], show that while retrofit BF options (PCI optimization, top-gas recycling, partial CCS) can deliver incremental CO₂ cuts, only a full switch to hydrogen-DRI coupled with EAF scaled with renewable electricity and green hydrogen offers a pathway consistent with mid-century climate targets [42].

In Italy’s case, as discussed, the strategy is indeed to replace blast furnaces at Taranto with gas-based DRI (as an interim step) and then transition to hydrogen-based DRI. A study on Italian steel sector decarbonization scenarios by Mio et al. [43] found that a hydrogen DRI scenario (using “blue” hydrogen initially and then green hydrogen) yielded the greatest CO₂ reductions in the long term, compared to scenarios relying more on carbon

capture or incremental improvements. This underscores that from the literature, hydrogen is viewed as the only viable route to fully decarbonize primary ore-based steel, whereas other measures can only achieve partial reductions.

One of the key challenges to implementing hydrogen in steelmaking is its current high production cost, which remains far above that of coal or natural gas for the same reducing potential. A techno-economic assessment of 61 off-grid hydrogen supply chains for a 15 Mt steel/year plant in 2030 showed that the cost of hydrogen production and renewable power are among the largest contributors to total steel cost under H₂-DRI pathways [44]. Multiple techno-economic studies indicate that for hydrogen-DRI steel to become economically competitive under today's conditions, renewable electricity and hydrogen production costs must fall significantly often implying hydrogen costs in the range US\$1.5–2/kg, and carbon pricing be in the range of US\$30–50/tCO₂ (or higher) [45,46].

Without policy support or carbon pricing, steel produced with green hydrogen can be markedly more expensive than conventional steel. For example, the ECCO Taranto analysis estimates today's LCOP for green-hydrogen DRI at 669 EUR/ton versus 580–592 EUR/ton for coal-based BF, excluding carbon costs, but projects that falling renewable electricity prices and rising CO₂ costs could make hydrogen-DRI steel competitive [24]. Some recent European policy developments, such as reforms to the EU Emissions Trading System (ETS) [47], the gradual roll-out of the Carbon Border Adjustment Mechanism (CBAM), and proposals for Carbon Contracts for Difference (CCfDs) [48], are creating stronger incentives for low-carbon steel by making high-emission steel more expensive. Overall, the literature shows that the speed of adoption of green steel depends heavily on policy support such as carbon pricing, green public procurement (mandating low-CO₂ steel in infrastructure), and subsidy schemes (like the EU Innovation Fund and IPCEIs) to close the cost gap for early projects.

Existing studies largely provide technology overviews, pilot-scale evidence, or national scenarios, but few deliver a plant-specific, process-simulated assessment for Italy's integrated route or explicitly link LCOH to steel cost and EU-ETS compliance at the site level.

This study makes a novel contribution by closing a critical research gap in the techno-economic assessment of hydrogen-based steelmaking. It develops a DWSIM-calibrated mass-energy model that simulates the complete hydrogen direct reduction of iron (H₂-DRI), explicitly linked to the operating conditions and scale of the Taranto steelmaking site. Unlike prior analyses that rely on simplified or generic assumptions, the model establishes a transparent mapping between the levelized cost of hydrogen (LCOH) and the corresponding steel production cost, while explicitly incorporating hydrogen intensity and specific energy consumption (SEC). In parallel, the framework monetizes CO₂ emissions abatement under the EU Emissions Trading System (EU-ETS), thereby bridging detailed process simulation with carbon-market incentives.

3. Methodology

This study models hydrogen production via water electrolysis powered by renewable electricity and its utilization in the DRI-EAF route for primary steel production. The system boundary covers quantifying hydrogen demand, green hydrogen generation, iron ore reduction, and subsequent steelmaking to estimate CO₂ mitigation potential and equivalent cost saving for techno-economic feasibility, Figure 5.

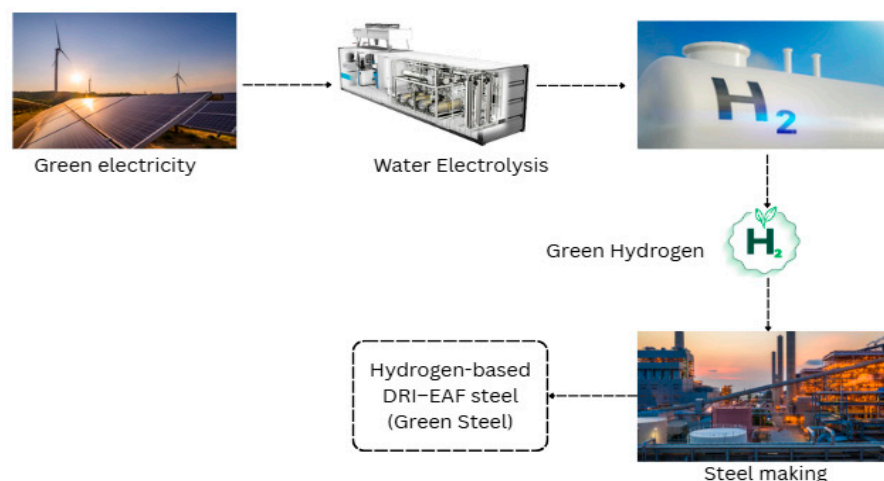


Figure 5. Simplified block diagram of the study methodology, showing the system boundary from green hydrogen production to hydrogen-based DRI-EAF steelmaking (green steel).

3.1. Process Simulation Model (DWSIM)

A process simulation model was developed using DWSIM to evaluate the integration of hydrogen into the Taranto steel plant's production route. DWSIM is an open-source chemical process simulator that provides pre-built unit operation models (reactors, separators, etc.), thermodynamic property databases, and tools for flow-sheeting and sensitivity analysis [49]. In the simulation, a Proton Exchange Membrane (PEM) electrolyzer unit was modeled to produce hydrogen by splitting water ($\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$) [50]. The simulation accounted for the continuous operation of the hydrogen plant, meaning the electrolyzer is assumed to run near full capacity (8000 h per year) to supply a steady hydrogen flow. This aligns with the steel plant's operational mode and ensures a continuous reducing gas supply for the Direct Reduced Iron (DRI) unit. The electrolysis was modeled under steady-state assumptions in DWSIM, using the NRTL (Non-Random Two-Liquid) thermodynamic/activity coefficient package, which is among the thermodynamic models supported by DWSIM for aqueous electrolytes and reactive gas–liquid systems [51]. The flowsheet contains water feed and recycle networks, a preheating step, the PEM electrolyzer stack, gas–liquid separation for hydrogen and oxygen, condensate recycle loops, and final product coolers. The process was designed to achieve near-stoichiometric water utilization and maximize overall energy efficiency. Figure 6 illustrates the DWSIM flowsheet.

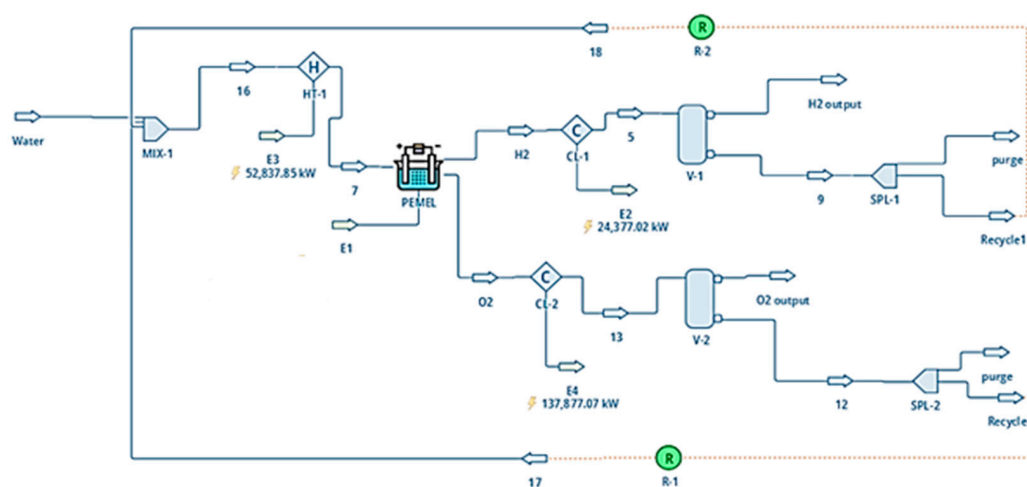


Figure 6. Process flow diagram of PEM electrolysis modeled in DWSIM.

The hydrogen output from the DWSIM electrolyzer model was conceptually linked to a DRI reactor and an electric arc furnace (EAF) in the steel production chain. As mentioned earlier, approximately 0.06 tons of H_2 are required per ton of steel produced via the DRI-EAF route [52]. Using this ratio, the model ensures that the hydrogen production rate corresponds to the steel production target of the Taranto plant. For instance, for an annual production of 8 Mt of steel (the assumed full capacity of Taranto in this case study), about 0.48 Mt of H_2 per year is needed as reductant. The DWSIM provides the energy and material requirements for producing this hydrogen, around 55 tonnes of H_2 per hour of operation, consuming roughly 52 MWh/t H_2 . The DRI reactor and EAF units were not modeled in this study, as the focus was on techno-economic assessment rather than on simulating the detailed chemical and metallurgical kinetics of iron reduction and steelmaking. Further, iron ore reduction with H_2 was assumed to go to completion (100% metallization of iron ore to iron), and the EAF was assumed to melt the DRI using electric power. The electricity demand for the EAF and any associated energy needs (pellet pre-heating) was included in the overall energy balance as fixed inputs based on literature values, ensuring consistency with a typical hydrogen DRI-EAF process. All simulations and calculations were performed in steady-state, reflecting a nominal full-capacity operation of the integrated hydrogen-steel production system.

Renewable Energy and Storage

We assume the electrolyzer is supplied by a mix of dedicated renewables and grid electricity that is effectively carbon-free (either via direct PPA with renewables or grid with near-100% renewables). In practice, to sustain 95% utilization, oversizing renewables and adding energy storage would be required. For simplicity, we account for the cost of electricity as an average price (EUR/MWh) input to the model, and we assume sufficient grid/back-up to maintain continuous operation. Taranto's southern Italy location has strong solar and wind potential, and port infrastructure that could facilitate hydrogen import or renewable electricity import if needed. These factors are qualitatively considered, but detailed grid modeling is beyond the scope of this study. Instead, the scale of renewables needed (on the order of gigawatts) is later discussed and noted as an area for further study.

3.2. Economic Parameters and Scenario

To assess the system under different economic and operational conditions, a scenario analysis was conducted. Multiple scenarios were defined and evaluated using the model by adjusting key input parameters for each case (while keeping the physical process model unchanged). The scenario definitions included the following:

3.2.1. Base Case Scenario

This scenario represents the reference conditions using current or conservative estimates. For the base case, the average renewable electricity price for hydrogen production was set to 60 EUR/MWh [53], and the PEM electrolyzer capital cost was assumed at approximately 1000 EUR per kW of capacity [54]. All other baseline assumptions (efficiencies, steel production level of 8 Mt/year, etc.) remained as described above. This case provides the benchmark for performance, emissions, and costs.

3.2.2. Low Electricity Price Scenario

This scenario explores the impact of lower energy costs, which could result from dedicated renewable power sources (such as solar PV or wind contracts in southern Italy) or future reductions in electricity prices. The electricity price was considered significantly lower than the base case to 40 EUR/MWh, in line with [55]. Also, this value is informed by projected declines in renewable energy generation costs by IRENA [56].

3.2.3. Low Electrolyzer CAPEX Scenario

This scenario simulates a future where electrolyzer technology becomes less expensive due to technological learning and economies of scale. The capital cost of the PEM electrolyzer system was reduced to 500 EUR per kW (0.5 million EUR per MW) in this case, in line with [57].

3.2.4. Combined Optimistic Scenario

While the two scenarios above were run independently to isolate each factor, a combined scenario is also evaluated where both cheap renewable electricity and advanced low-cost electrolyzers are available. This combined case would yield the lowest hydrogen production cost and thus the greatest impact on steel decarbonization economics.

For each case, key outcomes such as hydrogen production cost, green steel cost, annual CO₂ emissions avoided, and carbon cost savings were computed to compare against the base case. This scenario-based approach provides insight into which factors (electricity price vs. electrolyzer cost) have the most influence on the feasibility of hydrogen-based steelmaking in the Taranto context. The key techno-economic indicators were computed as follows:

The levelized cost of hydrogen is calculated using Equation (1).

$$LCOH = \frac{\text{Annualized CAPEX} + \text{Annual OPEX} + \text{Annual Electricity Cost}}{\text{Annual H}_2 \text{ production}} \quad (1)$$

With annualized CAPEX calculated using Equation (2)

$$\text{Annualized CAPEX} = \text{CAPEX} \times \text{CRF} \quad (2)$$

and CRF is the capital recovery factor, calculated using Equation (3)

$$\text{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (3)$$

where r = discount rate (WACC), n = plant lifetime (years). The electricity cost was calculated using Equation (4):

$$\text{Electricity Cost} = \text{SECTotal} \times \text{Annual H}_2 \text{ Production} \times \text{Pel} \quad (4)$$

SECTotal is specific energy consumption (MWh/kg), and Pel is electricity price (EUR/MWh).

The annual hydrogen production is calculated using Equation (5)

$$\text{Annual H}_2 = m.H_2 \times CF \times 8760 \quad (5)$$

3.3. Water Consumption

Water usage for the PEM electrolyzer is calculated from reaction stoichiometry. About 9 L of water are required per kilogram of H₂ produced [58]. It is assumed that this water is demineralized and sourced sustainably (from processed water or desalination, given Taranto's coastal location), to avoid straining local freshwater resources. Notably, the hydrogen used in steelmaking converts back to water vapor in the DRI furnace, and this could potentially be condensed and recycled to partially offset water input, though our model does not explicitly credit this recycling.

3.4. Carbon Price

For evaluating emissions compliance costs, a carbon price of 60 EUR per ton of CO₂ is assumed in the base case. This is in line with recent EU Emissions Trading System prices, which have been estimated to remain in the 60–70 EUR/t range in the mid-2020s [59].

3.5. CO₂ Emissions Estimation

A comparative calculation of carbon dioxide emissions was performed for the baseline BF-BOF route and the hydrogen DRI-EAF route. The goal was to quantify the direct and indirect CO₂ emissions per tonne of steel produced under each configuration. The methodology for calculating emissions is as follows:

3.5.1. Baseline BF-BOF Emissions

The BF-BOF route uses coal and coke, leading to significant CO₂ generation from coal combustion and iron ore reduction. An emissions intensity factor was applied on a per-tonne-of-steel basis. Based on industry benchmarks, the BF-BOF process emits roughly 2.2 tCO₂/t of crude steel produced [60]. This value includes direct emissions at the steel plant and indirect emissions from power usage, averaged for typical operations. For a given steel output (in tonnes), the total annual CO₂ from the baseline route is given in Equation (6).

$$CO_{2(BF-BOF)} = M_{steel} \times EF_{BF-BOF} \quad (6)$$

where EF_{BF-BOF} is the emission factor (here 2.2 tCO₂/t steel). For instance, at 8 Mt/year steel production, the baseline Taranto plant would emit on the order of 17.6 Mt of CO₂ per year (if no mitigation measures are in place).

3.5.2. Hydrogen DRI-EAF Emissions

In the hydrogen-based route, carbon-intensive inputs are replaced by green hydrogen and renewable electricity, dramatically lowering CO₂ emissions. The direct emissions from the DRI shaft furnace using H₂ are essentially zero, as the reduction of iron ore by H₂ produces water vapor instead of CO₂. The EAF stage can also be nearly emissions-free if powered by renewable electricity. Thus, the process can achieve near-zero CO₂ emissions per tonne of steel. Any remaining emissions would come from minor sources (carbon in auxiliary materials or grid electricity impurities), which are small; studies indicate values on the order of 0.05 tCO₂ per tonne for fully green hydrogen steel [61], Equation (7).

$$CO_{2(H2-DRI-EAF)} = M_{steel} \times EF_{H2-DRI-EAF} \quad (7)$$

which, for practical purposes, is insignificant when $EF_{H2-DRI-EAF}$ is near zero. In the Taranto case, the direct CO₂ avoidance is essentially the full 17.6 Mt/yr that would otherwise be emitted by BF-BOF. (Note: If the electricity for the electrolyzer or EAF were not fully renewable, one would include those generation emissions here. However, our model assumes green power, consistent with a true decarbonization scenario).

3.6. Emission Compliance Cost Calculation

To quantify the economic benefit of CO₂ reduction, the methodology includes a calculation of savings in carbon emission compliance costs when switching to the hydrogen-based process. This is particularly relevant under the EU Emissions Trading System (ETS), or any carbon tax regime where emitters must pay for each tonne of CO₂ emitted [62]. The

cost saving is computed by comparing the baseline and hydrogen scenarios' CO₂ emissions and multiplying the difference by the carbon price. The general formula is as follows:

$$\Delta_{carbon} = (E_{base} - E_{hydrogen}) \times P_{CO_2} \quad (8)$$

where

E_{base} = CO₂ emissions per tonne of steel in the baseline (BF-BOF) route (tCO₂/t steel),
 $E_{hydrogen}$ = CO₂ emissions per tonne of steel in the hydrogen DRI-EAF route (tCO₂/t steel),
 and P_{CO_2} = carbon price (EUR/tCO₂).

For this study, E_{base} is taken as 2.2 tCO₂/t and $E_{hydrogen}$ = 0 tCO₂/t, as established above. Thus, the avoided emissions per tonne of steel are 2.2 tCO₂. With a carbon price of, say, 60 EUR/t, the cost saving is about 132 EUR per tonne of steel produced. For the entire annual production of 8 Mt, this translates to roughly 1.06 EUR billion per year in avoided carbon costs. These savings are substantial and would partially offset the higher production costs associated with green hydrogen.

3.7. By-Product Oxygen and Water

The PEM electrolysis produces a stoichiometric oxygen output (½ O₂ per H₂). At full Taranto scale (55 t H₂/h), oxygen output is 442 t O₂ per hour. This by-product oxygen could potentially be valorized. In this study, no such by-product oxygen sales are considered in the base economics (assuming it is vented or minimal value for now). However, if there is industrial demand (e.g., local chemical plants or medical oxygen), it could provide additional revenue or savings (steelworks themselves might use oxygen in EAFs or other processes, though with DRI-EAF the O₂ need is far less than in BOF steelmaking). A qualitative discussion on this is given in Section 5. Likewise, water consumption for 0.48 Mt H₂/year is roughly 10 million m³ per year (at 9 L water per kg H₂). Such water demand, while a small fraction of regional agricultural or power-plant water use, could strain local resources in Puglia, which is a water-stressed region. Options like seawater desalination or water recycling may be needed to supply electrolyzers sustainably. These considerations are included in the discussion.

4. Results and Discussion

4.1. Hydrogen Production Simulation for H₂-DRI Steelmaking

The DWSIM PEM electrolysis modeled system produces 55 t/h of H₂ to feed a hydrogen-based DRI-EAF route, which corresponds to roughly 480,000 t of hydrogen per year under continuous operation. This energy demand includes the core electrolyzer duty (2.68 GW) plus auxiliary loads (0.215 GW for feed preheating, product gas cooling, etc.), reflecting the balance-of-plant needs. The simulation predicts an overall system energy efficiency of about 74% (HHV basis), meaning a specific energy consumption of around 54 kWh/kg H₂, which is in line with industrial PEM electrolyzers reported in the literature. Table 1 summarizes the key parameters from DWSIM results.

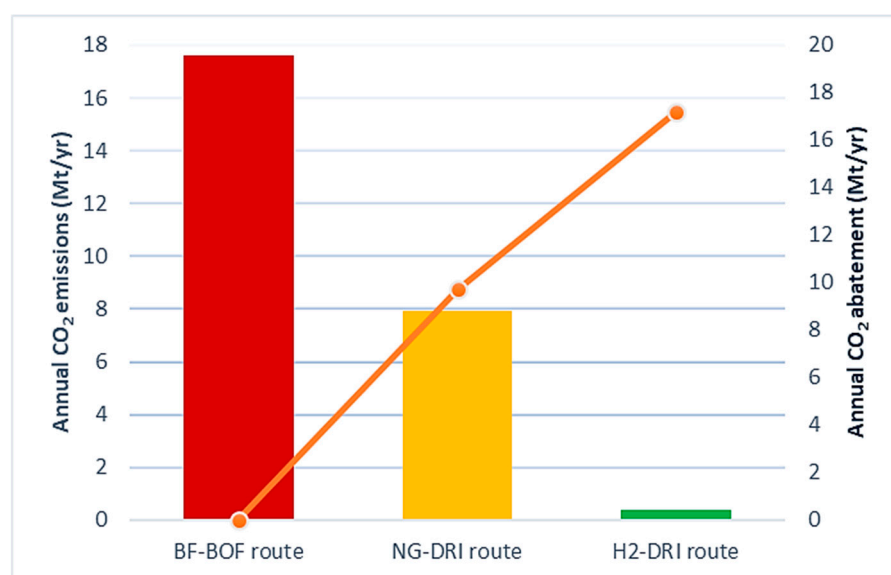
Water consumption is likewise substantial but manageable; roughly 9 L of water per kg H₂ (about 10 million m³/year for full output) is required, which could be met via desalination or water recycling, given Taranto's coastal location. Notably, the by-product oxygen (around 442 t/h O₂) offers a potential integration benefit if utilized on-site or sold, which is not considered in this study.

Table 1. Key performance parameters for the modeled PEM electrolysis system.

Parameter	Value
Hydrogen production rate	55 t/h
Annual hydrogen production	0.48 Mt/y
Electrolyzer power duty	2.68 GW
Auxiliary power duty	0.215 GW
Specific energy consumption	54 kWh/kg H ₂
Overall efficiency (HHV)	74%
Water consumption	10 million m ³ /y

4.2. Full-Scale Hydrogen Supply and Emissions Mitigation

Supplying 55 t/h of hydrogen to the DRI unit represents a full conversion of Taranto's ironmaking to hydrogen. This full-scale H₂-DRI scenario would replace the blast furnace–BOF route entirely, yielding dramatic CO₂ emissions reductions. Direct CO₂ emissions at the steel plant could be cut by roughly 90% relative to the baseline. Given Taranto's current emission intensity (on the order of 2.2 tCO₂ per t steel) and anticipated output of 8 Mt production, this translates to avoiding approximately 17.6 Mt of CO₂ per year. The small remaining emissions in the H₂-DRI-EAF route are around 0.4 Mt per year (on the order of 0.05 tCO₂/t steel). The annual CO₂ abatement is illustrated in Figure 7, which compares the baseline BF-BOF emissions to natural gas DRI and subsequently to the near-zero emissions of the H₂-based process at equivalent steel output.

**Figure 7.** Annual CO₂ emissions by steel production route.

At current EU ETS carbon prices (60 EUR/tCO₂), the modeled CO₂ mitigation would yield an estimated 1.056 EUR billion per year in avoided carbon compliance costs for the Taranto plant. These savings could substantially offset the operating cost of green hydrogen production. For comparison, at 60 EUR/tCO₂, a typical BF-BOF route emitting 2.2 tCO₂ per tonne of steel would face a carbon cost of about 132 EUR per tonne of steel, highlighting the strong incentive carbon pricing creates for shifting to lower-emission technologies. The impending EU Carbon Border Adjustment Mechanism (CBAM) [63], effective from 2026, will phase out free ETS allowances for sectors including steel, in parallel with CBAM

implementation, thereby increasing the cost burden on carbon-intensive steel production. This further strengthens the case for the rapid adoption of hydrogen-DRI technologies.

Operationally, a continuous 2.9 GW green-hydrogen plant demands a massive amount of renewable energy (5–10 GW of new solar and wind in southern Italy plus grid reinforcements to ensure a reliable supply). Maintaining high electrolyzer utilization (95%) will likely require storage and grid-balancing solutions to manage intermittency. Taranto's strong solar/wind resource and port infrastructure are favorable, and the modeled 74% HHV efficiency and output align with demonstrated projects [9], indicating scalability with current technology. Overall, the pathway is feasible but infrastructure-intensive, with a transformative climate impact contingent on rapid renewable and electrolyzer build-out. Recent work on the HyPLANT100 initiative highlights how the modularized manufacturing of electrolyzer systems can help bridge the gap between pilot-scale units and gigawatt-scale deployment [64].

4.3. Hydrogen Production Cost (LCOH) and Green Steel Cost

A central result of the analysis is the economics of hydrogen production and its effect on steel production cost. Under base-case assumptions (electricity at 60/MWh and electrolyzer capital cost 1000 EUR per kW), the modeled levelized cost of hydrogen (LCOH) is about 3.61 EUR per kg H₂. This LCOH translates into an estimated green steel production cost of roughly 653 EUR per tonne of crude steel via the H₂-DRI-EAF route. By comparison, conventional blast furnace steel is currently produced at 550–580 EUR per tonne [65] (excluding any carbon costs). Thus, without carbon pricing or subsidies, hydrogen-based steel in the base case is slightly more expensive (on the order of 70–100 EUR extra per tonne).

The breakdown of the hydrogen cost reveals why the electricity price is by far the dominant component, constituting about 85% of the LCOH in the base case. Capital-related charges (annualized electrolyzer CAPEX) are the next largest cost share, followed by fixed O&M and periodic stack replacements, which together make up the remaining 15%. The cost structure is visualized in Figure 8, highlighting that reductions in electricity price or electrolyzer CAPEX would have the greatest impact on lowering hydrogen cost.

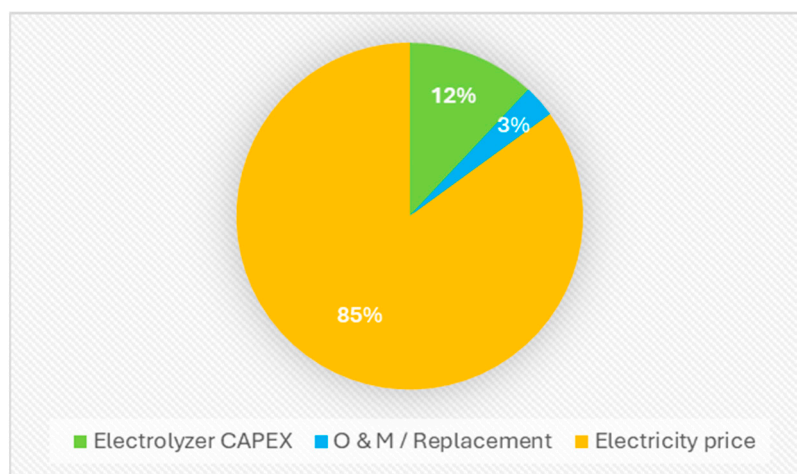


Figure 8. Cost breakdown of hydrogen production.

When translating hydrogen costs into steel production costs, the analysis finds that green H₂-DRI-EAF steel can approach cost parity with conventional steel if carbon costs are considered. In the base case, H₂-based steel (653 EUR/t) is somewhat more expensive than unabated BF-BOF steel (550 to 580 EUR/t). However, once a realistic carbon price is applied to the BF-BOF route (EU ETS at 60 EUR/t and emission factor of 2.2 tCO₂ per t steel), the effective cost of conventional steel rises substantially, to roughly 680–700 EUR/t.

Figure 9 illustrates this comparison: the blue bar shows the approximate current cost of blast furnace steel without carbon cost, the red bar shows the cost when including carbon emissions at 60 EUR/t, and the green bar is the cost of hydrogen DRI-EAF steel. With carbon pricing, green steel becomes competitive or even cheaper than coal-based steel. This underscores that climate policies like carbon pricing or Carbon Contracts for Difference (CCfDs) can bridge the remaining cost gap and make fossil-free steel commercially viable. Indeed, the Taranto case aligns with other studies showing that moderate carbon prices (≥ 50 –100 EUR/t) combined with declining renewable costs could make green steel economically feasible in the near future.

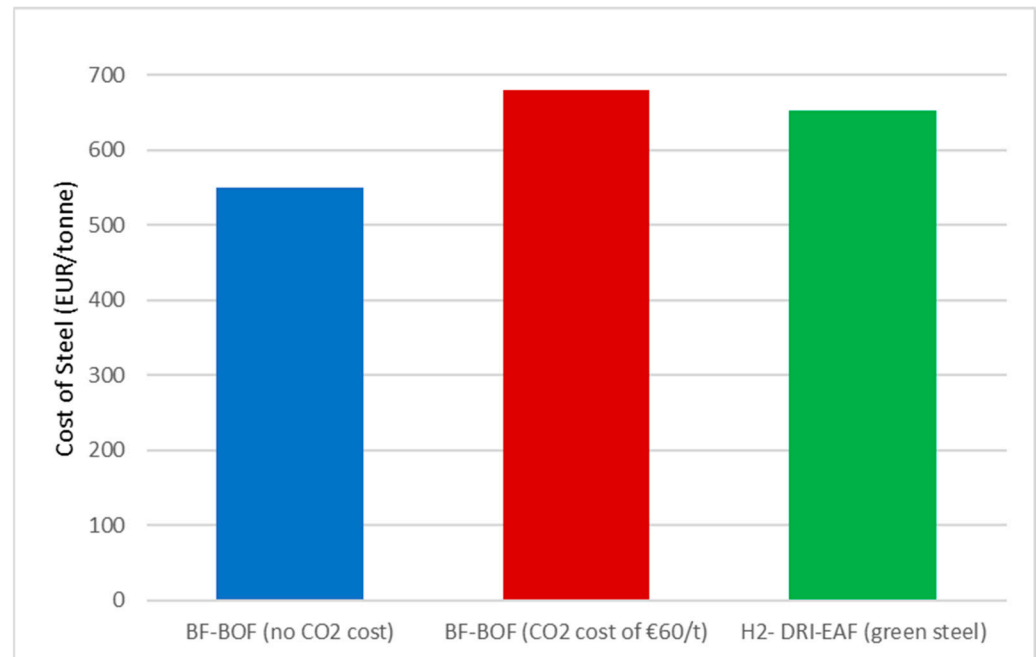


Figure 9. Comparison of crude steel production costs via BF-BOF and H₂-DRI-EAF routes.

4.4. Scenario and Sensitivity Analysis of Hydrogen Cost

Since electricity and capital costs dominate hydrogen economics, several scenarios were analyzed to test the sensitivity of LCOH and resulting steel costs. The following scenarios were considered:

- **Base Case:** Electricity price 60 EUR/MWh, electrolyzer CAPEX 1000 EUR/kW. This resulted in an LCOH of 3.6 EUR/kg H₂, as described above.
- **Low Electricity Cost:** Electricity price reduced to 40 EUR/MWh (reflecting long-term renewable PPA rates). This results in LCOH dropping to 2.6 EUR/kg, a 28% reduction, significantly improving economics. In fact, at 2.6 EUR/kg H₂, the hydrogen-based steel cost would be very competitive with BF-BOF costs, even without carbon pricing.
- **Low Electrolyzer CAPEX:** Capital costs reduced to 500 EUR/kW (consistent with optimistic 2030 projections). This results in an LCOH lowered by roughly 0.3 EUR/kg to around 3.3 EUR/kg. This reflects the smaller but non-negligible influence of CAPEX on hydrogen costs.
- **Combined Optimistic Scenario:** Both low electricity (40 EUR/MWh) and low CAPEX (500 EUR/kW) together. The resulting LCOH falls to approximately 2.3 EUR/kg (nearly 36% below the base case). This scenario represents a plausible future case (early 2030s) where continued renewable energy cost declines and technology learning curves make green hydrogen far more affordable. At ≤ 2.5 EUR/kg H₂, the production cost of hydrogen-based steel would drop well below current BF-BOF costs (even

without carbon costs), indicating full cost competitiveness of fossil-free steel. Table 2 summarizes the scenario results.

Table 2. Scenario results for hydrogen-based steel.

Scenario	Electricity Price (EUR/MWh)	Electrolyzer CAPEX (EUR/kW)	LCOH (EUR/kg H ₂)	Steel Cost (EUR/t)	CO ₂ Avoided (Mt/y)	Avoided Carbon Cost (EUR/y)	Steel Cost vs. Base Case
Base Case	60	1000	3.6	653	17.6	1.06 bn EUR	--
Low Electricity Price	40	1000	2.6	591	17.6	1.06 bn EUR	−9.5%
Low CAPEX	60	500	3.3	638	17.6	1.06 bn EUR	−2.3%
Combined Optimistic	40	500	2.3	576	17.6	1.06 bn EUR	−11.8%

These scenario results are summarized in Figure 10, which compares the LCOH across the different cases, and Figure 11, which shows LCOH and steel cost for different scenarios. As shown, reducing electricity cost has the largest impact on hydrogen price, followed by capital cost reductions. In the most optimistic case, the LCOH approaching 2.3 EUR/kg would translate to green steel costs firmly within the same band (price competitive) as conventional steel, even without any carbon charges. Conversely, a high electricity price scenario: at 80 EUR/MWh, LCOH would exceed 4.7 EUR/kg, making green steel significantly more expensive unless carbon prices reach > 120 EUR/tCO₂ to compensate. This underscores that access to abundant, low-cost renewable electricity is an indispensable factor for hydrogen-based decarbonization of steel.

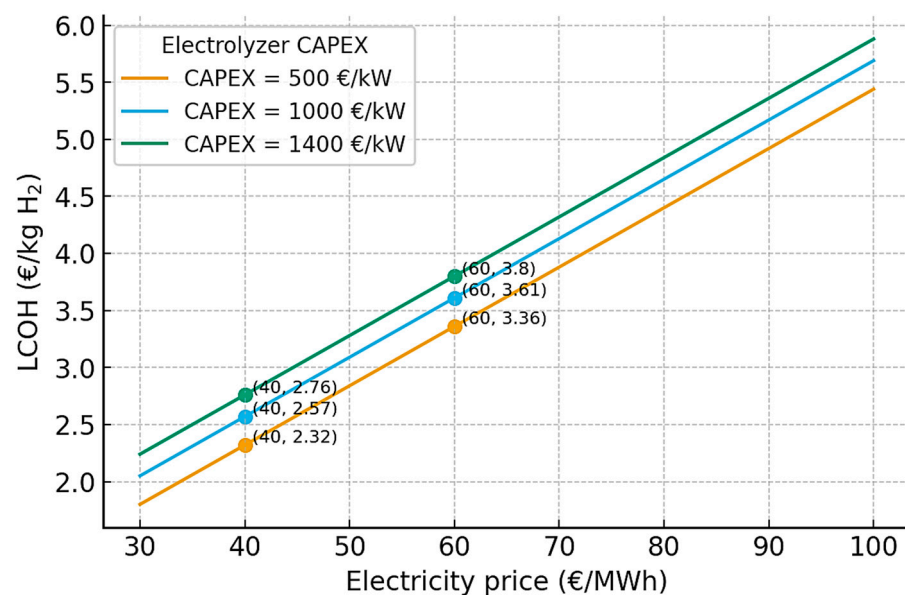


Figure 10. LCOH for different scenarios considered.

In addition to the economic sensitivities, the model's technical assumptions were also tested. The simulation assumes ideal Faradaic efficiency and steady operation. Increasing the specific energy consumption (SEC) by 3–5% to reflect degradation or non-ideal efficiency raises the LCOH by 0.09–0.16 EUR/kg at 60 EUR/MWh (linearly proportional to power price), which does not change the qualitative feasibility conclusions. Varying the electrolyzer capacity factor from 95% to 90% increases the CAPEX/O&M term by

0.03–0.04 EUR/kg (depending on CAPEX level), and plausible changes in stack replacement/O&M shift the LCOH by only 0.02 EUR/kg. These increments are small and did not qualitatively change the results. These findings give confidence that the economic viability of the H₂-DRI pathway is robust against moderate uncertainties in technical performance. It is also important to compare these findings with other projects and studies:

Comparison with HYBRIT and ArcelorMittal

The HYBRIT initiative (Sweden) targets fossil-free steel by 2026, initially at a pilot scale. While detailed costs are proprietary, public statements imply that initial fossil-free steel comes at a 20–30% cost premium, which aligns with our base case (12–18% premium) when excluding carbon pricing. ArcelorMittal's planned Hamburg H₂-DRI plant (100 kt H₂-based DRI per year) is supported by funding; our scenario analysis suggests that with German renewables (if at 40 EUR/MWh via offshore wind) and expected CAPEX declines, they too would be close to break-even by the 2030s. In essence, our cost range of LCOH 2.3–3.6 EUR/kg and required carbon price < 60 EUR/t is in line with figures often cited in industry roadmaps (e.g., hydrogen at 2 EUR/kg with 50–100 EUR/tCO₂ prices can enable green steel competitiveness). Thus, our site-specific Taranto model corroborates the broader understanding that green steel is within reach given supportive conditions. It also highlights the importance of location: Taranto's sun/wind resources could yield low-cost power, and its existing port could allow hydrogen import or renewable electricity import if needed, which not all steel sites have.

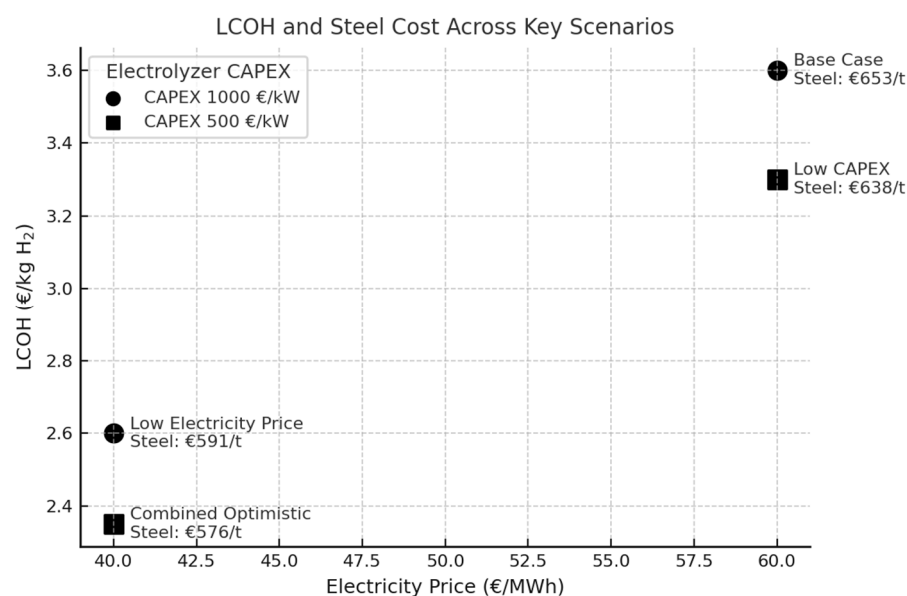


Figure 11. LCOH and steel cost across key scenarios.

Capital Investment vs. Savings

Decarbonizing Taranto will require multibillion-euro capital investments. Rough estimates from the data used in this study: a 2.9 GW electrolyzer at 500–1000 EUR/kW is 1.5–2.9 billion EUR. New DRI furnaces and EAFs could add another 1 billion EUR (the Italian government estimated 0.8–1.0 billion EUR for a new DRI module in initial plans). Plus, 5–10 GW of renewables might cost between 5 and 10 billion EUR (at 1 EUR/W installed). Even allowing for overlap and phased investment, we are looking at perhaps 5–10+ billion EUR total investment to transition Taranto to green steel fully. The avoided carbon cost of 1.05 billion EUR/year indicates that over, say, a 10-year horizon, carbon savings could equal 10 billion EUR—remarkably, as much as the necessary CAPEX. This comparison suggests that, from a societal perspective, using policy (carbon pricing revenue

or direct subsidies) to finance the upfront investment could be justified by the subsequent carbon cost avoidance. In practice, mechanisms like IPCEI grants or EU Innovation Fund awards are indeed providing hundreds of millions of euros to initial projects (e.g., the Puglia Green Hydrogen Valley 330M EUR noted earlier, and an EU Innovation Fund grant of 402 million USD to Italian energy groups for green hydrogen). These reduce the effective CAPEX burden on the project, thereby improving project IRR and bankability.

By-product Oxygen Utilization

The oxygen output (442 t/h) from electrolysis is a double-edged sword. If there is industrial demand or medical demand nearby, this oxygen could be captured, purified, and sold, generating revenue. Industrial-grade O₂ prices can vary widely (40–100 EUR per tonne at scale); even if valued at 50 EUR/t, 442 t/h (3.9 million t/y) would be 195 million EUR/year of potential value. In reality, local demand would be a limiting factor, as it is unlikely that the region could absorb millions of tonnes of O₂ per year without a specific offtake plan (such as oxy-combustion processes, gasification plants, or large chemical complexes). There could be opportunities: for example, a nearby petrochemical or cement plant could use O₂ for oxy-fuel combustion to reduce its emissions. However, storing or transporting such large O₂ volumes is non-trivial (cryogenic distillation or compression would be needed). In summary, by-product O₂ is a potentially valuable co-product, but realizing that value would require new supply chains or co-located industries. Taranto's existing steelworks do have an air separation unit for BOF oxygen; in a post-BOF configuration, that ASU could be repurposed or downsized. The oversupply of O₂ from electrolysis might even replace the need for standalone ASUs in other industries if piped regionally. At this stage, we conservatively did not credit any O₂ revenue, but note that further economic optimization could include O₂ valorization, improving project economics.

Water Supply Considerations

Ten million m³/year of water is roughly the consumption of a city of 150,000 people or several large thermal power plants. Puglia is known for water scarcity, so withdrawing this from existing freshwater could stress resources (and invite local opposition). One solution is seawater desalination. Producing 10 million m³ via reverse osmosis would require up to 20–30 MW of continuous power (assuming 3–4 kWh per m³), which is not insignificant but relatively small compared to 2.9 GW for electrolysis. Desalination would add to both CAPEX and OPEX (though cost per m³ might be only 1 EUR, adding 10 million EUR/yr cost (negligible per kg H₂). Alternatively, using treated wastewater from municipal sources could be a sustainable feed. The Taranto plant, being coastal, is well-positioned for a dedicated desalination facility if needed. In any case, ensuring a sustainable water source will be important for environmental and community acceptance, even if the impact on costs is minor. Policymakers should integrate water planning into hydrogen strategies for regions like Puglia.

Site-Specific Advantages

Taranto has some unique advantages to highlight. It has port infrastructure that could allow for the import of green hydrogen or ammonia from elsewhere if domestic supply is constrained. It also sits in an industrial cluster, potentially enabling symbiotic exchanges (e.g., by-product O₂ usage as discussed, or supply of hydrogen to nearby industries beyond steel). Moreover, replacing the highly polluting ILVA (Taranto) blast furnaces with clean DRI-EAF would bring huge local air quality benefits (reduction in SO_x, NO_x, particulate, dioxins, etc., from coke combustion). These co-benefits (improved public health, avoidance of environmental compliance costs) provide additional economic justification that is not fully captured in a narrow LCOH or steel cost metric. Indeed, Taranto could become a green steel hub, anchoring a broader clean tech ecosystem in the South of Italy.

In comparison to other locations, southern Italy's high solar irradiance might allow for cheaper green hydrogen than, say, Germany or even northern Italy. However, regions like the Middle East or North Africa could produce even cheaper hydrogen (1.5 EUR/kg potential) and export it. A policy question is whether to import hydrogen or produce locally. Our work implicitly assumes local production; if imported ammonia or H₂ were used, additional conversion and transport costs would come into play. But given Taranto's port, one could envision a future where some hydrogen (or renewable ammonia) is shipped in to supplement domestic production, especially if that proves cheaper. This scenario would require a different infrastructure (e.g., ammonia crackers or import terminals), which is beyond our scope but worth noting for strategic planning.

Future Outlook

If another breakthrough low-carbon technology emerges (for example, direct electrolysis of iron ore or some novel biomass reduction), would the conclusions change? In the absence of such, hydrogen DRI appears the most viable. Even if PEM electrolysis were to be "surpassed" by a different hydrogen production method (say high-temperature electrolysis or photochemical H₂), the result would still be cheap green hydrogen, which only strengthens the case for hydrogen-DRI. Thus, starting with PEM now does not lock Taranto out of future improvements; rather, it establishes the hydrogen usage infrastructure, which can accommodate even cheaper H₂ later. Hence, the conclusions are not dependent on PEM per se; any technology delivering green H₂ at scale (including future ones) would produce similar benefits, only likely at a lower cost. In that sense, the analysis is robust: if a cheaper and more efficient renewable hydrogen technology emerges, the general conclusion "renewable hydrogen enables deep decarbonization of steel" will be even more strongly validated.

5. Conclusions

This study provides a comprehensive techno-economic assessment of transitioning the Acciaierie d'Italia (Taranto) integrated steelworks from a blast furnace–basic oxygen furnace (TCO) configuration to a hydrogen-based direct reduction–electric arc furnace (H₂-DRI-EAF) route. Using a detailed DWSIM, the analysis demonstrates that a 2.9 GW PEM electrolyzer plant operating at near full capacity could supply the 55 t/h of hydrogen required for an annual crude steel output of 8 Mt. The process achieves an overall energy efficiency of approximately 74% (HHV basis), requiring about 20 TWh/y of renewable electricity. The large-scale hydrogen production would enable a reduction in direct CO₂ emissions by about 17.6 Mt per year, representing roughly a 90% abatement relative to the baseline BF-BOF route.

From an economic perspective, the base-case levelized cost of hydrogen (LCOH) is found to be 3.6 EUR/kg, with electricity purchase contributing about 85% of the total cost. Consequently, the cost competitiveness of green steel is highly sensitive to electricity prices. A reduction in electricity price to 40 EUR/MWh reduces the LCOH by more than 28% (to 2.6 EUR/kg) and brings green steel within reach of parity with conventional BF-BOF steel. Under current EU ETS carbon prices (60 EUR/tCO₂), the avoided compliance costs amount to 1.05 billion EUR per year, which would make hydrogen-based steel economically feasible. The combined effect of declining renewable prices, technology learning curves for electrolyzers, and carbon cost escalation suggests that full cost competitiveness is achievable within this decade.

This case study suggests that with green hydrogen costs falling into the 2.3–2.6 EUR/kg range and carbon prices in the 50–60 EUR/t range, green steel can be produced at costs comparable to conventional steel. Even using current PEM electrolysis technology, the path appears feasible, and it will only improve as electrolyzers become cheaper and more

efficient. This case thus provides a tangible example that heavy industry decarbonization is achievable with known technologies, given the right mix of cheap renewables and policy support.

Beyond the economic viability, the study identifies significant co-benefits: improved air quality due to the elimination of coal combustion emissions, potential revenue from the sale of by-product oxygen, and alignment with Italy's industrial decarbonization roadmap. Taranto also has favorable conditions, such as port infrastructure, an industrial cluster, and access to renewable resources, making it a prime candidate for becoming a flagship green steel hub in Europe.

Limitations and Future Work

Despite the promising findings, several limitations remain. The simulation assumes ideal electrolyzer performance, constant efficiency, and continuous operation at a high capacity factor. In reality, stack degradation, maintenance downtime, and partial-load operation due to renewable intermittency could increase LCOH modestly. The study also assumes a fully renewable power supply; if a fraction of grid electricity is fossil-based, the net CO₂ savings would be lower. Economic assumptions for electricity price, electrolyzer CAPEX, and carbon price carry inherent uncertainty, which may shift the break-even point.

Future work should extend this study as follows:

- Dynamic modeling of hydrogen storage and electrolyzer operation under renewable intermittency is recommended (to optimize electrolyzer sizing and storage needs for a variable supply).
- Detailed integration studies including grid reinforcement, hybrid renewable portfolios, and energy storage sizing for continuous supply.
- Life-cycle assessment (LCA) covering upstream pellet production, transportation, and EAF slag handling to confirm cradle-to-gate CO₂ savings.
- Socio-economic impact analysis examining job creation, supply chain opportunities, and policy instruments (e.g., CfDs, green steel standards) needed to accelerate deployment.

These extensions would provide a more holistic picture of the technical, environmental, and socio-economic viability of a full hydrogen transition at Taranto and similar large integrated steel plants.

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Abbreviations

Abbreviation	Full Form
BF-BOF	Blast Furnace–Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCfD	Carbon Contracts for Difference
DRI	Direct Reduced Iron
DWSIM	Open-Source Chemical Process Simulation Software
EAF	Electric Arc Furnace
ETS (EU ETS)	European Union Emissions Trading System
H ₂ -DRI	Hydrogen-Based Direct Reduced Iron
HHV	Higher Heating Value
ILVA	Former name of the Taranto Steel Plant (Acciaierie d'Italia)
IPCC	Intergovernmental Panel on Climate Change
LCOH	Levelized Cost of Hydrogen
PCI	Pulverized Coal Injection
PEM	Proton Exchange Membrane (Electrolyzer)
PPA	Power Purchase Agreement
SEC	Specific Energy Consumption

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