Future Scenarios for Reducing Emissions and Consumption in the Italian Steelmaking Industry

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The amount of CO_2 emissions, water and electricity consumption, and soil exploitation of the main steel production routes (integrated cycle, scrap recycling, and direct reduction) are analyzed applying three possible future scenarios: use of carbon capture and storage (CCS); use of green hydrogen in substitution of natural gas; use of biomethane. Using actual process data and theoretical assumptions, the emissions and consumptions of the whole steel production cycle (from the iron ore extraction to the final steel product) are computed, taking into account also the auxiliary sources of emissions (i.e., limestone calcination and gas compression). The assessment results have highlighted the huge energy requirements and soil exploitation related to the application of green hydrogen in the steelmaking cycle, despite its low CO_2 emissions. On the contrary, the use of biomethane appears more attractive if combined with carbon capture and storage systems. Overall, the results of the assessment provide a starting point for understanding the current level of sustainability of steel production and allow the identification of the most promising and plausible scenario for the steel industry of the future and the possible criticalities of each.

1. Introduction

Steelmaking is recognized as one of the most fundamental activities for the industrial sustaining. The several steel grades are suitable for a wide range of applications thanks to their variety of mechanical and physical properties. Consequently, steel can be considered more than essential for a wide range of production sectors, such as building, automotive, mechanical equipment, machinery, and power generation. According to World Steel Association (WSA) the worldwide steel production in 2020 touched 1.878 billion tons.[1] In the European Union, the apparent steel consumption in 2020 was 140.6 million tons. Although

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Italy steel production decreased by about 12% from to the previous year due to the global pandemic, it is still the second largest producer in Europe with 20.9 million tons of crude steel, and an average consumption of about 25 million tons. The difference between the apparent consumption and the internal production is covered by the import.[1,2] Even though steel is considered a fully recyclable material, its production is recognized as one of the most energy and carbon intensive in the world. Indeed, the overall emission of greenhouse gases produced by steelmaking activities can be estimated roughly 2.8 billion tons, which represents 5.5–6% of total annual greenhouse gas emissions.[3,4]

Therefore, it is more than necessary to analyze steel and iron production processes to provide a detailed picture of their current environmental impact together with possible scenarios concerning the most promising solutions to reduce their footprint and their economic feasibility. Consequently, this study focuses its attention on the Italian steelmaking and ironmaking industry, analyzing four fundamental parameters for the environmental sustainability of production processes: 1) CO_2 emissions to atmosphere; 2) water consumption; 3) electricity consumption; 4) soil exploitation.

In particular, electricity consumption and CO_2 emissions are two widely used environmental impact indicators. Specifically, this study takes into account the energy expended for moving, compressing and processing all auxiliaries (i.e., internal movement of raw materials, gas compression, etc.). Contrary, emissions and consumption derived from the construction of infrastructures (i.e., steel pipelines, solar panels, digestors, etc.) and transportation of raw materials are not included. Finally, the impact of coal mining, its treatment to obtain coke, and limestone calcination are considered because of their importance and extensive use in ironmaking and steelmaking processes. Heavy fuel oil, lubricating oil, and fluxes are not included in the analysis because their main use is outside the scope of the analysis and their contribution to the environmental impact can be considered as negligible.

Concerning water consumption, only evaporated water should be considered as removed from the system boundaries, as treated, and recovered water is still available and can recirculate in the plant.

Finally, soil exploitation was chosen as fourth parameter as it is considered as a nonrenewable resource by both the Italian government and the EU, and because of the wide heterogeneity of soilscape morphologies that characterize the Italian peninsula.[5] Furthermore, soil exploitation is directly linked to agricultural production capacity, which is particularly relevant for the Italian economy. In fact, a reduction in food production potential would further increase the disadvantages of the Italian agricultural sector compared to European standards.[6,7]

1.1. Steelmaking Routes Emissions

The overview and emission points of each process for steel production, starting from iron ore to crude steel or reduced iron, are shown in **Figure 1**.

To date, Direct Reduced Iron (DRI) and Hot Briquetted Iron (HBI) production is mainly located in the Middle East and Asia, with Iran and India alone producing 28.5% and 31.7% of total world production (106 Mt) in 2020.[1] The process is based on the coupling of a Pelletizer Plant (PP), which is used to provide the oxide pellets that are successively reduced inside the Direct Reduction (DR) reactor or shaft furnace. The integrated ironmaking and steelmaking route, which is based on the combination of blast furnace (BF) and basic oxygen furnace (BOF), is still the most diffused worldwide (73.2%) in 2020.[1] It is mainly focused on the processing of coal for the coke production, necessary for the following iron ore reduction inside the BF; whereas, the remaining raw materials are supplied by sintering or pelletizer plant. Finally, the 2020 share of the scrap recycling route,

through their melting in an electric arc furnace (EAF), is 26.3%. This is expected to reach over 27% by 2030 to be in line with the net zero emissions by 2050 scenario, which sets nearly 40% of total crude steel production.[8]

Italy can be considered a special case in the world, since it has a steel production mainly based on the scrap cycle (82% and 84.7% in 2019 and 2020, respectively) with 37 active EAF production sites. The only other countries with a similar production and share of crude steel from EAF are, in order of tonnage: USA, Turkey, Iran, Mexico, and Spain.[1,2]

The remaining 15.3% of the Italian production is covered by integrated cycle, even if constrained by the environmental policies imposed by the Italian authorities. However, the potential production is 28%, which will be exploitable after the fulfilling of the environmental plan.[9]

For each steel production route, CO_2 emissions, water, and electricity consumption and soil exploitation are reported together with the average chemical composition of the waste gases generated during the steel production (**Table 1** and **2**). Data were mainly estimated according to the Best Available Techniques Reference documents (BREF) for steel and from five Italian steel mills and reported in the following paragraph.[10]

1.1.1. Direct Reduction

Modern direct reduction processes are based on the exploitation of CO and H_2 used as the reducing agents for the ore reduction. At the moment, there are two leading technologies for prereduction based on the natural gas exploitation: MIDREX and
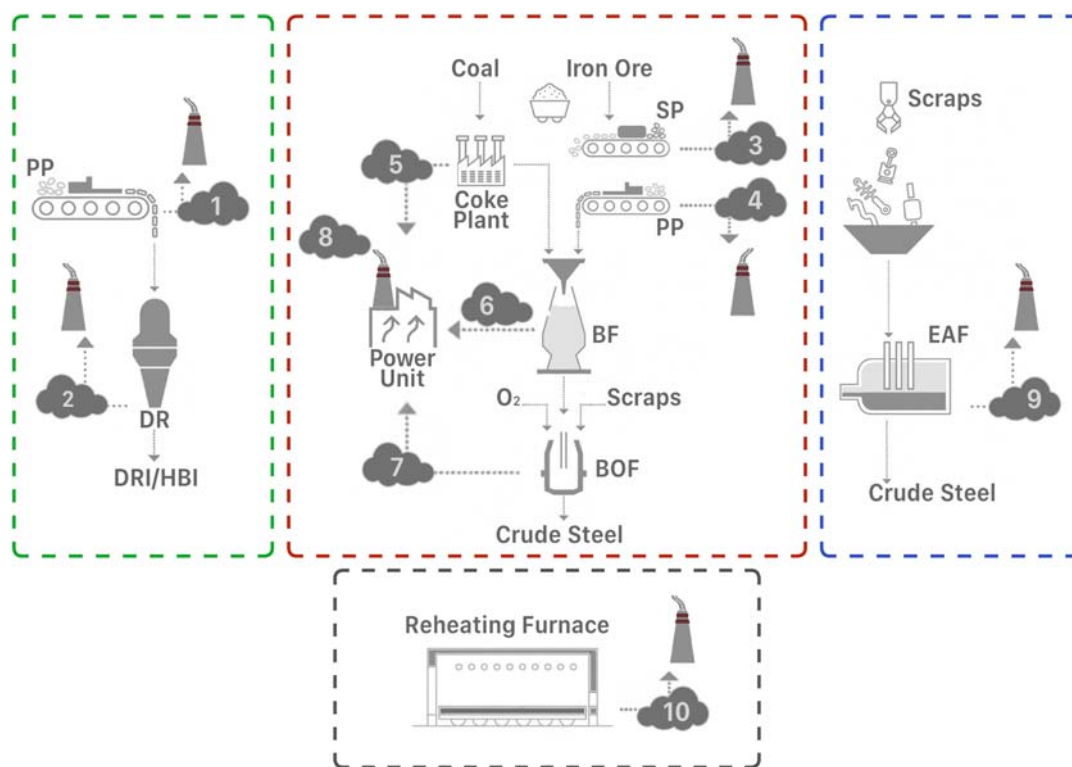
Figure 1. General overview of the steelmaking routes and respective emission points (PP: pelletizer plant, SP: sintering plant).

Table 1. Consumes and emissions.

	CO_2 emissions [t_{CO2}/t_{STEEL}]	H_2O consumption [m^3/t_{STEEL}]	Electricity consumption [kWh/t_{STEEL}]	Soil consumption [$m^2/kt_{STEEL/day}$]
Direct reduction				
Pelletizer	0.045	0.154	30.0	14.0
PP + DR	0.770	0.300	123.5	24.7
Sinter	0.370	0.028	48.0	–
Integrated cycle				
Pelletizer	0.045	0.154	30.0	–
Coke Ovens	0.336	0.250	2.8	–
BF + BOF charged with 310 kg_{coke}/t_{STEEL} + 200 kg_{PCI}/t_{STEEL}	2.089	1.300	85.0	247.0
BF + BOF charged with 370 kg_{coke}/t_{STEEL} + 200 $Nm^3_{NaturalGas}/t_{STEEL}$	1.966	1.100	85.0	247.0
BF + BOF charged with 350 kg_{coke}/t_{STEEL} + 100 kg_{PCI}/t_{STEEL} + 20% DRI	1.857	1.200	92.7	247.0
BF + BOF charged with 350 kg_{coke}/t_{STEEL} + 165 $Nm^3_{NaturalGas}/t_{STEEL}$ + 20% DRI	1.815	1.100	92.7	247.0
Scrap recycling				
EAF	0.135	0.200[a]	514.0[b]	20.0
Reheating furnace of semis				
Reheating furnace	0.050	0.006	2	–

[a] The value includes also the water needed to perform the natural gas extraction; [b] The value of specific electric consumption is the sum of the electric energy spent for the melting (390 kWh/t), the amount consumed for other treatment and service (120 kWh/t).

Table 2. Average gas composition.

	CO	O_2	H_2	N_2	CO_2	H_2O	CH_4	Flow rate	Pressure
	[%vol.]							[$Nm^3/t_{product}$]	[bar]
Direct Reduction									
No-reforming	12	–	49.7	12	9	23.4	4.4	1700	5
Reforming	14	–	52	–	15	19	–	1700	5
Integrated Cycle									
Sinter	3	15	–	55	13	14	–	2250	1
Pelletizer		9	–	67	14	10	–	2000	1
Coke oven	7	1	58	3	2	2	26	439	1
BF	22	–	3	52	18	5	–	2000	1
BOF	69	0.5	1	15	15	–	–	475	1
Scrap Recycling									
EAF	9	–	0.5	68	9	–	–	5000	1
Reheating Furnace of Semis									
Oxy-fuel Burners	–	–	–	25	35	39	–	235	1
Air-fuel Burners	–	–	–	68	17	15	–	235	1

HyL.[11,12] Both the technologies are based on the reduction by CO and H_2 but in the MIDREX process they are produced in a reformer and then introduced into the reduction reactor. Whereas in most modern HyL (also known as Energiron ZR), a more recent approach is fulfilled. The natural gas is directly inserted into the reduction reactor and, at this stage, the formation of CO and H_2 takes place directly in the reduction reactor itself.[13]

The same process and plant can work using only H_2 avoiding the exploitation of CO, although this procedure may decrease the kinetics of the reduction reaction and the productivity of the plant. Moreover, reduction by H_2 alone does not allow for proper carburization of the reduced iron.[14] This is an important limitation for the carbonless DR route, because the increase of the DRI carbon content is a favorable aspect for the electricity consumption and melting time reduction in the EAF.[11,15,16]

Therefore, in order to overcome this drawback, it is necessary to add hydrocarbons during the production process.[14]

The CO_2 emissions, electricity consumption, and wastewater and soil consumption of the direct reduction route are summarized in Table 1. The analysis of this cycle must take into account the environmental impact of the pelletizer plant that supplies the iron ore pellets required by the shaft furnace.[10] More precisely, for the pelletizer an energy supply of 794 MJ/t_{PELLET} is needed, which is provided by natural gas. Anthracite or coke breeze (5–10 kg/t_{PELLET}) are added to the iron oxide mix to improve energy supply and bond kinetics when pellets are used in the BF, in contrast coke breeze is not added in the direct reduction process. In this study an average value of 7.5 kg/t_{PELLET} has been considered. In case of use of natural gas, the specific overall direct emissions of CO_2 are 528–586 kg$_{CO2}$/t_{DRI} that implies 580–645 kg$_{CO2}$/t_{STEEL}.

The emission flow rate of the gas is not affected by significant variations, the average temperature of gas is 380–400 °C and they are featured by the oxidation of the reducing agent after a first cycle of reduction (Table 2).[17] For thermodynamic reasons, a maximum of 36% of reducing agents can be oxidized, whereas the remaining part is available for other reactions. Consequently, this high fraction of reducing agent still available is reintroduced inside the reactor with the addition of new reducing gas in substitution of the fraction loss in the previous cycle.[11,12]

1.1.2. Integrated Cycle

In the integrated cycle, the iron ores are reduced in the BF after the production of pellets and/or sintering of the iron ore powders.[11,12] In this study, the definition of the base case includes the use of sintered iron ores because they are the main raw material used for feeding the Italian BFs. The iron ores, under the form of pellets and sintered agglomerates, are top charged in the BF along with limestone and coke which act as reducing agents and structural stabilizers.[10] The average amount of charged limestone is 27.7 kg/t_{STEEL} and an additional 211 kg/t_{STEEL} is charged in the sintered materials combined with iron ores. After the reduction of iron ores and their carburization, the hot metal is tapped, collected and delivered to the steelshop where it is converted into steel by decreasing the amount of carbon through oxidation reactions in the BOF. Following the BOF, the steel is sent to secondary metallurgy treatments and finally to the continuous casting machines for the solidification.[11,12]

The CO_2 emissions, electricity consumption, and wastewater and soil consumption of this route are summarized in Table 1. Because of the significant amount of CaO used within the BOF (48.5 t_{CaO}/t_{STEEL}) to arrange the slag chemical composition, the contribution for its production must be considered with respect to the integrated cycle. Similarly, the contribution of pelletizer and sintering plants, and, especially, coke ovens (used for the production of coke from fossil coal) must be added into the analysis of the integrated cycle.[10] In particular, the sinter and pelletizer plant emissions have to be multiplied for the specific amount of hot metal produced in the evaluation of the integrated cycle. Regarding the reduction of BF emissions, two options have to be considered: the first is the coal powder injection (PCI) at the

tuyeres, the second is the natural gas injection, which implies a significant decrease in CO_2 emissions. In the case where DRI is added to the charged material of the BF, the CO_2 emissions, water consumption, and soil consumed by the direct process have to be considered and evaluated based on the fraction of DRI inserted.[16] These alternative cases of the base production process were evaluated along with the base case and reported in Table 1.
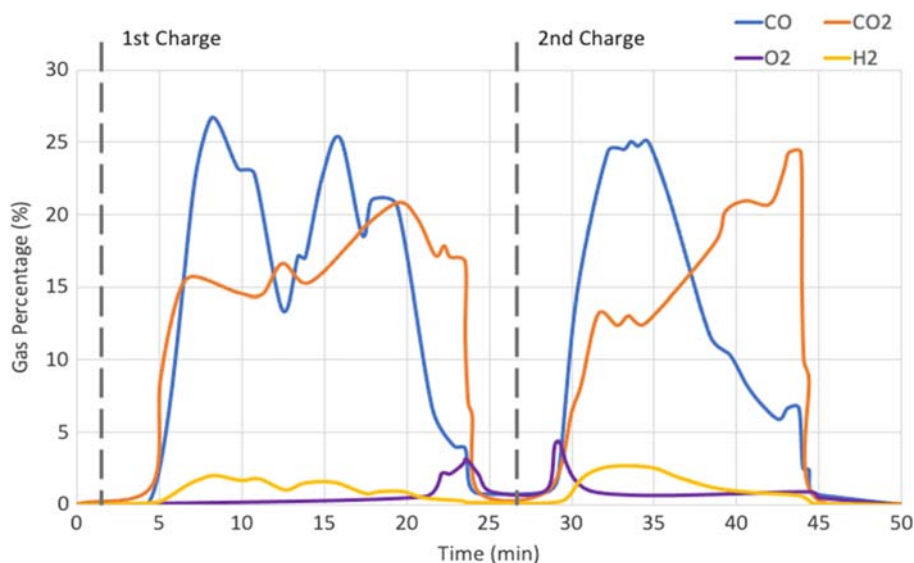
1.1.3. Scrap Recycling

The purpose of the EAF is the fast melting of the charging materials, whereas the refining of the molten bath is performed during the secondary metallurgy treatments. In particular, the charging materials are mainly composed by metallic and ferrous scraps, pig iron (maximum 30%), DRI/HBI, and fluxes.[10–12] Lime is usually introduced in the process to obtain a proper bath chemistry and achieve the so called "slag foaming practice," which allows an increase of the energy efficiency of the furnace.[18,19]

The heating is provided by a synergic work of the arc and the chemical reactions that take place during the melting. The electric arc provides an average energy of 360–420 kWh/t_{STEEL}. To speed up the process and reduce electrical consumption, chemical energy is added during the melting, which is provided primarily by the combustion of natural gas and injected carbon. Additional chemical energy comes from oxidation of the charged scraps, which varies depending on their quality and dimensions.[15,20] The use of postburners provides the needed oxygen to process the not combusted CO inside the furnace, providing another source of additional energy (166–200 kWh/t_{STEEL}). Otherwise, without the use of the postburners, the CO would react with H_2 inside the fume analysis duct, damaging the powder filters.[11,19] After the melting, the tap steel is transferred to the secondary metallurgy and to the continuous casting or to the ingot pit for the solidification of the semis (i.e., billets, blooms, slabs) that are then reheated for the plastic deformation treatments.

In this route, the CO_2 and waste gases emissions are associated with the melting of the charged raw materials inside the EAF. As shown in **Figure 2**, their chemical composition and flow rate vary during the process (the hydrogen in the waste gas is the result of the steam splitting performed by the plasma of the electric arc that is featured by a temperature of ≈5500 °C).

The CO_2 emissions, electricity consumption, and wastewater and soil consumption of this route are summarized in Table 1. The CO and CO_2 emissions are derived from different sources and requires a specific analysis. Auxiliary burners, powered by air and natural gas, have an average natural gas consumption of 17–20.5 Nm^3/t_{STEEL}, as a consequence, they are responsible for the production of 33–40 kg$_{CO2}$/t_{STEEL}.[21] Due to the great importance of lime in the process, the use of 40 kg/t_{STEEL} of CaO was assumed. Carbon, in form of graphite and/or anthracite, is charged in buckets during the melting or directly injected inside the slag for the foaming practice and the bath carburization.[22] By assuming an amount of 3–5 kg/t_{STEEL} it implies a CO_2 emission of 11–19 kg$_{CO2}$/t_{STEEL}. The subsequent steel bath decarburization required for achieving the chemical

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Figure 2. Example of the flow rate and variation of the chemical composition of EAF waste gases.

requirements is also responsible of 17–55 kg_{CO2}/t_{STEEL} under the assumption of an initial carbon concentration of 0.5–1.5%wt. (as a function of charged pig iron and carbon concentration of scrap) and a final concentration of 0.04%wt. The graphite oxidation is also responsible of CO_2 emissions due to electrodes consumption during the melting, assuming a mass loss rate of 0.8–1.2 kg/t_{STEEL}, the corresponding emission value is 3–4.5 kg_{CO2}/t_{STEEL}. Finally, another source of CO_2 is associated to the heating of the ladles that have to be maintained at the correct thermal level even when they are empty in order to avoid the fracture of their refractories. This operation causes an emission of 1.3–1.5 kg_{CO2}/t_{STEEL} that must be multiplied for the number of ladles. The emissions associated to the heating of the ladle furnace cannot be conveyed to the primary abatement system and thus, are further abated by the secondary exhaust gases system of the doghouse.[23,24] The overall specific emission of CO_2 belongs to range of 79–133 kg_{CO2}/t_{STEEL}.

All the CO and H_2 contained in the waste gas stream must be oxidized in order to avoid damage to the filters. The percentage volume composition of the gas during the working period of EAF (excluding tapping and charging periods) is variable (Table 2).

1.1.4. Reheating Furnace of Semis

Except of direct in-line rolling facilities, the semis produced by continuous casting machines (i.e., billets, blooms, slabs) have to be reheated before the plastic deformation at an average temperature of 1250–1300 °C (T_{fin}).[25] Several kinds of furnaces equipped with regenerative or recuperative systems can be used, but considering an average efficiency (η) of 0.6 and a specific heat for the steel of 502 J $(kgK)^{-1}$, the energy required for reheating a casting semis can be estimated by Equation (1)[25]

$$\Delta H = \frac{1000 kg * 502 * (T_{fin} - 25)}{0.6 * 3600} = 285 \div 296 kWh/t_{STEEL} \quad (1)$$

that corresponds to 26–27 Nm^3_{CH4}/t_{STEEL}, and a direct CO_2 emission of 50.8–52.7 kg_{CO2}/t_{STEEL}. If the semis are charged in the reheating furnace with a temperature higher than the room temperature, each 100 °C of preheating implies an energy saving of 7.8%.

The CO_2 emissions, electricity consumption, and wastewater and soil consumption are summarized in Table 1. The reheating furnace gases flow rate is not affected by significant change and variations. The average temperature in the piping is 250–350 °C and it depends on which burner is used, oxy-fuel or air-fuel, respectively. Similarly, the chemical composition of the gases varies as a function of the kind of burners used (Table 2).

When oxy-fuel burners are used, in order to avoid an excessive formation of NO_x specific systems have to be applied. Furthermore, in some specific configurations of the integrated cycle the coke oven gases can be used as fuel for the reheating furnace.[25]

2. Literature Review

Thanks to the growing interest in reducing the environmental impact of the steelmaking industry, research and development of new steel production technologies and procedures has grown rapidly in recent years, further enhanced by the establishment of national and international programs (e.g., the European Steel Technology Platform ESTEP and the WSA's CO_2 Breakthrough Programs).[26,27] The carbon footprint mitigation can be summarized in three main pathways: recycling and replacement of carbonaceous materials, substantial modifications and upgrades of existing processes, introduction of carbon capture and storage (CCS) while maintaining current production processes.[28]

Following these paradigms, and with the aim of halving the CO_2 emission per ton of steel produced by 2050, the Ultra Low Carbon dioxide Steelmaking (ULCOS) consortium was

created in 2004, comprising 48 companies from 15 different European countries. The key focus of this project is the research and development of new CO_2 mitigation solutions and technologies. Starting from more than 80 possible technologies, four commercially and environmentally feasible technologies were selected, namely: a radically new gas recycle blast furnace (TGR-BF), a new direct reduction process (ULCORE), a new smelting reduction process (HIsarna) and iron ore electrolysis (ULCOWIN, ULCOLYSIS). In addition, hydrogen steelmaking technologies and biomass utilization practices have also been investigated.[29,30]

In the academic field, several studies have focused their attention on the use of renewable carbon sources such as biomasses (e.g., biochar, biohydrogen, and biomethane) as reducing or carburizing agents to replace currently used carbon fossil-based ones.[31] The first and foremost advantage of switching from fossil to renewable fuels is that the net increase in direct CO_2 emissions is avoided.[32] This possibility has been deeply investigated for the integrated and scrap recycling route. Especially in the former, which is the main consumer of fossil coals among the different steel production processes. A number of reviews regarding the use of alternative carbon sources have already been conducted and published for the integrated route.[31,33,34] In contrast, only recently Echterhof published a review on the use of alternative carbon sources in EAF steelmaking.[35] The use of biomasses in direct reduction processes is still new, although some studies have been carried out. The results obtained by Guo et al. showed that the use of iron ore-biomass composites could improve the reduction extent and reduction rate of DRI production processes at laboratory scale.[36] More recently, Yuan et al. investigated the possibility of DRI production by replacing fossil fuels with biomass as reducing agents in a rotary heart furnace (RHF).[37] Many of the presented studies have already obtained promising results in both laboratory and early industrial scale. However, it was also pointed out that there is still a lack of knowledge concerning the introduction of biomasses in steelmaking and ironmaking processes, such as the total reduction of CO_2 emissions achievable.[34,38] Furthermore, the higher production cost of biomass, compared to fossil fuels, can be considered as one of the biggest barriers in their industrial utilization.[33] Therefore, despite the possibility to lower emissions associated with the use of fossil carbon materials and the increasing potential for biomass availability in the coming decades, biomass has not been considered along with other drastic measures to mitigate CO_2 emissions in ironmaking and steelmaking.[39,40]

Quader et al. published a comprehensive review on energy-efficient CO_2-breaking technologies, focusing mainly on the use of high-temperature waste heat energy recovery technologies along with CCS.[41] The review highlighted how these scenarios would be an effective solution to current biomass application limitations.

Similar to the ULCOS consortium, other national research programs were established in the early 2000s. In Japan, the CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 2050 (COURSE50) focused its attention on reducing emissions from the integrated cycle, especially from the BF. The objectives of the project are the development of new chemical absorbers to decrease the specific energy demand of CO_2 capture of the BF gases ($\approx 30\,t_{CO_2}$/day), and the introduction of hydrogen-rich reducing gas coming from coke ovens into the BF to improve iron ore reduction.[42–44] In South Korea, POSCO established a national program for the application of CCS to BF gas in 2006 and began construction of the first pilot plant in 2008. The plant achieved promising results with a CO_2 capture efficiency of 90%, achieved by recovering and recycling ammonia used as absorbent. Subsequently, a second pilot plant for CO_2 capture in 2010 in Pohang. In recent years, POSCO has developed new waste heat recovery technologies from slag and reheating furnaces to improve the overall energy efficiency and reduce the environmental impact of steelmaking processes.[41,45]

In the USA, the USA. Department of Energy and the USA. Steel Association have initiated the development of new technologies to mitigate environmental impact, focusing on clean energy sources and carbon capture and separation technologies, through the joint action of several top universities in the metallurgical field.[45] Other national projects concerning the application of CCS to BFs are being developed in Germany (ROGESA) and Sweden (STEPWISE). To date, CCS facilities are mostly located in North America (11 of the current 26 commercial CCS facilities) and are applied to gas processing or enhanced oil recovery plants, with the remaining plants spread across the chemical, hydrogen, fertilizer, and energy sectors. In the steelmaking field, CCS plants are currently being applied to DRI plants in both Abu Dhabi and Mexico, thanks to the easy applicability of CCS to the direct reduction route.[27] Finally, Mastropasqua et al. have explored the use of Molten Carbonate Fuel Cells (MCFCs) as a CCS technology for the steel sector following the experience gained from research and applications of them in the energy and cement sector.[46–48]

In recent years, many efforts have been made for the application of hydrogen steelmaking, which is considered as one of the most promising solutions for reducing environmental impact and is expected to be feasible by 2040.[49] Especially in Europe, where the price of CO_2 has increased in recent years, which have favored low-emission technologies and processes, a high number of projects have been established.[30] As a result, pilot plants are planned or currently under construction in several countries across Europe. More specifically, a green hydrogen plant is planned to be built in Linz as part of the H2FUTURE project, a collaboration between Voestalpine, Siemens and Verbund, while in Sweden, SSAB, LKAB and Vattenfal, with the HYBRIT initiative have inaugurated the world's first fossil-free steel technology in 2020.[50,51] In Germany, ArcelorMittal has built a DRI hydrogen plant in Hamburg, the plant is expected to switch from hydrogen derived from natural gas to green hydrogen from offshore wind during its service in the next years, even if currently the second reduction shaft is feed by pure H_2 coming from the purification of the first reductor off-gases.[52] Also in Germany, Salzgitter AG, together with Tenova and Fraunhofer-Gesellschaft, initiated the SALCOS project in 2015, with the goal of demonstrating the feasibility of gradually converting the integrated route into a DR-EAF hydrogen hybrid route (green hydrogen supply is expected to be provided by the GrinHy subproject).[53,54] Finally, the only commercial hydrogen HBI production process plant (CIRCODED) was built outside Europe, in Trinidad and Tobago, specifically. However, the plant

has undergone continuous production shutdowns from its inception in 1999 until now, due to trends in the HBI market.[30,55]

Further to laboratory scale testing, and prior to the actual construction of pilot plants, the use of life cycle and environmental impact assessments has found a broad range of application in the steelmaking industry. This methodology has proven particularly useful when assessing the impact of different steelmaking pathways is required and national constraints and culture must be considered. Consequently, several national case studies have been published in recent years. Globally, WSA, Eurofer, and International Stainless Steel Forum have commissioned several Life Cycle Inventory (LCI) studies over the past several years. Different types of steel products (e.g., coils, plates, bars, and so on) and grades (e.g., carbon and stainless steel) have been analyzed through integrated, scrap recycling and direct reduction routes. Specifically, data collected from several steel production facilities in Europe and worldwide were used.[56]

Renzulli et al. carried out an environmental analysis of the largest integrated steelmaking facility in Italy following a cradle-to-gate approach.[57] Their investigation showed that the most impactful stages of the integrated route are the activities related to the BF + BOF and coking plant, that emit 0.91 t_{CO2_eq}/t_{STEEL} and 0.36 t_{CO2_eq}/t_{STEEL}, respectively. Similarly, Korol[58] performed the first life cycle assessment of steel production by integrated and scrap recycling routes in Poland. Based on average data from existing national steel mills, he investigated the greenhouse gas (GHG) emissions and electricity requirements of the two routes. In particular, he obtained a carbon footprint equal to 2.46 t_{CO2_eq}/t_{STEEL} and 0.91 t_{CO2_eq}/t_{STEEL} for the integrated and scrap recycling route, respectively. The higher value of CO_2 emissions from integrated cycle obtained by Korol than that obtained by Renzulli stems from the fact that the electricity is based on the combustion of coal and lignite in Poland.[58] The study conducted by Korol also highlighted that due to fuel consumption, raw materials, and waste generations, the sintering plant is responsible of a significant environmental impact. Therefore, the replacement of coke breeze with cleaner fuels (anthracite and charcoal) were investigated, too. The analysis showed that although introduction of charcoal would allow a reduction of the carbon footprint of about 10 kg_{CO2_eq}, the total energy demand would increase of 5.5% and most importantly an agricultural land occupation corresponding to 0.12% of Poland total area would be required.

More recently, a Swedish case study was proposed by Toktarova et al. in which the potential implementation of CO_2 mitigation measures over time toward zero-emission steelmaking of three different plausible future scenarios was investigated.[49] By assuming, as first case, the use of CCS technologies and fossil fuels replacement with biomasses in both the integrated steelmaking and scrap recycling route, a reduction of 80% of the current CO_2 emissions is expected by 2030, and an additional 3% reduction by 2045. Contrary, the use of hydrogen direct reduction steelmaking processes and the scrap recycling as main production route would allow an almost fossil free steel production by 2040. However, this latter possibility implies a dramatically increase of electricity demand of about 12 TWh by 2045.

Finally, Gielen et al. studied the feasibility of relocating emissions from East Asian steelmaking to Australia.[30] The key point of this new area of industrial ecology research is the possibility of exploiting the production of DRI/HBI in those countries where

green hydrogen is economically viable and the subsequent shipment of feedstock. In this way, the production of importing countries can be maintained, while their emissions reduced through delocalization. Through a combination of technology assessment, material flow, and microeconomic analysis they assumed that, if the right policies and funding are put in place, this economic and production model could be applied from 2025 onward, not only in Australia but also in other low-cost renewable energy countries.

Although the above works provide important insight into possible solutions and future scenarios for the steelmaking and ironmaking industry, there is a lack of knowledge regarding energy and water consumption and soil exploitation associated with these scenarios and the three main steelmaking routes in the Italian scenario.

Thus, this study aims at performing an evaluation of the emissions and consumptions of the whole ironmaking and steelmaking routes (from the iron ore to the final steel product) and the possible solutions for their reduction. The use of CCS, the use of green hydrogen and the use of biomethane have been analyzed as three possible future scenarios for the sustainable development of the steelmaking processes. These scenarios have been applied to the three main production routes and the results compared to the current state of the steelmaking industry to define the most promising scenario that can be followed in the future development and upgrading of the production plants.
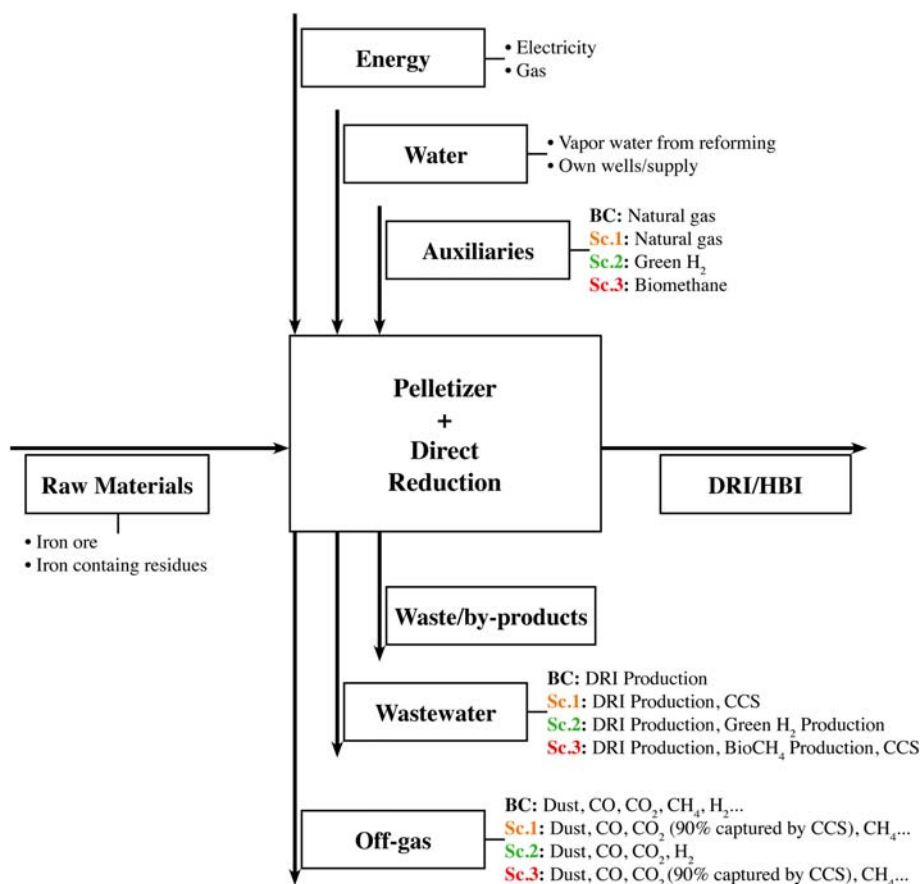
3. Experimental Section

In order to evaluate the current situation of the three main steelmaking routes and the contribution of the RF (labelled as base case), the data regarding the CO_2 emissions, water and electricity consumption and soil exploitation were estimated starting from the values reported in BREF documents for steel and European Union directives.[10,59]

Then, the analysis of three different scenarios for the reduction of the emission and consumption reduction have been carried out: 1) Scenario 1: capture 90% of intercepted CO_2; 2) Scenario 2: use of H_2 in steelmaking and combustion processes; 3) Scenario 3: use of biomethane in steelmaking and combustion processes.

Flowcharts highlighting the major parameters of the three scenarios (applied to the direct reduction, integrated, and scrap recycling routes) are shown from **Figure 3–5**. In particular, the CO_2 emission values regard the direct emissions produced by each specific production cycle. On the contrary, the indirect emissions depend on the production matrix of electricity that can vary as a function of the electricity sources. Provided the wide variability of this data, the electricity consumption has been estimated to take into account also the possible CO_2 indirect emissions. Hydrogen, natural gas, and biomethane have been considered as possible resources as the source of the reducing agent and as heat supplier.

3.1. Scenario 1: Use of Carbon Capture and Storage and Natural Gas Extracted from Traditional Wells (No-Fracking)

For each of the three main route and RF, the CO_2 capture points have been defined and reported in **Table 3**. In this case, the formerly

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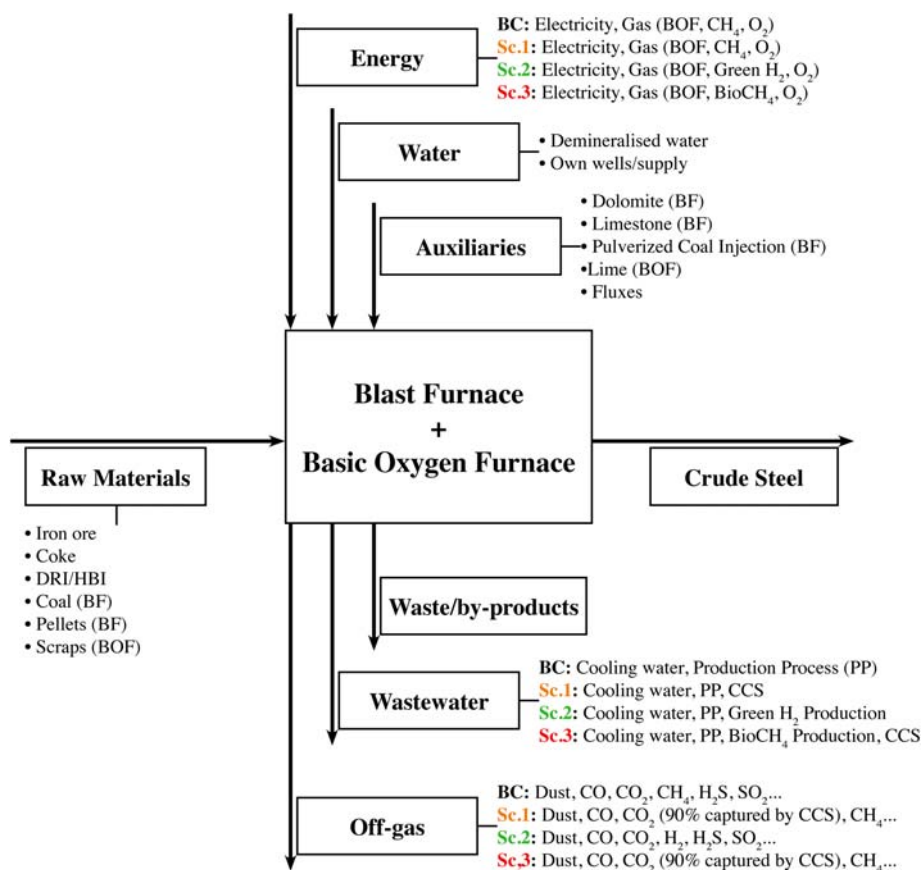**steel
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Figure 3. Direct reduction route flowchart of the major parameters (BC: base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).

defined emissions and consumption of natural resources have been taken into consideration and summed to the environmental exploitation associated, because the liquid absorbing CO_2 must be reheated to capture CO_2 again. This study assumes, as a basic case, that a natural gas boiler is used for the supply of the steam required for the regeneration of mono-ethanol amine (MEA) which are commonly used as capturing chemical species.[41]

The inventory feedstock is reported in **Table 4**. More precisely, the equivalent energy requirement (expressed in t_{CO2_eq}/ $t_{CO2\_captured}$) is mainly associated to the recovery of the solvents used for the CO_2 capture, under the hypothesis of a boiler powered by natural gas and includes also the transport and storage contributes. The amount of CO_2 produced by the capturing facilities could be decreased if the steam for the regeneration of MEA is recovered from the fumes of the furnace or from the slag.[41,60,61] The amount of natural gas consumed to produce steam by the boiler, and the related CO_2 emissions, could be decreased by exploiting the waste heat recovery of hot slag, which provides an enthalpic contribute of 61 kWh/t_{STEEL} at a temperature of 1250 °C. Another possibility would be the interception of the furnace exhaust gases, which are featured by an enthalpy content of 125 kWh/t_{STEEL} at 1500 °C or 12.5 kWh/t_{STEEL} at 150 °C. However, waste heat recovery technologies applicable to the steelmaking field, especially for the heat recovery from slag,

are still not well consolidated.[41] Concerning water consumption, a wastage of 5% of the freshwater withdrawn is assumed (0.22 m³$_{H2O}$/$t_{CO2\_captured}$), the contribution of the wastewater during the extraction in traditional well (no-fracking to produce shale oil) has been taken into account and stated at a maximum amount of 1.2×10^{-4} m³$_{H2O}$/m³$_{CH4}$.[41] The electricity consumption values in Table 4 are indicative of both the capture and compression steps. It is assumed that the former requires an amount of 40 kWh/$t_{CO2\_captured}$, whereas the electricity consumption of the CO_2 compression step depends on the pressure.[61] More precisely, in case of CO_2 transport via railway, compression up to 15 bar is required (91 kWh/$t_{CO2\_captured}$), further 69 kWh/$t_{CO2\_captured}$ must be included in the calculation for the liquefaction of CO_2 required for transport. A compression up to 40 bar allows for the gas transport through pipeline to a low-pressure deposit with an electricity consumption of 97 kWh/$t_{CO2\_captured}$. On the contrary, if a high-pressure deposit is used a compression up to 150 bar is required, which corresponds to 125 kWh/$t_{CO2\_captured}$. In this scenario, it is necessary to take into account also the 97 kWh/$t_{CO2\_captured}$ of the gas transport through the pipeline. For the case of PP + DR, only the CO_2 emitted from the DR has been considered as capturable (point of emission n.2 in Figure 1), on the contrary the fraction emitted from PP has not been considered captured.

Figure 4. Integrated cycle flowchart of the major parameters (BC: base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).

The exploitation amount has been computed through the sum of the consumptions associated to the ironmaking and steelmaking plants and the consumptions due to CCS facilities and natural gas extraction. The value of the exploited resources is the sum of the one consumed for the production process and for the capturing facilities. The CO_2 indicated in the case of CCS for the steelmaking represents the emission from plant after the capturing process.

3.2. Scenario 2: Use of Green Hydrogen in Substitution of Natural Gas

In the case of production of hydrogen from renewable energies, the inventory feedstock (Table 4) assumes that for the reduction of 1.4 t of Fe_2O_3, 627 Nm^3 of H_2 are needed. For each Nm^3_{H2} of green hydrogen, produced by freshwater splitting supplied by renewable energy sources, a waste of at least 4.5% of the corresponding withdrawal of freshwater (0.81 kg_{H2O}/Nm^3_{H2}) is assumed.[62]

For the evaluation of the specific soil consumption, it is necessary to take into account the value associated to the renewable energy source. In Italy, the share of renewable energy produced by wind turbines is lower than the one produced by photovoltaic power stations.[63,64] Fur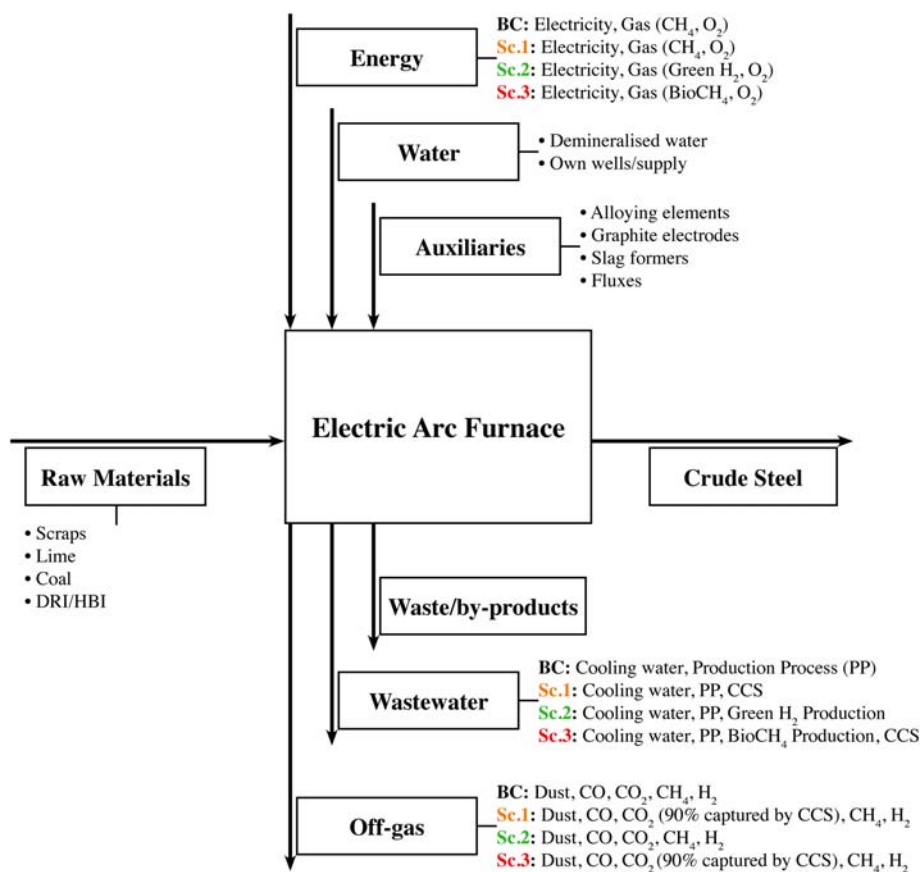thermore, the wind source is too irregular and weak to ensure a suitable power supply, thus the soil exploitation is associated to the coverage by photovoltaic panels. A photovoltaic panel with peak power of 300 W involves an area of 1.6 m^2, in Italy the yearly sum of solar electricity generated by a photovoltaic system with peak power of 1 kW, optimally inclined modules and a performance ratio of 0.75 is equal to 1300 kWh.[65] A theoretical peak power of 1 kW involves 5.33 m^2 and so 1 kWh of produced energy implies 0.0041 m^2 kWh^{-1}. By assuming an electricity consumption of 4.64 kWh/Nm^3_{H2} it is possible to obtain the specific soil consumption for 1 Nm^3 of H_2.

In this case, the production of CaO has been considered as performed by the heat developed by H_2 combustion as well as the heat needed for the production of pellets.

The estimation has been built through the substitution of the natural gas with H_2. In case of pellets production for DRI, although hydrogen could be used to substitute natural gas for heating, it is not possible to renounce to anthracite (or to coke breeze), thus 5–10 kg_{C_SOURCE}/t_{DRI} has to be mixed with the iron ore.

3.3. Scenario 3: Use of Biomethane

In the case of biomethane exploitation, the first hypothesis is that raw biogas is formed for 50% by CH_4 and the other fraction is

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Figure 5. Scrap recycling route flowchart of the major parameters (BC: base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).

mainly formed by CO_2. The inventory feedstock for a biogas plant taking into consideration a plant providing $500\ Nm^3\ h^{-1}$ of raw biogas is reported in Table 4.[59,66]

The amount of net CO_2 emission is estimated according to attachment V of European Union Directive (2018/2001) under the hypothesis of treatment upgrading and compression of biogas from biowastes and wet manure.[59] The soil consumption has to be computed only in the case that the land is left out from food production, however in this scenario, the production of biogas upgraded to biomethane is based on the organic material coming from agricultural wastes, from sewage deriving from cattle, pig and poultry farming and so there is not any net consumption of soil.[59]

This scenario is more complex than the other and so a brief indication of the estimated parameters is here provided. Starting from the Greenhouse Gas Emission (EF) of several sources the Gross Process Emissions (GPE) and Net Emissions without considering the CCS contribution (NEW) can be calculated as

$$GPE = EF_{BioCH4,production} + EF_{Process}$$
$$+ EF_{mining(coal+CaO)} + EF_{CaCO_3} \tag{2}$$

$$NEW = GPE - EF_{BioCH4,production} \tag{3}$$

on the contrary, when CCS is available the considered capture rate is 0.9 (this case also considers the capture of CO_2 produced in the digester and from raw biogas production). In this case, the GPE and the NEW are labelled as GPE_{CCS} and NEC, and calculated as follows

$$GPE_{CCS} = EF_{BioCH4,production} + (1 - CaptureRate)EF_{Process}$$
$$+ EF_{mining(coal+Cao)} \tag{4}$$

$$CaptureEmissions = 0.134 \times CaptureRate \times EF_{Process} \tag{5}$$

$$NEC = GPE_{CCS} + CaptureCO_2 Emissions - EF_{BioCH4,production} \tag{6}$$

The impact of extraction and production of coal, lime, and natural gas has been considered during the computation of the three scenarios, the environmental impacts are shown in **Table 5**.[67–69]

In terms of reducing capacity $627\ Nm^3$ of H_2 corresponds to $270\ Nm^3$ of CH_4 (in this case, this value is considered and not $285\ Nm^3$ because the absence of iron carburation is taken into account in order to compare the hydrogen effect that does not imply any iron carburation). On the basis of the available data and the pipeline transport has been compared because it is the most usual delivering modalities in Italy for in-land transport

Table 3. Capture points for CO_2. The emission point refers to Figure 1.

Plant	#	Emission point	Capture point
Direct reduction			
Pelletizer	(1)	From the pelletizer to the chimney	The exhaust gases can be captured after the filter and before the chimney
Direct reducer	(2)	From the shaft furnace to the chimney	The exhaust gases can be captured after the filtration and before the chimney
integrated cycle			
Sintering plant	(3)	From the sintering plant to the chimney	After the filter and before the chimney the exhaust gases can be captured
Pelletizer	(4)	From the pelletizer to the chimney	After the filter and before the chimney the exhaust gases can be captured
Coke ovens	(5)	From the ovens to the electrical power unit	The gas is delivered to the power generation unit of the plant and after its burning to power the turbines it can be captured before the chimney of the power units. In some cases (especially when S concentration is high) the coke oven gases are sent also to sintering plant, pelletizer, reheating furnaces, so it can be captured before the chimney of such plants.
BF	(6)	From the BF to the electrical power unit	The gas is delivered to the power generation unit of the plant and after its burning to power the turbines it can be captured before the chimney of the power units
BOF	(7)	From the BOF to the electrical power unit	The gas is delivered to the power generation unit of the plant and after its burning to power the turbines it can be captured before the chimney of the power units
Scrap Recycling			
EAF	(9)	From the EAF to the chimney	The gas can be captured after the filter and before the chimney
Reheating Furnace of Semis			
Reheating furnace	(10)	From the reheating furnace to the chimney	The exhaust gases can be captured after the heat recovery facilities (if present) and before the chimney

Table 4. Inventory feedstock of the three different scenarios.

CO_2 emissions	H_2O consumption	Electricity consumption	Soil consumption	CH_4 emissions
Scenario 1: Use of carbon capture and storage and natural gas				
0.134 $t_{CO2\_eq}/t_{CO2\_captured}$	0.23 $m^3_{H2O}/t_{CO2\_captured}$	200[a] 137[b] 222[c] kWh/$t_{CO2\_captured}$	40 $m^2/kt_{CO2\_captured}$/day	69.5 $Nm^3_{CH4}/t_{CO2\_captured}$
Scenario 2: Use of green hydrogen				
–	0.036 kg_{H2O}/Nm^3_{H2}	4.64 kWh/Nm^3_{H2}	0.019 m^2/Nm^3_{H2}	–
Scenario 3: Use of biomethane				
8×10^{-4} kg_{CO2}/Nm^3_{CH4}	0.1 kg/Nm^3_{CH4}	0.1 kWh/Nm^3_{CH4}	0.5-1.82 m^2/Nm^3_{CH4}	–

[a]CO_2 compression up to: 15 bar, [b]40 bar, [c]120 bar.

of large gas amount. The evaluation of hydrogen transport has been performed for a reference distance of 55 km at 88 MPa, on the contrary for natural gas the reference distance is 500 km at 4–7 MPa.[70] Also, the energy spent for specific developed energy can be estimated (**Table 6**).

4. Results and Discussion

The numerical values of the emissions and consumption of the three previously defined scenarios, divided by production route, are reported in Appendix A from Table A1–A3. For an easier

Table 5. Impact of extraction and production of coal, lime and natural gas.

	CO_2 emissions [$kg_{CO2}/t_{product}$]	H_2O consumption [$m^3/t_{product}$]	Electricity consumption [$kWh/t_{product}$]	Feedstock/product [t/t]
Coal extraction	56.2	1.2	0.1	1.29
Calcination by CH_4	186.5	–	–	1.78
Calcination by H_2	0.78	–	1397	1.78
Natural gas extraction[a]	0.135	0.0003	0.19	–

[a]For natural gas extraction, the values are expressed per Nm^3 of CH_4 produced.

Table 6. Specific energy consumed for transport of CH_4 and H_2 used as reducing agent to produce 1 t of steel and to produce Wh of heat developed by combustion.

| Pipelines	H_2	CH_4
$kWh/(t_{STEEL} \times km)$	3	0.013
$kWh/(kWh_{developed} \times km)$	1.5×10^{-3}	5×10^{-6}

visualization and qualitative comparison of data, they are reported in a graphical form (**Figure 6–9**) highlighting both the contribution of the production process and the contribution of the CCS or H_2 production process, depending on the scenario considered. Again for simplicity, the average of the values of the different subcases of the integrated cycle is used.

The comparison of the CO_2 emission values of the base cases of the main route shows a general reduction for all three cases analyzed (Figure 6). Among the three production routes, the BF + BOF one is the one most positively affected using CCS with a reduction of about 70% (Scenario 1). This reduction is in good agreement with the reduction value foreseen by Toktarova et al. for the Sweden steelmaking industry.[49] Similarly, the PP + DR is characterized by a reduction of about 65% thanks to the capture of the CO_2 emissions coming from the sintering plant, which is responsible of the highest CO_2 emissions in this route. On the contrary, only a slight decrease of CO_2 emissions is observed for the EAF route. This is since the scrap recycling route already provides the greenest option among the steel production technologies; therefore, it is difficult to further reduce the amount of CO_2 emitted and such reduction will be less appreciable.

The introduction of green hydrogen in substitution of natural gas (Scenario 2) appears highly appealing for the PP + DR route, thanks to the total elimination of emissions, on the other hand, the overall reduction of the BF + BOF and EAF is only of about 15% and 30%, respectively. This difference in savings percentage is strongly related to the different amount of methane used in the three steel production routes. In fact, since the PP + DR route is inherently based on the use of natural gas as the iron ore reduction agent, it is the one that benefits most from the introduction of hydrogen, thus bringing its emissions to zero. On the other hand, the DRI produced in such a scenario would be characterized by a lower amount of carbon. Consequently, the environmental and energetical benefits associated with the use of high-carbon DRI in the EAF as a charging material would not be exploited.[71] Conversely, the substitution of natural gas in integrated and scrap recycling pathways is less effective due to the presence of other emission sources during the steel production cycle.
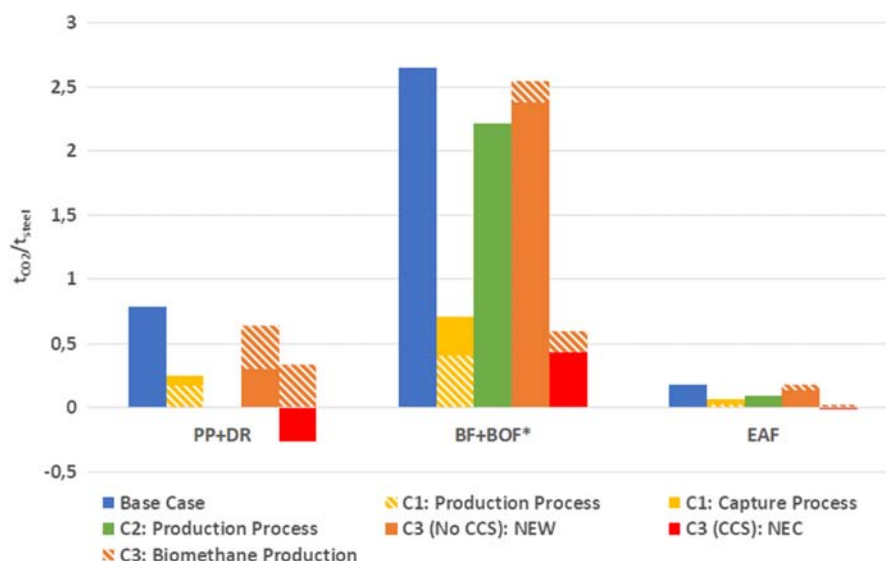
Figure 6. Comparison of the specific CO_2 emissions per ton of produced steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF and BOF scenarios reported in Appendix A, wine-colored box represents the final CO_2 emissions of PP + DR in Sc.3).
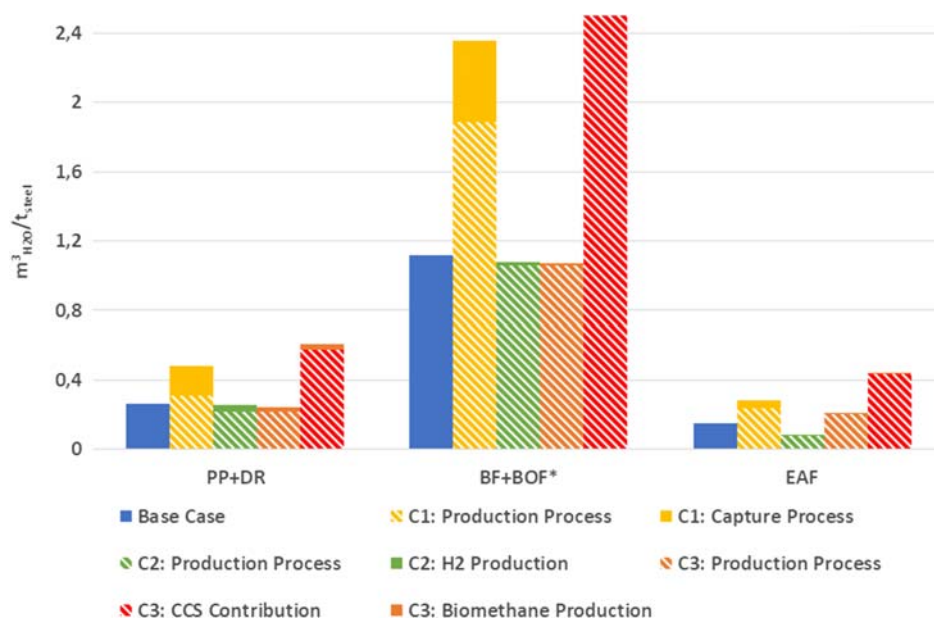
Figure 7. Comparison of the specific wastewater per ton of produced steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF and BOF scenarios reported in Appendix Appendix A).
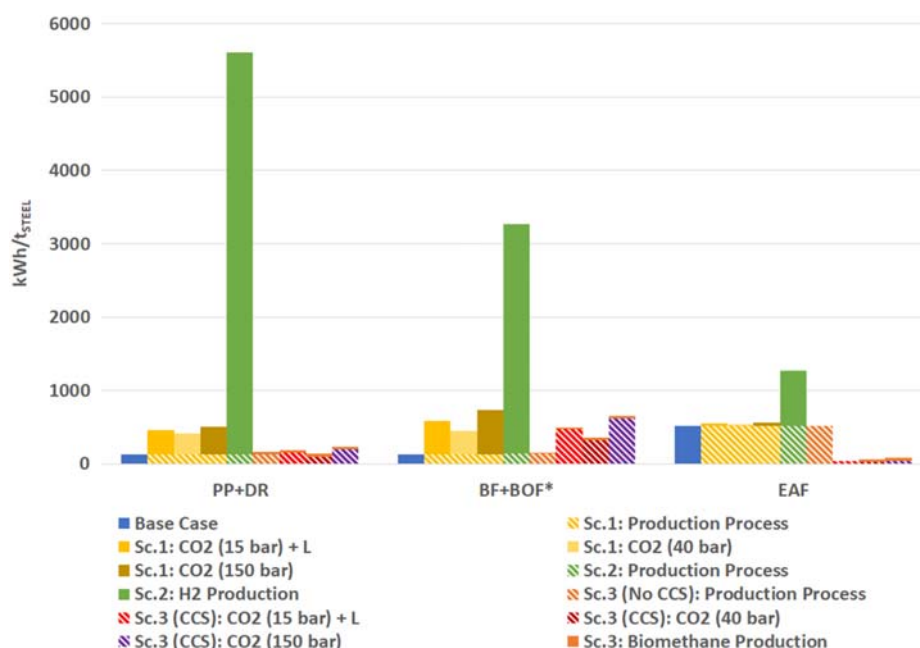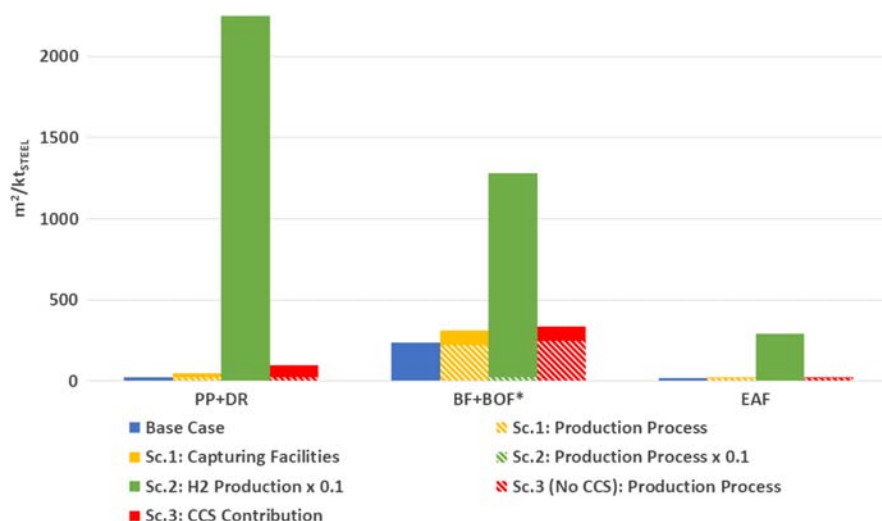

Figure 8. Comparison of the specific electric consumption per ton of produced steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF + BOF scenarios reported in Appendix Appendix A).

The introduction of biomethane in combination with CCS (Scenario 3) allows to obtain a net negative CO_2 emission value (NEC) in the direct reduction route. Specifically, the negative value is associated to the capture of CO_2 from biogenic sources that are characterized by a neutral carbon footprint.[72] Moreover, contrary to what observed in Scenario 2, the use of biomethane and CCS is also beneficial for the BF + BOF and EAF routes,

mainly due to the presence of CCS that allows to obtain specific CO_2 emission values even lower than the ones observed for Scenario 1. This is confirmed by the fact that, if no CCS is utilized in Scenario 3, the overall amount of CO_2 emissions is slightly lower than the base case ones.

Overall, to date none of the steelmaking processes can achieve zero or negative CO_2 emissions from a system-wide perspective

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Figure 9. Comparison of the specific soil consumption per kton of produced steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF and BOF scenarios reported in Appendix A).

due to the difficulty of producing carbon neutral material and energy. This is primarily related to emissions produced off-site (e.g., soil exploitation, biomass harvesting), transportation of the material, and emissions related to currently used technologies (e.g., CCS).[73,74]

Regarding the total amount of wastewater (Figure 7), slight savings are observed in both Scenario 2 and Scenario 3 (without CCS). More precisely, only the EAF route is characterized by a significant reduction of specific wastewater of about 50% when the use of green hydrogen (Scenario 2) is considered. This reduction is mainly related to the low amount of specific water consumption for the hydrogen production, considered in the inventory feedstock, together with the low amount of hydrogen required by the EAF route. On the contrary, an increase in the total amount of wastewater is observed for Scenario 1 and Scenario 3 (with CCS). It appears that the use of CCS is the main responsible of this increase, especially in Scenario 3, in which the water consumption associated to the biomethane production provides a significant lower amount of water. Indeed, if the wastewater associated to the CCS contribution in Scenario 3 is compared to the base case of each production route, an increase of about 70%, 60%, and 100% is observed for the PP + DR, BF + BOF, and EAF route, respectively. Considering Italy's annual steel production in 2020 and the highest consumption scenario (Scenario 3 with CCS), this would result in a total of 20.5 Mm^3 of freshwater consumption per year, which would correspond to 0.25% of Italy's total industrial water use. Consequently, water consumption can be considered as a non-limiting factor.[75]

As with wastewater consumption, electricity consumption (Figure 8) is also characterized by an overall increase in each scenario, with the only exception being the values observed for the scrap recycling route when Scenario 3 is applied, where a slight electricity consumption reduction is observed. Among the three scenarios, Scenario 2 appears to be the most unfavorable due to the high electrical demand required for H_2 production. This increase is related to the energy required by the electrolysis of

water, needed for the green hydrogen production, which must be multiplied for the specific amount of hydrogen required by each production process to produce steel. Indeed, the PP + DR, being based on the reduction of the iron ore trough gas circulation, is the most energy requiring process with a dramatical increase of about 50 times in comparison with the base case. Similarly, also the BF + BOF route is characterized by an increase of about 25 times if compared to the current electrical energy demand. Finally, the scrap recycling route is characterized by an increase of 100% thanks to the lower amount of gases required by the EAF melting process.

In order to evaluate the incidence of energy consumption related to the production of hydrogen, these must be compared with the current production of renewable energy in Italy. In 2020, the amount of renewable electricity produced was about 108 TWh of which only 25 TWh produced by photovoltaic, the remainder was produced by hydroelectric, wind, and geothermal, in order of quantity.[76] For the current steel production in Italy, the amount of energy for the production of hydrogen required would be equal to 18.8 TWh: corresponding to 17.4% of the total production of renewable energy and 75.2% of the photovoltaic share.

In accordance with the Hydrogen Strategy of the European Commission, Italy has recently defined a National Plan for Recovery and Resilience (PNRR), in which 3.2 billion euros are allocated for the development and diffusion of green hydrogen technologies.[77] Consequently, according to EU targets, the amount of renewable energy must be increased to over 200 TWh/y by 2030, 10% of which would be required by the Italian steelmaking and ironmaking sector alone, assuming a constant steel production in the coming decade. However, there are some doubts about the feasibility of hydrogen production in Italy, as highlighted by Armaroli and Barbieri in the last decade 20 GW of photovoltaics have been installed in Italy.[75] To reach the targets, set by the Italian government and the EU, a further 75 GW are required before 2030 (excluding the GW required by the capacity of electrolyzers and storage capacities). Considering

that 40 GW is the target for the whole EU by 2030, this increase will require a strong political commitment and will generate a more than challenging scenario.[75]

It is interesting to evaluate the equivalent CO_2 emissions in the case that the electricity demand of the hydrogen production is provided by a conventional thermoelectrical plant. In Italy, according to the National System for Environmental Protection (ISPRA) the gross CO_2 emissions per kWh is equal to 0.444 kg_{CO2_eq} in 2018. This value is lowered to 0.296 kg_{CO2_eq} by excluding electricity production from pumped storage units using water that has previously been pumped uphill.[78] Therefore, assuming the latter value the indirect CO_2 emissions would be about 1.5, 0.8, and 0.12 t_{CO2_eq}/t_{STEEL}, for the direct reduction, integrated, and scrap recycling route, respectively. However, this solution appears as nonapplicable due to the fact that the specific CO_2 emissions of each production route would become bigger than the respective base case, thus nullifying the environmental impact reduction of Scenario 2.

Similar considerations can be applied to the soil consumption. No significant increases are observed except for Scenario 2 where specific soil consumption dramatically increases by two orders of magnitude for the integrated route and three orders of magnitude for both the direct reduction and scrap recycling routes. This high increase is strongly related to the energy demand of the H_2 production, which, due to its high value, requires massive use of solar panels and consequently of land for their installation.

Taking into account the latest data on Italian steel production and the soil consumption required for the green hydrogen production, an area equal to 483 km^2 (nearly one third of Milan province territory) would be necessary for the direct reduction route alone.[9] According to the Italian National Institute of Statistic (ISTAT), in Italy, the current not occupied agricultural area is equal to 4.2 million ha.[79] Therefore, assuming the best arrangement possible of solar panels, 1.15% of the currently available area would be occupied exclusively to produce electricity required for the water electrolysis, which similar to the water

consumption for Scenario 3 with CCS can be considered as a nonlimiting factor.

Given that the estimates for the reheating furnace are different in order of magnitude from those calculated for the other plants considered, they have been represented by additional graphs (**Figure 10–13**). The comparison of the emissions and consumption of the three different scenarios, applied to the reheating furnace, is in complete agreement with the one carried out at the direct reduction, integrated, and scrap recycling route, with no significative difference.

Figure 14 and **15** show the specific emissions and production costs per ton of steel produced in the scenarios studied, evaluated in 2021 and 2050, respectively. Specifically, under the assumption of a constant economical investment by the mills over the years and due to the strong influence of different market drivers on raw materials and commodities costs, the analysis did not consider Capital and Operating Expense (CAPEX and OPEX).[49] In contrast, the change in carbon tax, CCS and production costs have been estimated for the Italian context (values reported in Table A4). Finally, given the variability of these values before 2050, the values obtained should be considered as indicative and used for a general assessment of the change in costs of the scenarios in the coming decades.

Given the current low value of the carbon tax applied by the Italian government, none of the three scenarios appears attractive at the moment, mainly due to the additional cost associated with CCS and the production of green hydrogen and biomethane.[80] On the contrary, the increase of the carbon tax to more than 300 USD/t_{CO2}, foreseen for 2050, leads to economic savings compared to the base case.[30]

The use of CCS (Scenario 1) appears to be a viable solution in the first period due to values comparable to the base case. Moreover, due to the low CO_2 emissions associated with Scenario 1 and the future decrease in CCS costs, the increase in the carbon tax does not provide any significant drawback in their future use. In fact, among the three scenarios, it generally appears to be the one capable of providing most of the economic
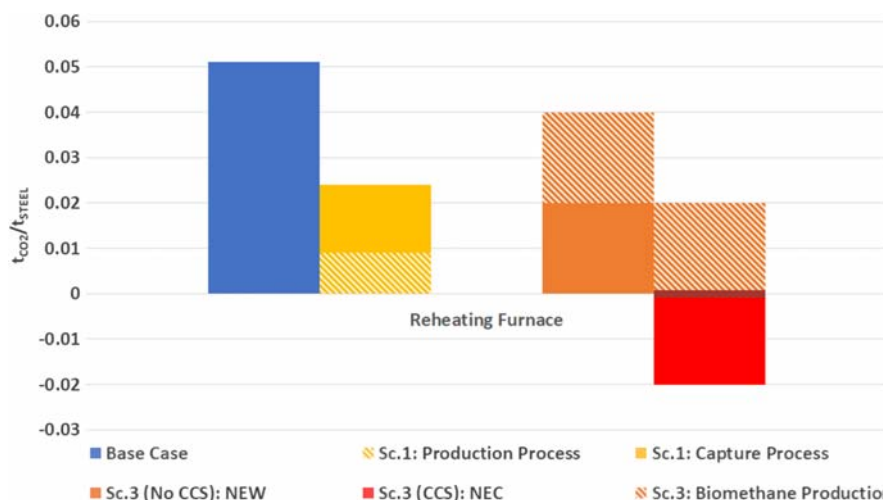
Figure 10. Comparison of the specific CO_2 emissions per ton of heated steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane, wine-colored line represents the final CO_2 emissions of PP + DR in Sc.3).
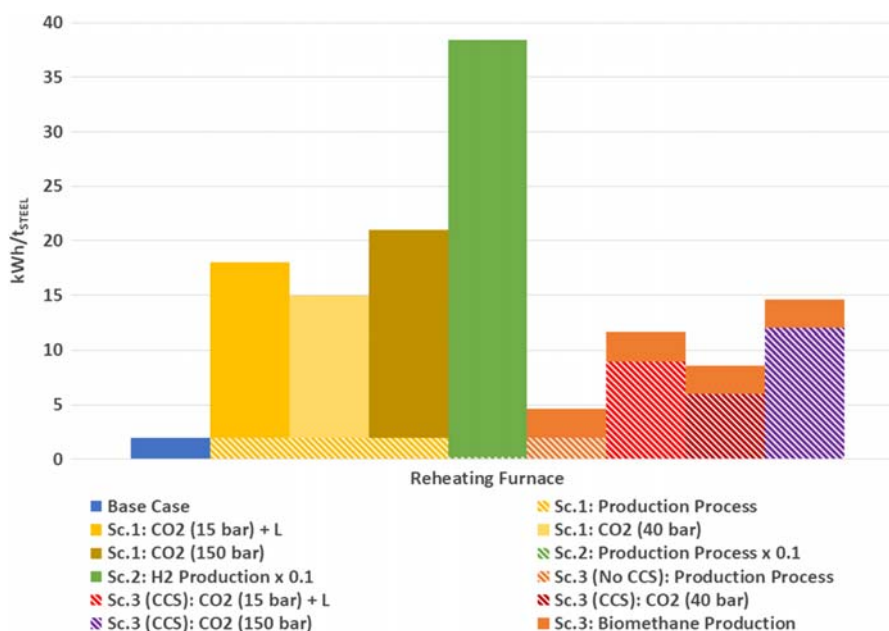
Figure 11. Comparison of the specific electric consumption per ton of heated steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).
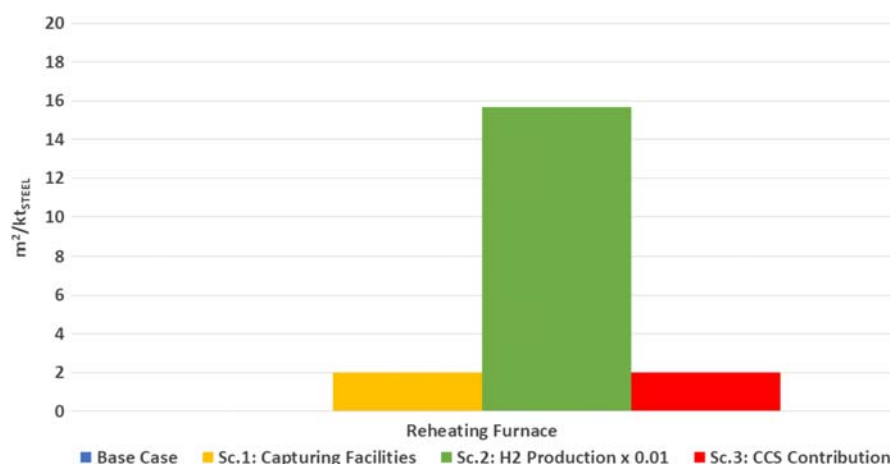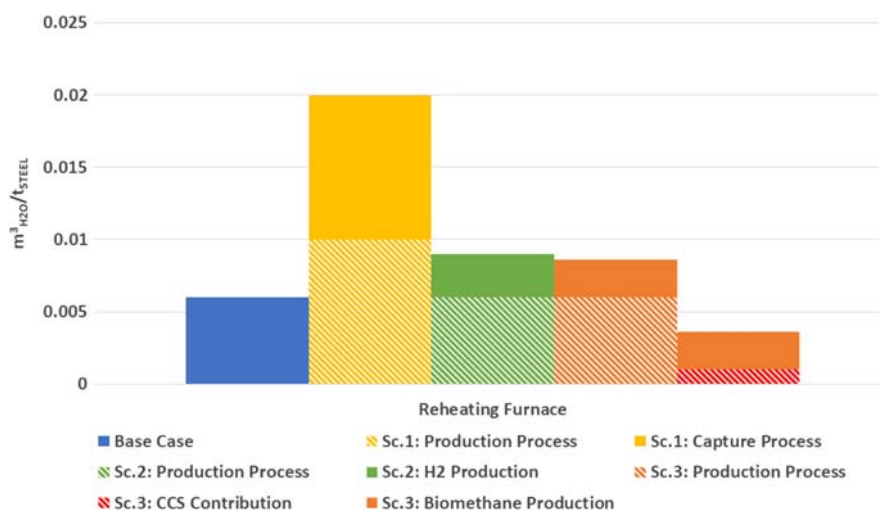

Figure 12. Comparison of the specific soil consumption per kton of heated steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).

savings in 2050, assuming the current steelmaking technologies present in Italy.

The use of green hydrogen is highly prohibitive due to its high production cost, which can be considered a limiting factor for the applicability of Scenario 2 in Italy in the coming years. On the contrary, the significant lowering of the production cost foreseen for 2050, makes this scenario the most convenient for the direct reduction route. This is not true for the feasibility of green hydrogen in the integrated cycle, where no significant savings are observed mainly due to emissions from the production process through BF. On the other hand, this value could be decreased by upgrading the current Italian integrated steel mills with new technologies capable of providing lower emissions in steel production.[49]

Finally, focusing solely on the use of biomethane plus CCS for Scenario 3, this is expected to provide significant savings in 2050 at the expense of an initial increase in the cost of production, similar to what was observed for Scenario 2. More specifically, it appears to be the best possible scenario for both the integrated and scrap recycling routes.

However, considering an average steel mill with an annual production of 450 kt_{STEEL}, the amount of methane required from raw steel production, the reheating furnace, and final heat treatments would be $\approx$30–35 Mm^3/y. Currently, biomethane production facilities capable of supplying this amount are not available in Italy. In addition, this plant would require a significant amount of biomass, which would have to be imported into Italy with a consequent increase in

Figure 13. Comparison of the specific wastewater per ton of steel of heated steel (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane).
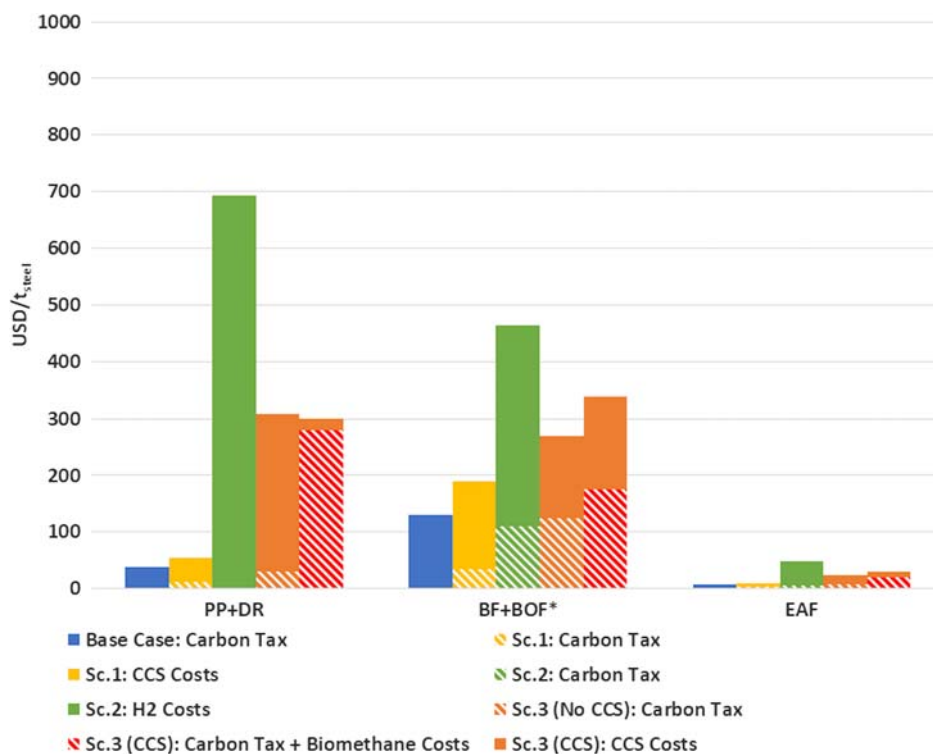
Figure 14. Comparison of the specific emission and production costs per ton of produced steel in 2021 (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF and BOF scenarios reported in Appendix A).
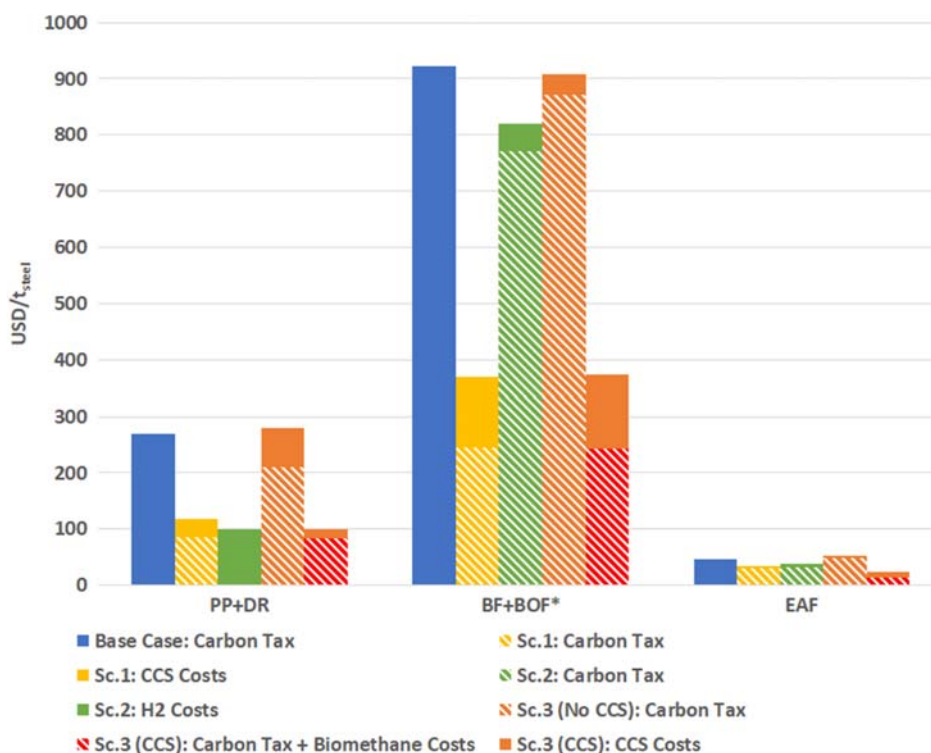
environmental impact due to their transportation and an almost unsustainable production cost without government incentives, which are currently under consideration by the PNRR.[77]

Nevertheless, it should be noted that, ENI S.p.A (an Italian oil and gas company, considered one of the seven "supermajor" oil companies in the world) has recently declared its willingness to increase biomethane production aiming to supply more than 50 Mm^3_{BioCH4} per year and becoming the leading biomethane producer in Italy.[81]

5. Conclusions

The need to reduce environmental impact has now become a crucial objective for the steelmaking and ironmaking industry,

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Figure 15. Comparison of the specific emission and production costs per ton of produced steel in 2050 (base case, Sc.1: use of carbon capture and storage, Sc.2: use of green hydrogen, Sc.3: use of biomethane. BF + BOF*: average of the different BF and BOF scenarios reported in Appendix A).

further promoted by the steady increase in global demand for steel observed in recent decades. In order to achieve this ambitious goal, the development and proposal of new technologies and practices applicable to the three traditional steel production routes (integrated cycle, scrap recycling cycle and direct iron ore reduction) has been strongly encouraged.

CO_2 emission, water and electricity consumption, and soil exploitation, associated with the application and introduction in steel production processes, of CCS, use of green hydrogen and use of biomethane were evaluated and compared with the current environmental impact of the Italian steelmaking industry. In addition, the economic feasibility of future scenarios was evaluated in both 2021 and 2050. The results of this study provided further insight into the most promising scenario for achieving a more sustainable steel production process in Italy.

Based on the estimate, the use of biomethane is the most favorable scenario, but this scenario is penalized by finding amount of biomethane large enough to support the needs of an ironmaking and steelmaking cycle. On the other hand, the recent interest in biomethane production in Italy could fortify the feasibility of this scenario in the coming years and further strengthen the relationship between the world of agriculture and the world of energy with a view to long-term sustainability.

Production and use of hydrogen are interesting in terms of CO_2 elimination and by the low cost of transport if compared to biomethane and natural gas, although the transport of hydrogen is recommended only as solution up 20% in the natural gas

stream as a consequence of the reactivity of the gas. However, a significant penalization in the use of green hydrogen is the increase of water consumption but above all the dramatic electric energy consumption and soil exploitation. Moreover, the increase in renewable energy production for the exclusive production of green hydrogen foreseen in the current decade appears as a serious challenge in the Italian context, taking into account that this production should be produced ex novo in Italy. Therefore, in order to overcome this drawback, the increase in the import of hydrogen from steel could be considered as a possible solution, at the cost of higher costs and a consequent increase in indirect emissions related to the transport of the material.

Finally, the use of natural gas and CCS has provided appealing results, especially if combined with biomethane. Such a scenario is particularly favorable in a steelmaking route involving the charging of DRI in the EAF, especially if it is previously preheated. In that situation, depending on the specific characteristics of the furnace and DRI composition it would be possible to achieve an additional energy saving of 20–40 kWh/t_{STEEL} per each 100 °C of DRI preheating.[71] Furthermore, taking into account the increase in the cost of CO_2 emissions and the decrease in costs related to CCS expected in the coming years,[82,83] the retrofitting of production systems currently in use appears to be the most plausible solution for the environmental impact reduction of the steelmaking and ironmaking industry.

Appendix A

Table A1. Specific emissions and consumption in case of use of CCS (scenario 1).

	BF + BOF 310 kg$_{coke}$/t$_{STEEL}$ + 200 kg$_{PCI}$/t$_{STEEL}$	BF + BOF 370 kg$_{coke}$/t$_{STEEL}$ + 200 Nm^3$_{NG}$/t$_{STEEL}$	BF + BOF 350 kg$_{coke}$/t$_{STEEL}$ + 100 kg$_{PCI}$/t$_{STEEL}$ + 20% DRI	BF + BOF 350 kg$_{coke}$/t$_{STEEL}$ + 165Nm^3$_{NG}$/t$_{STEEL}$ + 20% DRI	PP + DR	EAF	RF
Specific CO$_2$ emissions [t$_{CO2}$/t$_{STEEL}$]							
Capture process	0.32	0.3	0.29	0.29	0.082	0.039	0.006
Production process	0.4	0.41	0.38	0.39	0.16	0.016	0.009
Overall	0.72	0.71	0.67	0.68	0.24	0.055	0.015
Base case	2.79	2.67	2.56	2.52	0.77	0.135	0.051
Specific wasted freshwater [m^3$_{H2O}$/t$_{STEEL}$]							
Capture process	0.55	0.3	0.5	0.49	0.16	0.03	0.01
Production process	2.1	1.8	1.9	1.7	0.3	0.23	0.01
Overall	2.65	2.1	2.4	2.19	0.46	0.26	0.02
Base case	1.3	1.1	1.2	1.1	0.21	0.2	0.006
Specific electricity consumption [kWh/t$_{STEEL}$]							
Production process	136*	175*	92.7*	92.7*	123.5	514	2
CCS CO$_2$ up to 15 bar & liquefaction	478	453	437	427	322	20	16
CCS CO$_2$ up to 40 bar	327	310	299	292	281	12	13
CCS CO$_2$ up to 150 bar	626	593	573	559	363	27	19
Base case	136[a]	175*	92.7*	92.7*	123.5	514	2
Specific Soil Consumption [m^2/kt$_{STEEL/day}$]							
Capturing facilities	96	91	87	85	26	5	2
Production process	247	247	203	202	25	20	–
Base case	247	247	203	202	25	20	–

[a] Electricity produced in the integrated cycle compensate the consumed amount.

Table A2. Specific emissions and consumption in case of use of green H$_2$ (produced by photovoltaic power generation) in substitution of natural gas (scenario 2).

	BF + BOF 370 kg$_{coke}$/t$_{STEEL}$ + 633 Nm^3$_{H2}$/t$_{STEEL}$	BF + BOF 350 kg$_{coke}$/t$_{STEEL}$ + 495 Nm^3$_{H2}$/t$_{STEEL}$ + 20% DRI	PP + DR	EAF	RF
Specific CO$_2$ emissions [t$_{CO2}$/t$_{STEEL}$]					
Production process	2.25	2.18	–	0.092	–
Base case	2.65	2.5	0.68	0.135	0.05
Specific wasted freshwater [m^3$_{H2O}$/t$_{STEEL}$]					
H$_2$ production process	0.022	0.018	0.039	0.003	0.003
Production process	1.1	1	0.21	0.07	0.006
Base case	1.1	1	0.3	0.2	0.006
Specific electricity consumption [kWh/t$_{STEEL}$]					
H$_2$ production process	3008	2493	5100	379	382
Production process	135.8[a]	133*	123.5	510	2
Base case	135.8[a]	133*	123.5	510	2
Specific soil consumption [m^2/kt$_{STEEL/day}$]					
H$_2$ production process	12 055	9946	20 913	1326	1567
Production process	247	247	25	20	–
Base case	247	247	25	20	–

[a] Electricity produced in the integrated cycle compensate the consumed amount.

Table A3. Specific emissions and consumption in case of use of biomethane (scenario 3).

	BF + BOF 370 kg_{coke}/t_{STEEL} + 200 Nm^3_{BioCH4}/t_{STEEL}	BF + BOF 350 kg_{coke}/t_{STEEL} + 165 Nm^3_{BioCH4}/t_{STEEL} + 20% DRI	PP + DR	EAF	RF
Specific CO_2 emissions [t_{CO2}/t_{STEEL}]					
Bio_{CH4} production	0.16	0.132	0.28	0.018	0.02
GPE	2.8	2.63	1	0.16	0.07
NEW	2.41	2.31	0.32	0.12	0.02
NEC	0.45	0.46	-0.24	0.01	-0.02
Base case	2.67	2.52	0.77	0.135	0.06
Specific wasted freshwater [m^3_{H2O}/t_{STEEL}]					
Bio_{CH4} production	0.02	0.0165	0.034	0.0022	0.0026
With CCS	2.8	2.65	0.36	0.43	0.001
Base case	1.1	1.1	0.21	0.2	0.006
Specific Electricity Consumption [kWh/t_{STEEL}]					
Bio_{CH4} production	20	16.5	34.7	2.2	2.6
CCS CO_2 up to 15 bar & Liquefaction	482	454	138	24	9
CCS CO_2 up to 40 bar	329	311	95	17	6
CSS CO_2 up to 150 bar	630	595	182	32	12
Base case	175[a]	92.7*	123.5	514	2
Specific soil consumption [$m^2/kt_{STEEL/day}$]					
With CCS	91	85	75	4.87	2
Base case	247	247	25	20	–

[a] Electricity produced in the integrated cycle compensate the consumed amount.

Table A4. Specific production costs and carbon tax for investigated scenarios in 2021 and 2050.

		2021	2050
Carbon Tax	[USD/t_{CO2}]	49.78[80]	350[30]
CCS cost BF	[USD/t_{CO2}]	80[84]	64[83]
CCS cost EAF	[USD/t_{CO2}]	100[84]	80[83]
CCS cost DR	[USD/t_{CO2}]	80[84]	64[83]
Green H2 production	[$USD/t_m^3_{H2}$]	0.63[85]	0.09[85]
Biomethane production	[$USD/t_m^3_{BioCH4}$]	0.8[86]	0.2[86]

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