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Consequences of the Direct Reduction and Electric Steelmaking Grid Creation on the Italian Steel Sector

Gianluca Dall'Osto *, Davide Mombelli and Carlo Mapelli

Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, 20156 Milano, Italy; davide.mombelli@polimi.it (D.M.); carlo.mapelli@polimi.it (C.M.)
* Correspondence: gianluca.dallosto@polimi.it

Abstract: The consequences on the Italian steel sector following the conversion of the sole integrated steel plant and the establishment of a direct reduction/electric arc furnace (DR/EAF) grid in the period 2022–2050 were analyzed. Imported natural gas (pathway 0), green hydrogen (pathway 1) and biomethane (pathway 2) were studied as possible reducing gases to be exploited in the DR plant and to be introduced as a methane substitute in EAFs. The results showed that the environmental targets for the sustainable development scenario could be achieved in both 2030 and 2050. In particular, the main reduction would occur by 2030 as a result of the cease of the integrated plant itself, allowing for an overall reduction of 71% of the CO_2 emitted in 2022. On the other hand, reaching the maximum production capacity of the DR plants by 2050 (6 Mton) would result in final emission reductions of 25%, 80% and 35% for pathways 0, 1 and 2, respectively. Finally, the creation of a DR/EAF grid would increase the energy demand burden, especially for pathway 1, which would require three times as much green energy as pathway 0 and/or 2 (36 TWh/y vs. ca. 12 TWh/y).

Keywords: CO_2 emissions; iron and steel industry; direct reduction; decarbonization; green H_2; biomethane

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1. Introduction

Steel, along with cement, plastics and ammonia, has always been recognized as one of the most crucial products for the industrial sustenance of both advanced and developing economies. Of the 1884 Mton of crude steel produced in 2022, 71.5% was obtained through the integrated cycle, while only 28.2% was covered by the scrap recycling route, a share of production that has remained more than constant over the past 20 years despite the long-anticipated desire and need for its increase [1].

Indeed, despite the growing demand for steel products, the parallel growth of social awareness regarding the high environmental impact associated with steel production has raised shadows about the future of this industry. According to the IEA latest measurements and data collection [2], the steel sector is responsible for 2.8 Gton of CO_2 emissions per year, accounting for 8% of total energy system emissions, a value that raises to 10% if indirect emissions from electricity generation are included.

To achieve the climate goals of the Paris Agreement and the Sustainable Development Scenario (SDS) for the steel and iron sectors, direct emissions would have to drop dramatically to 0.6 tons of CO_2 per ton of crude steel, corresponding to 1.2 Gton of CO_2 emitted per year, more than half of the current value [3,4]. Therefore, to meet this need, the replacement of fossil fuel with alternative carbon sources [5], the use of low-or-zero emission gaseous streams instead of natural gas (NG) [6], the exploitation of carbon capture and storage (CCS) [7], the continuous technological upgrade of existing steel plants as well as the creation of steel plants coupled with green hydrogen (H_2) direct reduction (H_2-DR) [8] or electrowinning (EWIN) [9] are generally considered promising pathways [10]. Consequently, several breakthrough projects have been created in the last decade to investigate the feasibility of one or more specific technologies for the carbon footprint mitigation [11].

Despite the large number of projects, the actual implementation of which is underway or planned, the scrap recycling route is overall considered to be the production route that will become the predominant one in the near future. In fact, it is predicted that, by 2050, the actual production of steel by melting scrap inside an electric arc furnace (EAF) will almost double its share, reaching a value of 53% [12]. The main reason for this trend can be easily identified in the specific CO_2 emission per ton of crude steel of the EAF compared to that of the integrated cycle, based on the reduction of iron ore by a blast furnace (BF) and basic oxygen furnace (BOF), namely 10^2 kg_{CO2eq}/t_{CS} vs. 10^3 kg_{CO2eq}/t_{CS} [13]. It is noteworthy that, even in the context of the EAF, several studies have focused on the process decarbonization mainly through the introduction of alternative carbon sources, either as a reductant or a foaming agent (Table 1).

Table 1. Main usages and studies of alternative carbon sources in the scrap recycling route.

Scale Investigated	Main Usage/Scope of the Research	Material Used	Reference
Laboratory	Foaming agent	Biochar	[14]
Laboratory	Foaming agent	Biochar	[15]
Laboratory, pilot and industrial	Overall feasibility as carbon substitute	Biochar and hydrochar	[16]
Laboratory and industrial	Carburizing agent	Biochar	[17]
Simulation and industrial	Overall feasibility as carbon substitute	Biochar	[18]
Simulation of an industrial EAF	Foaming and carburizing	Biochar and hydrochar	[19]
Industrial	Overall feasibility as carbon substitute	Biochar and hydrochar	[20]

Along with the transition to a more scrap-based steel production, the demand for clean iron sources to be introduced as charging material inside the EAF is expected to increase to counter the inevitable depletion of high-quality scrap in the near future [21]. Specifically, with clean iron sources, the intent is a pollutant-free iron obtained by the direct reduction (DR) of iron ores to obtain so-called sponge iron, or in other words, direct reduced iron (DRI) or hot briquetted iron (HBI).

The production of these sources of clean iron is not new to the steel industry, and several commercial plants (e.g., MIDREX® (Charlotte, NC, USA), Rotary Kiln (FLSmidth, Inc., Tucson, AZ, USA) and HyL (Tucson, AZ, USA)/Energiron® (Buttrio, Italy)) are active around the world with the main producers belonging to the Middle East/North Africa and Asia/Oceania regions. In particular, India is currently leading DRI production with 43.55 Mton out of the total 127.36 Mton produced in 2022 alone [21]. According to market trends and company estimates, the largest increase in the mid-term will occur in the European Union (EU) with a dramatic increase in production capacity of 50 times that of today (20 Mton in 2030 compared to 400 kton in 2019). NG is expected to remain the main reducer, although green H_2 will account for a significant share of production mainly in Scandinavia and perhaps other regions [22]. In addition, biosyngas, which can be obtained through the gasification of biomass within fluidized bed gasifiers, has reached a mature technological level (TRL 7–9) and could play an important role in DRI production as an alternative reducer to both NG and green H_2 [23].

It will, therefore, be necessary for most countries that rely or will rely on the scrap recycling route to decide whether it is more cost-effective to build a DR/EAF grid within national borders or, as is currently done, to rely on importing DRI. In this regard, Italy, currently the world's 11th largest producer, can be considered a worthy case study as its steel production is based almost exclusively on the scrap recycling route (18 Mton produced by EAF vs. 3 Mton by BF/BOF in 2022), and as there is still no DR plant within the national borders, it relies on the import of approximately 2 Mton of clean iron sources (e.g., DRI, HBI and pig iron) per year and approximately 5 Mton of scrap per year to feed its 37 EAF production sites [24]. To make up for this deficiency, a memorandum was signed in 2023 for the decarbonization of the Italian steel sector with a focus on the conversion of the BF/BOF plant of Taranto into a DR plant [25,26]. In order to analytically understand the feasibility of this transition and which strategies/technologies are best suited to actually achieve it, techno-economic or techno-assessment modeling appears to be an appropriate methodology. In fact, they have proven to be a more than reliable tool for highlighting the main barriers that the transition from hard-to-abate to near-zero emissions term would entail, especially if the analysis is limited to individual countries or technologies. In the EU context, Mandova et al. [27] focused their attention on the implementation of biomass and bio-CCS technologies to primary steelmaking, highlighting an overall CO_2 reduction of 20% and 50%, respectively. Still in the primary steelmaking framework, Fischedick et al. [28] as well as Arens et al. [29] studied the possible future of the German steel industry. They both concluded that the high production share of the integrated cycle (approximately 70%) created an urgent need for emissions cutting in the short to medium term achievable through the use of heat-recovery technologies, an increase in the scrap recycling production share and the use of by-products for the production of base chemicals. In Norway, Bhaskar et al. [30] developed a techno-economic assessment of a H_2-DR/EAF plant, highlighting that, though on the one hand the availability of green electricity and magnetite ore is the main influencing factor, on the other the national offshore wind energy potential makes the country an ideal location for hydrogen-based steel production. A similar pathway was suggested in Sweden by Toktarova et al. [31], who concluded that the H_2-DR/EAF process could abate 10% the total Swedish CO_2 emissions, but the main challenge would be the 14 TWh demanded for the electrification of the primary steel production while maintaining constant steel production throughout the time period of the analysis. Furthermore, they also highlighted that the implementation of CCS and biomass in the BF along with the transition of the primary steel production plant to the scrap recycling route would result in an 80% reduction with respect to the current Sweden steel sector emissions. Furthermore, CCS technologies must also overcome the obstacles caused by the removal of contaminants (e.g., N_2, SO_2, NO_x, fly ash, trace metals) in the furnace flue gases before the actual capture of CO_2 that would otherwise hinder the efficiency of the process [32].

Despite the importance of the steel sector in Italy, a specific technical assessment model on the feasibility of creating a DR/EAF grid is still lacking. To date and to the authors' knowledge, there are only two papers that investigated the sector from a general point of view, and they were published in 2016 and 2022 by Renzulli et al. [33] and Mapelli et al. [13], respectively. However, the former focuses exclusively on the environmental impact of the ILVA plant, while the latter evaluates possible options for impact mitigation, focusing on the advantages and disadvantages they would bring to each of the specific steel production pathways while leaving out the variation over time.

Therefore, this study aims to investigate the transition of the Italian steel sector toward the creation of a national DR/EAF grid with the goal of filling the lack of a technology assessment, which is currently present in the literature, while also providing new insights into the consequences of this transition. The focus is on the 2030 and 2050 CO_2 emission thresholds and the weight that green H_2-DR would have on renewable electricity and bio-CH_4-DR would have on biomethane production. In addition, the results will be compared with those of a traditional NG-DR plant in order to highlight the barriers and risks associated with such a transition in the near future.

2. Materials and Methods

The proposed analysis derives and estimates the amount of CO_2 and electricity demand associated with the creation of a DR/EAF grid in the Italian context over a time period from 2022 to 2050. Prior to the analysis, the following assumptions were made:

- A constant steel production of 22 Mton is assumed between 2022 and 2050. According to Federacciai [24], Italian steel production has fluctuated between 31 Mton in 2007 and 21 Mton in 2022, mainly due to the macro-economic context. On the other hand, if only the time period between 2015 and 2022 is considered, the overall production has remained more constant with an average output of approximately 22 Mton.
- The share of the scrap recycling route is assumed to increase linearly until 2030, the year in which the production relies solely on electric furnaces. After 2030, it is assumed

that the amount of EAFs that will begin to exploit domestically produced DRI and the annual capacity of the DR plants will increase at a rate equal to that described by Arens et al. [29].

- The metallic charge of EAF is assumed to be covered for 10 wt.% by DRI as the only source of clean iron, whereas the import of scraps and DRI is assumed to be ensured for the entire time period of the analysis [34].

2.1. Model Input Parameters and Pathways

The amount of CO_2 and electricity demand related to the Italian steel industry were evaluated based on the results obtained by Mapelli et al. [13], which are summarized in Table 2. The evaluation considered three DR/EAF pathways to show the differences and advantages of DRI production via NG (pathway 0), green H_2 (pathway 1) produced by water electrolysis and exploiting photovoltaic (PV) renewable energy and, finally, biomethane (pathway 2). Furthermore, in pathways 1 and 2, it is assumed that the EAFs that will exploit internally produced DRI will replace methane with the corresponding reducing gas in the pathway. Finally, steel casting, hot and cold working and coating are not included in all pathways because of their significantly lower energy consumption and carbon emissions compared to production.

Table 2. Specific CO_2 emissions and energy demand per ton of steel per type of production process and pathway [13].

Pathway, Process	**Specific CO_2 Emissions, ton_{CO2}/ton_{steel}**	**Specific Energy Demand, kWh/ton_{steel}**
Pathway 0		
Blast furnace with basic oxygen furnace (BF/BOF)	2.515	131.25
Electric arc furnace (EAF)	0.135	514
Direct reduction plant fed by natural gas (DR)	0.77	123.5
Pathway 1		
Blast furnace with basic oxygen furnace (BF/BOF)	2.515	131.25
Electric arc furnace (EAF)	0.135	514
EAF fed by green H_2 (H_2-EAF)	0.092	510
Green H_2 production for EAF	0	379
Direct reduction plant fed by green H_2 (H_2-DR)	0	123.5
Green H_2 production for DR	0	2552
Pathway 2		
Blast furnace with basic oxygen furnace (BF/BOF)	2.515	131.25
Electric arc furnace (EAF)	0.135	514
EAF fed by biomethane (Bio-CH_4-EAF)	0.12	514
Biomethane production for EAF	0.018	2.2
Direct reduction plant fed by biomethane (Bio-CH_4-DR)	0.32	123.5
Biomethane production for DR	0.28	34.7

2.2. Key Mathematical Equations

The annual CO_2 emissions for each of the three pathways were evaluated by considering the specific emissions of the production cycle, their share and the total amount of steel and DRI produced per year.

$$TE_{i,t} = \left(\sum_j s_{j,i} \cdot \chi_{j,i,t} + s_{DR,i} \cdot \xi_{i,t} \right) \cdot P_t \quad (1)$$

where TE is the total CO_2 emission expressed in Mton, s is the specific CO_2 emission related to steel production and reducing gas production expressed in ton_{CO2}/ton_{steel}, χ is the share of the specific production cycle, ξ is the parameter that considers the amount of production capacity of the DR plant per year, and P is the amount of steel produced per year expressed in Mton. The symbols j, i and t represent the specific production cycle (integrated cycle, scrap recycling and DR), the pathway and the year.

Similarly, the annual energy demand for each of the three pathways was evaluated by considering the specific emissions of the production cycle, their share and the amount of DRI introduced inside the furnaces and the total amount of steel produced per year.

$$TEC_{i,t} = \left(\sum_j q_{j,i} \cdot \chi_{j,i,t} + q_{DR,i} \cdot \xi_{i,t} \right) \cdot P_t \quad (2)$$

where TEC is the total electrical consumption expressed in TWh, q is the specific energy demand related to steel production and reducing gas production expressed in TWh/ton_{steel}, χ is the share of the specific production cycle, ξ is the parameter that considers the amount of production capacity of the DR plant per year, and P is the amount of steel produced per year expressed in Mton. The symbols j, i and t represent the specific production cycle (integrated cycle, scrap recycling and DR), the pathway and the year.

2.3. Sensitivity Analysis

Sensitivity analysis was performed on the total CO_2 emissions to highlight the level of decarbonization achievable in the three DR/EAF pathways by applying Equation (1) for years 2030 and 2050. The comparison was performed with respect to the IEA projection for the SDS of the corresponding year per ton of steel produced [12].

Furthermore, it is strongly discussed that, in addition to direct CO_2 emissions, the decarbonization of steel and, particularly, electrical steelmaking are highly dependent on the level of decarbonization of the national power grid; hence, a sensitivity analysis was performed on the energy demand of the steel production, evaluated by applying Equation (2) with respect to the renewable energy expected in 2030 and 2050. To date in Italy, more than 70% of the energy is imported with most of it of fossil origin. Hence, to decrease this dependency, the Integrated National Plan for Energy and Environment set very ambitious targets for renewables, aiming to reach 30% in total energy consumption and 55% in electricity generation in 2030. It is foreseen that its pursuit will increase the photovoltaics PV capacity to 52 GW in 2030 and, in order to achieve the carbon neutrality imposed by the EU, to 200 GW in 2050 [12,35,36]. Based on the latest data provided by Terna [37], the resulting TWh would account for approximately 57 TWh in 2030 and 218 TWh in 2050.

Finally, for pathway 2, a sensitivity analysis was performed on the amount of biomethane required compared to the total potential production from biomass. Specifically, biomethane production is assumed to reach a total potential of approximately 6 Gm^3 in 2030 and 13.5 Gm^3 in 2050, as estimated by the European Biogas Association [38,39].

3. Results

3.1. Outline of the Steel Production

Figure 1a shows the amount of steel produced by process type and that of domestically produced DRI (DRI-IT) regardless of the reducing agent assumed in the specific pathway.

Following a conservative approach regarding DRI production, the electrical steelmaking was divided into two separate routes (EAF and DRI-IT/EAF). Specifically, the orange area represents the portion of EAF plants that will continue to take advantage of imported DRI, while the blue area represents the electric steel plants that will feed furnaces with DRI-IT and replace methane with green H_2 (pathway 1) or biomethane (pathway 2). This is in order to avoid an over-demand for DR plant production in the initial years, allowing for them to reach their full production potential without compromising DRI quality.

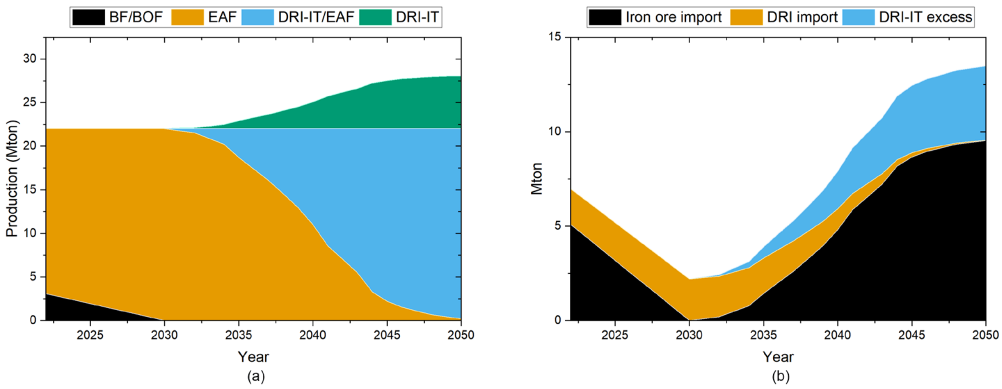

Figure 1. (**a**) Steel and DRI production by process (BF/BOF: integrated cycle, EAF: scrap recycling route, DRI-IT/EAF: scrap recycling route utilizing domestic produced DRI, DRI-IT: domestic produced DRI), (**b**) required iron ore, DRI import and excess of DRI-IT with respect to that charged into DRI-IT/EAF available for the Italian steel sector from 2022 to 2050.

To highlight the consequences of setting up the DR plants, Figure 1b shows the changes in the import demand for DRI and iron ore as well as the amount of excess DRI-IT available that could be further introduced into the furnaces or exported. The net difference between DRI-IT charged and DRI-IT produced, depicted in Figure 1b, was estimated by considering an EAF metal charge covered for 10 wt.% by DRI [34].

Although the production of DRI-IT would be able to cover the demand of the furnaces while also producing an excess of material for each year of the analysis, the main consequence of the domestic DRI production would be an increase in the import of iron ores. Indeed, an amount equal to that currently imported for the BF/BOF plant (5 Mton) would again be required in 2040 and would almost double in 2050, assuming the best-case scenario and the maximum yield of iron ore reduction in which approximately 1.55 ton of iron ore (64 wt.% Fe) is needed for 1 ton of DRI [40].

Remarkably, if the excess of DRI-IT is reintroduced directly into the domestic market, the import of DRI can be abandoned as early as 2038, the year when DR plants reach a level of maturity and productivity that can fully cover furnace demand. Furthermore, also in the same year, the amount of imported DRI would be less than the 5 Mton in 2022 and equal to 3.2 Mton.

3.2. Estimation of the Pathways' CO_2 Emissions

Figure 2 illustrates the CO_2 related to each pathway and unbundled by type of production process, either intended as steel production or the production of gaseous streams to be introduced within the furnaces or DR plant.

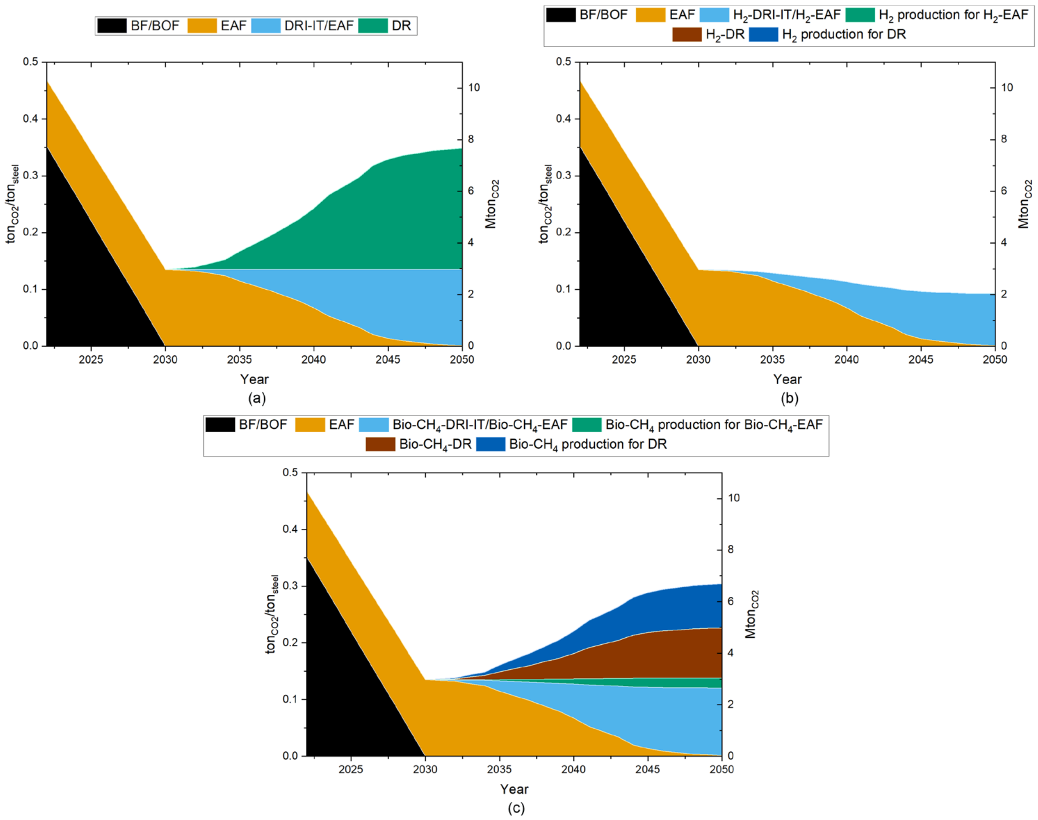

Figure 2. Specific and total CO_2 intensities for (**a**) pathway 0 (use of NG), (**b**) pathway 1 (use of green H_2) and (**c**) pathway 2 (use of biomethane).

In each pathway, the largest reduction in total CO_2 emissions is expected between 2022 and 2030 due to the closure of the BF/BOF plant and its replacement by electric steelmaking. Specifically, by 2030, emissions would be reduced by 71% compared to 2022 while maintaining a constant steel production of 22 Mton. In fact, of the 10.30 $Mton_{CO2}$ emitted in 2022, the BF/BOF plant alone accounts for 7.75 $Mton_{CO2}$. The value appears more than abnormous when compared with that of the EAF plants for the same year (2.55 $Mton_{CO2}$) and bearing in mind that only 14% of production was covered by the integrated cycle.

Since pathway 0 (Figure 2a) assumes a continuity in the use of methane in the EAFs, the value of total emissions from electric steelmaking will remain constant over the period 2030–2050 (2.97 $Mton_{CO2}$). On the contrary, the start-up of NG-DR plants from 2030 onward would lead to an increase in the sector emissions until 2050 due to the reaching of the DR plants' full capacity (6 $Mton_{DRI\text{-}IT}$). Specifically, DRI-IT production would be responsible for 60% of the total 7.67 tons of CO_2 emitted by the sector in 2050, which, though it would still be less than that emitted by the 3 Mton of steel produced by the BF/BOF plant in 2022 (7.75 $Mton_{CO2}$), would not provide a significant effective decarbonization. On the other hand, in 2038, the year when it might be possible to cover the desired 10% of the metal charge of all EAFs with DRI-IT, the value of emissions associated with DR plants would account for 35% of the total 4.58 Mton of CO_2 emitted by the sector, 1.7 times lower than that associated with DRI-IT production in 2050.

The lowest CO_2 emissions are achievable through the application of pathway 1 (Figure 2b) through the substitution of methane with green H_2 in electric steelmaking and the charging within the furnaces of zero-emission H_2-DRI-IT (2.03 $Mton_{CO2}$). Specifically, in 2050, emissions would be reduced by 80% compared to the 2022 value but only 30% compared to the 2030 value. On the other hand, in 2040, when steel production is equally divided between traditional EAF and H_2-DRI-IT/H_2-EAF, the total emissions would be comparable to those of electric steelmaking in 2022 (2.50 $Mton_{CO2}$ vs. 2.55 $Mton_{CO2}$), which can be considered a more than positive result when considering that scrap production would increase by 3 Mton in the same time period.

Finally, pathway 2 (Figure 2c) shows an intermediate situation in which total emissions could be reduced by 3.6 $Mton_{CO2}$ in 2050, representing a 35% mitigation compared to 2022, mainly due to emissions related to Bio-CH_4-DR plants and their respective biomethane production (1.95 $Mton_{CO2}$ vs. 1.70 $Mton_{CO2}$). It is noteworthy to highlight that, if only emissions related to steel production are considered, the decrease would be 74% over the same time period, which rises to 70% if those related to the production of biomethane to be introduced into the furnaces are also considered. Finally, contrary to pathway 1, if the comparison is limited to electric steelmaking in the periods 2022–2040 and 2022–2050, the emissions would increase by 0.02 $Mton_{CO2}$ and 0.06 $Mton_{CO2}$, respectively.

3.3. Estimation of the Pathways' Energy Demand

Figure 3 shows the energy demand of each route broken down by type of production cycle and production of gaseous streams to be fed into the furnaces or DR plants.

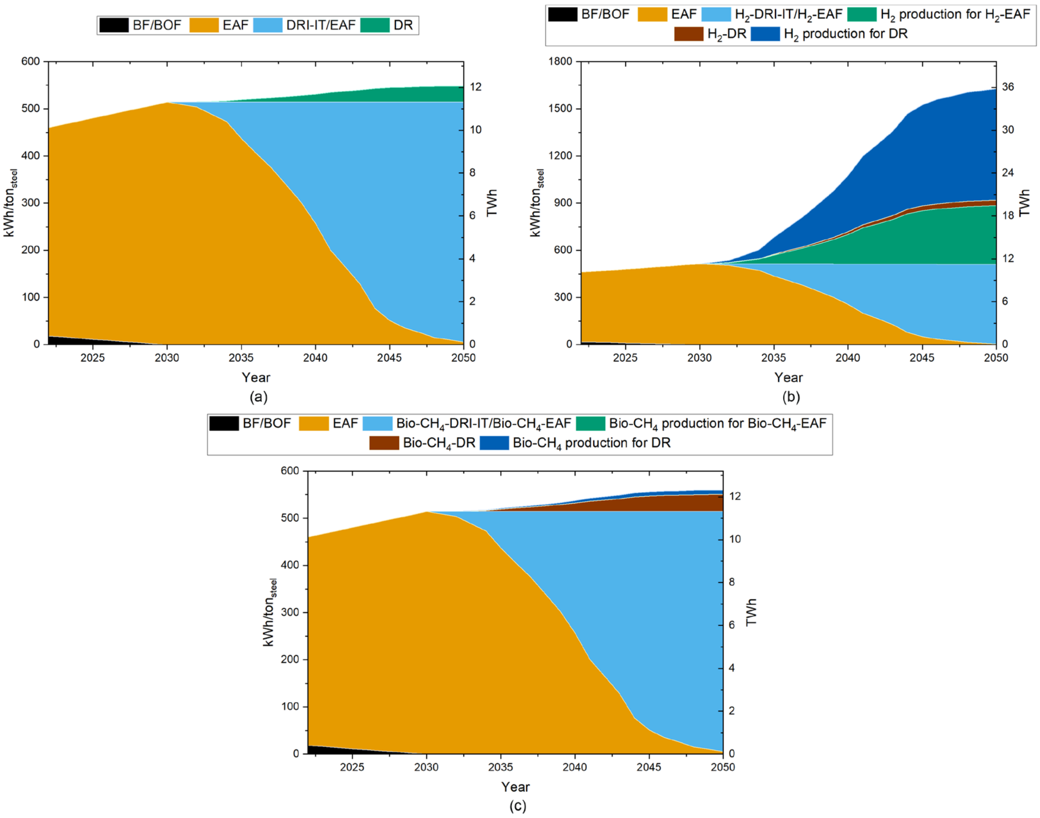

Figure 3. Specific and total energy demand for (**a**) pathway 0 (use of NG), (**b**) pathway 1 (use of green H_2) and (**c**) pathway 2 (use of biomethane). Note the different scale of the y-axis of (**c**).

The results indicate that none of the routes studied are able to achieve energy savings over the entire period examined. Specifically, in the period 2022–2030, the supplanting of the BF/BOF plant with electric steelmaking has, as its main consequence, a 12% increase in the sector energy demand (10.13 TWh vs. 11.31 TWh), which increases further in the following 20 years due to the startup of DR plants.

Pathway 0 (Figure 3a) achieved the lowest increase in energy demand due to the import of NG gas with the sector aggravation on the power grid compared to 2022 being 15% and 19% in 2040 and 2050, respectively. Focusing only on the DR plants in 2040, the year when DRI-IT production would be equal to that of the crude steel produced by the BF/BOF plant in 2022 (3 Mton), the results showed a slight energy savings of 0.02 TWh.

In contrast, at full capacity of the DR plants in 2050, their demand would reach 0.75 TWh, 1.8 times that of the BF/BOF plant in 2022.

The highest energy demand is projected for pathway 1 (Figure 3b) due to the abnormous burden of H_2 production for both EAF and DR plants on the national power grid, which would account for 23.81 TWh of the total 35.79 TWh required by the sector in 2050. Even when considering hydrogen electric steelmaking alone, the demand would be higher than pathway 0 for any year analyzed, as the production of green H_2 to be used as a substitute for NG within electric furnaces would account for approximately 40% of the total demand of electric steelmaking, thus almost doubling the final value of the scrap recycling route. Therefore, it is important to consider the demand in 2038, when the energy demand settles at 19 TWh due to the lower production share of H_2-EAF compared to traditional EAF (34% vs. 66%) and H_2-DRI-IT production (2 $Mton_{DRI\text{-}IT}$).

Finally, pathway 2 (Figure 3b) appears to be an almost identical scenario to pathway 0 due to the low energy demand required for biomethane production. Specifically, an increase in energy demand of 2.19 TWh is expected in 2050 compared to 2022, which is more than comparable to that observed for pathway 0 over the same time period (1.93 TWh). Similarly, the observation made for pathway 0 in 2038 and 2040 could be translated to pathway 1 due to the negligible increase in energy demand (+0.10 TWh and +0.15 TWh compared to pathway 0 in 2038 and 2040).

3.4. Sensitivity Analysis

The estimated CO_2 emissions and energy demand were verified by comparing them with the SDS target provided by the IEA [12] and the national PV energy availability projected in the National Integrated Energy and Environment Plan [35–37] in 2030 and 2050, respectively. The estimated results from this study are given in Table 3.

Table 3. Estimated specific CO_2 emission and energy demand in 2030 and 2050 by pathway. Comparison with IEA target for SDS and Italian PV energy.

Year	**Pathway**	**Specific CO_2 Emissions, ton_{CO2}/ton_{steel}**		**Energy, TWh**	
		Estimated	**Target [12]**	**Estimated Demand**	**Target PV Capacity [35–37]**
2030	0	0.13	1.2	11.31	57
	1	0.13		11.31	
	2	0.13		11.31	
2050	0	0.34	0.60	12.06	218
	1	0.09		35.79	
	2	0.30		12.32	

For each pathway, the level of specific CO_2 emissions in 2030 is approximately 10 times lower than the SDS target (0.13 ton_{CO2}/ton_{steel} vs. 1.2 ton_{CO2}/ton_{steel}). Similarly, though the use of NG and biomethane in pathways 0 and 2 results in an increase in specific emissions over time, both values in 2050 are approximately half the strict SDS values imposed in the same year (0.34 ton_{CO2}/ton_{steel} and 0.30 ton_{CO2}/ton_{steel} vs. 0.60 ton_{CO2}/ton_{steel}).

The direct comparison with PV target capacities showed that, in principle, there would be enough renewable energy to be allocated to the full electric steel industry in Italy in 2030 and to cover the additional demand of DRI-IT production in 2050, regardless of the gas stream used. Specifically, in the former case, the steel sector would burden 19.84% of the PV renewable energy grid, and in the latter case, 5.53%, 16.41% and 5.65% based on the selected gaseous stream, imported NG and domestically produced green H_2 or biomethane, respectively. Finally, the amount of biomethane needed for DRI-IT production and as a substitute for methane within the EAFs would weigh 21.70% of the projected potential to 2050 (Table 4).

Table 4. Estimated biomethane demand in 2050 by pathway 2. Comparison with foreseen data by European Biogas Association.

Year	Pathway	Biomethane, Gm^3	
		Estimated	Expected [39]
2050	2	2.93	13.5

4. Discussion

One of the objectives of this study was to explore how three different pathways, based on NG, green H_2 and biomethane as the main gas stream, could change the emissions and energy demand of the Italian steel sector during the establishment of a DR/EAF grid.

It should be emphasized that, because of the uncertainty about the future of the BF/BOF plant in Taranto, this study should be understood as explanatory and not as an actual projection [41,42]. Furthermore, although this study does not focus primarily on the change in domestic and imported scrap, it is clear that, due to the replacement of the BF/BOF plant with EAF plants, an increase should be expected. As discussed by Pauliuk et al. [43], global scrap availability is expected to increase due to stockpiling in emerging economies, while availability in the EU is expected to stabilize. Thus, the main problem will be the decrease in high-quality scrap to be fed into the EAFs and the consequent increase in demand for clean iron sources for European electric steel plants. Consequently, it should be kept in mind that the expected increase in DRI/HBI production will inevitably generate additional problems related to the demand for high-quality iron ore, its availability and the resulting accelerated depletion of mineral resources. Indeed, if, on the one hand, the results showed that the sole Italian integrated plant conversion to a DR plant would be able to produce an amount of DRI that can cover up to 28% of the national EAF metallic charge by 2050, then, on the other hand, the amount of imported iron ore will be almost doubled compared to the current amount, regardless of the route taken.

Regarding the environmental impact and energy demand, the highest benefits were observed for the closure of the BF/BOF plant in 2030 (−7.33 $Mton_{CO2}$ emitted and +1.11 TWh of energy demand with respect to the 2022 value). Pathway 1 alone can slightly reduce overall emissions by another 1 $Mton_{CO2}$ by 2050 at the expense of a significantly greater burden on the renewable energy grid. The creation of a national H_2-DR/EAF grid is thus bound to the achievement of a PV capacity growth rate twice the average value of the past two years (3.35 GW/y) [37]. For a more comprehensive analysis, the demand for greening of grey H_2 production sites and power sector (e.g., transportation, heating) should be, hence, taken into account.

According to Armaroli et al. [44], they would require an additional 69.19 TWh, making the transition to green H_2 more challenging due to the high burden on the renewable grid. In fact, although the use of green H_2 would provide the greatest environmental benefits, the greening of the steel sector, grey H_2 production sites and power sector would require a total of 104.98 TWh of PV renewable energy, which translates to a total of 946 km^2 of surface covered by PV panels alone, 2.5 times the surface of Garda Lake. Similar difficulties were found in the analysis of the Swedish steel sector conducted by Toktarova et al. [31] in which the implementation of an H_2-DR/EAF plant to replace the national BF/BOF plants would lead to a near-zero emissions scenario at the expense of a significant renewable energy demand. Specifically, in the case where total Swedish steel production was maintained at 3 Mton of steel produced per year with an excess of 6 Mton of H_2-HBI for export, the additional energy demand of the steel sector would account for 33 TWh/year.

Hence, as also suggested by Toktarova et al. [31], pathway 2 appears to be a more reasonable scenario, being that the bio-CH_4-DR plants are able to emit, at full capacity, less than the current value of the BF/BOF plant (3.6 $Mton_{CO2}$ at 6 $Mton_{DRI\text{-}IT}$ vs. 7.74 $Mton_{CO2}$ at 3 $Mton_{steel}$) and require 17 times less energy demand than H_2-DR plants, also avoiding NG import as assumed in pathway 0. On the other hand, the application of biomethane could be limited by competition with other sectors that will consider it a viable gas stream for emissions mitigation [39].

Finally, regardless of the path, the Italian steel sector is already in a favorable situation compared to other major steel-producing countries, which could even be strengthened by the transformation of the BF/BOF plant into a conventional electric steel mill rather than the subsequent creation of the DR/EAF grid because of the little benefit brought by the latter compared to the challenge that is associated to each path. Indeed, to reflect the current decision-making process of the German and Japanese steel industry, Arens et al. [29] and Kuramochi et al. [44] analyzed the transition from an integrated plant to an innovative steel process (e.g., HIsarna, ULCORED, Top Gas Recycle Blast Furnace, CCS) without considering a significant increase in scrap route share. Their studies showed that the mitigation of emissions from the steel industries in the respective countries is highly limited by 2030 and would not meet the European and German climate targets by 2030 due to the high intensity of steel production from BF/BOF, even when applying the best available technologies.

5. Conclusions

This study explored the benefits and limitations of converting the Italian steel sector to a DR/EAF production following the closure of the Taranto BF/BOF plant in 2030 and its conversion to a DR plant with full capacity reached by 2050. Imported NG, green H_2 and biomethane were chosen to be studied as possible gas streams to be fed into the DR plant as reducing agents and into the EAF plants as methane substitutes. Finally, the metallic charge of the EAFs was assumed to be covered for 10 wt.% by DRI.

The results showed that, regardless of the chosen pathway, the closure of the integrated steel mill in 2030 would result in not only the highest emission reduction from the current value (71%) but also the lowest specific emissions, amounting to 1/10 of the IEA's SDS target. Similarly, the specific emission of each pathway in 2050 would remain far from the respective year's climate target, even considering a constant steel production of 22 Mton and a DRI production of 6 Mton, at the expense, however, of doubling the amount of imported iron ore from the 2022 value and increasing energy demand due to DR plant operation and reduced gas production.

The exploitation of imported NG and biomethane as a reducing gas in DR plants provided similar results in 2050 with a relative increase in emissions of 158% and 125% over 2030 due to plant operation and domestic biomethane production. In contrast, green H_2 would be able to further reduce emissions by 32% but at the cost of increasing the sector energy demand by 216% due to hydrogen production over the same time period.

Finally, the sensitivity analysis showed that, although in principle each of the pathways could be feasible, the creation and increase in the production share of the DR/EAF grid from 2030 onward are vitally linked to the establishment of a rigorous national renewable energy policy and the creation of biomethane production capacity as well as meeting the ambitious 2050 targets for the Italian renewable energy grid.

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Nomenclature

List of acronyms

BF	Blast furnace
Bio-CH_4	Biomethane
BOF	Basic oxygen furnace
CCS	Carbon capture and storage
DR	Direct reduction
DRI	Direct reduced iron
DRI-IT	Domestically produced DRI
DRI-IT/EAF	Electric steel plants exploiting (charging or fed by) domestic DRI
EAF	Electric arc furnace
HBI	Hot briquetted iron
NG	Natural gas
PV	Photovoltaic
SDS	Sustainable development scenario

List of Symbols

i	Pathway investigated (0: natural gas; 1: green hydrogen; 2: biomethane)
j	Specific production cycle (integrated cycle, scrap recycling and DR)
P	Amount of steel produced per year [Mton]
s	Specific CO_2 emission [ton_{CO2}/ton_{steel}]
t	Year
TE	Total CO_2 emission [Mton]
TEC	Total electrical consumption [TWh]
ξ	Amount of production capacity increase of the DR plant per year
χ	Share of the specific production cycle

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