TARANTO, PRIMARY STEEL PRODUCTION IN THE CHALLENGE OF DECARBONISATION

Index

1 Executive summary

The maintenance of primary steel production in the decarbonization process represents an important commitment to the development of the national economy. Italy is the second largest steel producer in Europe and the 11th in the world: in 2019 23,2 Mt of steel were produced in our country[1]. 82% of this is recycled steel, which is produced by melting mainly ferrous scrap in electric arc furnaces, together with additions of cast iron and iron sponge. The remaining 18% is primary steel, produced from iron ores at the *Acciaierie d'Italia* plant in Taranto[2]. In 2020 the ex ILVA produced 3,4 million tons of steel, emitting 8,3 Mt of CO_2 into the atmosphere[3]. In addition to greenhouse gases, various pollutants are also emitted, including dust, dioxins and polycyclic aromatic hydrocarbons (some of which are potentially carcinogenic), mainly deriving from the processing of coal and the use of its derivatives.

The present work of ECCO aims to deepen the question of the conversion of primary steel production in Italy, analysing the specific case of the only Italian plant that currently produces it, namely the Taranto steel plant. The forthcoming publication of the new industrial plan of Taranto, linked to the changed corporate structure, represents a unique opportunity to plan interventions and conversion solutions that can combine the economic and social sustainability of investments with the environmental and climate sustainability of the project. Although today at the international level the production of the so-called 'green steel' is still in pilot phase, the particular historical circumstances offer the possibility for the Taranto site to represent a flagship project of green steel in Europe and in the world, anticipating and driving change and bringing to the market a product whose demand will only grow in the future.

Based on our insights, it emerges that DRI (Direct Reduced Iron) technology is the solution that can best combine the different variables and that allows to achieve the complete decarbonization of the primary steel production process in the long term. For the conversion of the Taranto plant from coal blast furnaces to natural gas DRI, it is estimated that an investment of 2,5 billion euros is necessary, assuming a plant configuration that allows to produce 8 million tons of steel per year. In the literature no estimates have been found that foresee a reduction in the price of DRI and EAF units (Electric Arc Furnace, i.e. the electric arc furnaces where the products obtained with DRI are melted) by 2030. The transition to DRI technology also allows an immediate benefit in environmental terms, without the deterioration of the quality of the final product. There is therefore no justification for postponing this investment. Interventions aimed at maintaining the production with blast furnaces, on the other hand, are in complete contradiction with the objectives of climate neutrality by 2050, even if coal is partly replaced by natural gas.

The point of arrival of the complete conversion involves the use of green hydrogen, both as a fuel and as a reducing agent. However, now there are two problems:

1. Renewables and technologies for the production and storage of hydrogen are not yet sufficiently developed;

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[1] "È tempo di agire – L'industria siderurgica italiana 2019", *Federacciai*.
[2] "La siderurgia italiana in cifre", *Federacciai*.
[3] "Rapporto esercizio 2020 Allegato-1.2 Materiali prodotti in stabilimento", *Ministero della Transizione Ecologica.*
"European Union Transaction Log", *European Commission.*
This value includes also the emissions of the cogeneration plant of ex ILVA of Taranto, managed by *ArcelorMittal Italy Energy Srl*. In the EUTL register the *Main Activity Type* of the plant is classified as *Combustion of fuels*. However, the plant burns off-gases from the steel plant, to which gives electricity and heat. Therefore, in this analysis the emissions of the cogeneration plant are merged with those of the steel plant.

2. The investments necessary to store a quantity of hydrogen necessary to ensure the continuity of operation of a steel mill of this size are between 8,2 and 8,9 billion euros. However, by 2030 they are expected to decrease significantly, to 5,5 – 6,2 billion €. It is, therefore, more convenient to postpone to the next few years the investments necessary for the transition from natural gas to green hydrogen.

The reduced employment needs of the system formed by DRI and EAF can be compensated and diversified through a coordinated development of alternative job opportunities, such as those in the green hydrogen and renewable energy supply chains. Given that the revival of production in Taranto requires public intervention, investments must be hinged on a long-term national strategy, so that the hydrogen DRI option is the only viable one considering the climate neutrality objectives.

Maintaining coal blast furnaces is not a viable option in the long run. As will be seen in the proposed work, the emission profile of blast furnaces is in no way compatible either with the inclusion of the plant in the reference environmental context and with the objectives of climate protection. This would be a classic example of investment lock-in.

In the analysis of variable costs of production (OPEX), however, coal does not emerge as a competitive option compared to natural gas and hydrogen. With coal blast furnaces, the total OPEX is between 621 € and 634 € per ton of steel, while with natural gas DRI technology it stands between 511 € and 634 €/t, while for hydrogen it is 586 €/t. By 2030, thanks to the expected decrease in the price of electricity from renewables and the increase in the cost of carbon, it is estimated that DRI technology can allow steel to be produced in the most cost-effective way, with a variable production cost of 642 €/t with natural gas and 484 €/t with hydrogen, compared to 653 €/t in the case of coal blast furnaces.

2 The Italian steel industry

Italy is the second largest steel producer in Europe (after Germany) and 11th worldwide: 23,2 million tons of steel were produced in our country in 2019. 81,8% of this steel is from recycling, produced from scrap in electric arc furnaces. The remaining 18,2% is primary steel, that is produced in blast furnaces from iron ore and coal (full cycle). Primary steel is currently produced at the *Acciaierie d'Italia* plant in Taranto, as the other two sites producing steel from ore, Piombino and Trieste, were closed in 2014 and 2020, respectively.

As Figure 1 shows, the trend of primary steel production looks very different from that of secondary steel. Secondary steel production recovered its pre-crisis production level in 2018, while primary steel production has been continuously declining.

Due to the crisis from Covid-19, between March and April 2020, production dropped by 40% compared to the same months of the previous year; there was a brief recovery in the summer but, in the fall, during the second lockdown, production fell again by 18% (compared to September 2019)[4]. Since November 2020, production has been on the rise.

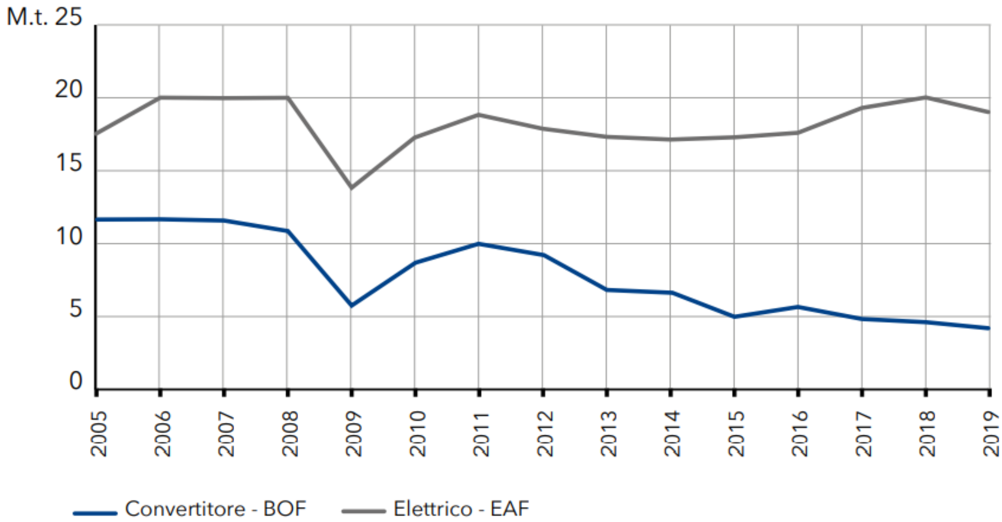

Figure 1 - Production of primary steel (Convertitore – BOF) and secondary steel (Elettrico – EAF) in Italy from 2005 to 2019[5].

The Italian steel industry, historically the second largest market in Europe in terms of both production and employment, is the leading European market by volume of steel produced from recycling[6], as shown in Figure 2.

[4] "Produzione Italia", *Federacciai,* 15 April 2021.

[5] "È tempo di agire – L'industria siderurgica italiana 2019", *Federacciai*.

[6] "Il settore siderurgico: Impatto emergenza Covid-19 e misure urgenti per il rilancio", *Federacciai.*

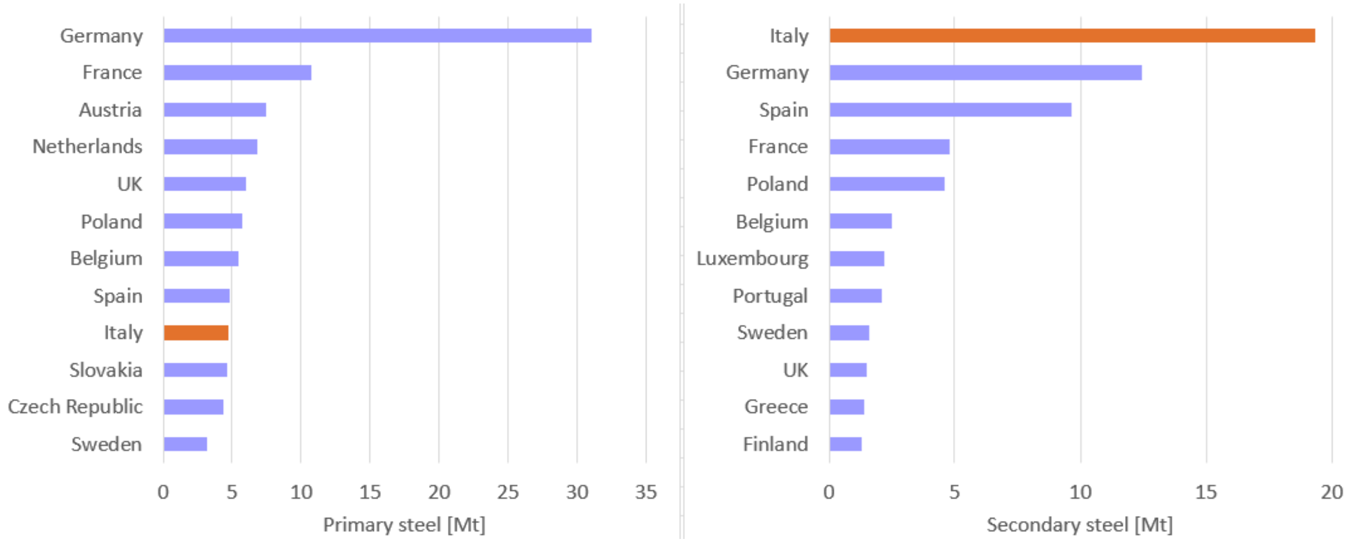

Figure 2 - Main European producers of primary and secondary steel (b) in 2017[7].

In Italy the primary steel industry employs almost 31 thousand people (Figure 3), of which more than 8 thousand are employed at the Taranto plant[8]. The Italian steel sector was heavily affected by the economic crisis of 2008, so much that from 2008 to 2019 this sector lost about 9 thousand workers and production fell by 24,2%[9]. In total, the steel sector, from the production of crude steel to its transformation into derivative products, now employs 70 thousand people, with an estimated employment impact of three times as much if the induced is also considered[10].

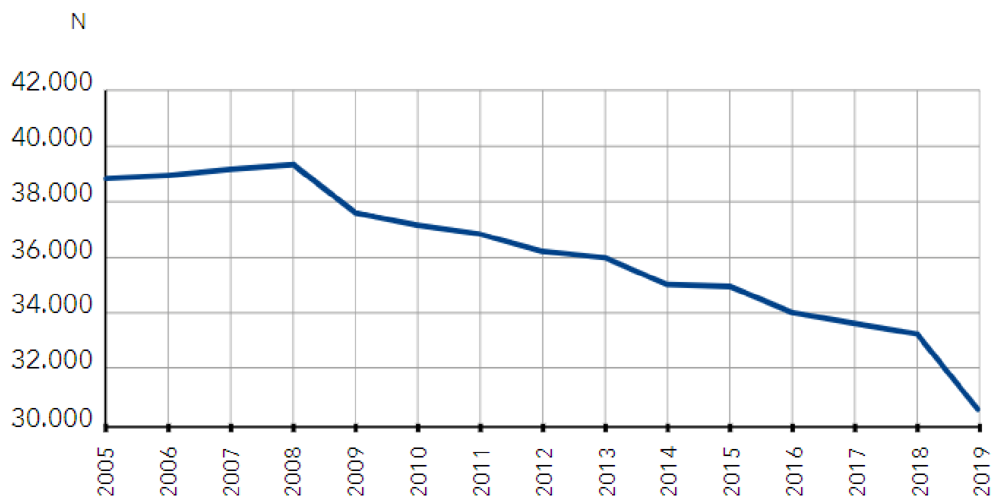

Figure 3 - Employment trends in the primary steel industry[11].

[7] "Breakthrough Strategies for Climate-Neutral Industry in Europe", *Agora,* April 2021.

[8] "È tempo di agire – L'industria siderurgica italiana 2019", *Federacciai*.
"Proposta di soluzione tecnica per il rilancio dello stabilimento di Taranto", *Federmanager,* May 2020.

[9] "La siderurgia italiana in cifre", *Federacciai*.
"World steel in figures 2009", *World steel association*.

[10] "Il settore siderurgico: Impatto emergenza Covid-19 e misure urgenti per il rilancio", *Federacciai.*

[11] "La siderurgia italiana in cifre", *Federacciai*.

In 2019 the turnover of the primary steel industry was 28,1 billion euros, with an important share coming from activities in foreign markets[12]. In fact, the Italian steel industry is an international excellence, so much that in 2019 our country exported 18 million tons of steel, mainly to Germany, France and Spain[13]. In the same year 20,6 Mt of steel was imported, mainly from Ukraine, Germany and France.

Table 1 summarizes the main data related to the Italian steel industry.

Table 1 - Main data related to the Italian steel industry.

Number of active enterprises	534	
Of which SMEs	511	(95,7%)
Employment	30'601	
Production	23,2 Mt	
% Italy compared to UE28 production		14,6%
% Italy compared to world production		1,2%
Export	18 Mt	
Turnover	28,1 billion €	
Of which SMEs		14%

3 The importance of maintaining a domestic primary steel production

In line with the goals of the Paris Agreement, Italy has pledged, with all EU countries, to reduce greenhouse gas emissions by at least 55% net by 2030, so as to achieve climate neutrality by 2050. Primary steelmaking is one of the so-called 'hard to abate' sectors, i.e., for which decarbonization is particularly complex and technologies for the complete abandonment of fossil sources in production processes are not readily available at affordable costs.

There are some applications where the use of primary steel is essential. In such applications it is necessary for steel to have excellent surface characteristics (both for aesthetic reasons and to better resist certain failure phenomena such as corrosion) and excellent ability to deform without fracturing (high ductility). Such applications include vehicle bodies, safety components, food cans, rails, complex profiles for furniture and parts of mechanical systems that require deep deformation. These areas of use cover about 30 percent of steel applications[14]. Taranto is home to the national primary steel presidium and its eventual closure would affect the entire manufacturing industry sector. In light of the useful life of these plants, new investments in plant renewal cannot fail to adequately consider zero- or low-emission technologies and aim to implement on an industrial scale solution in line with the goals of the ecological transition.

Steel is an easily and completely recyclable material and is, therefore, also compatible with the principles of the circular economy. Approximately 16 million tons of ferrous scrap is recycled each year in Italy, 73% of which comes from the domestic market (Figure 4)[15]. Secondary steel producers are highly dependent on the availability of scrap on the domestic market and maintaining primary steel production in the territory is also necessary to ensure stability and security of supply for Italian companies.

[12] "Risultati economici delle Imprese: Industria (Ateco 3 cifre) e classe di addetti", *ISTAT*.
[13] "È tempo di agire – L'industria siderurgica italiana 2019", *Federacciai*.
[14] Data *Politecnico di Milano*.
[15] "È tempo di agire – L'industria siderurgica italiana 2019", *Federacciai*.

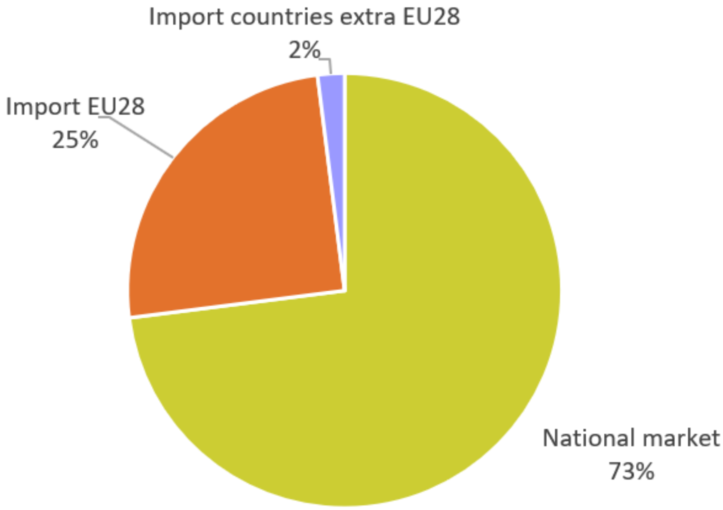

Figure 4 - Distribution of scrap origin in 2019.

China is the world's leading steel producer: in 2018 it produced 928 Mt of steel, 89,4% of which was full cycle[16]. Most of China's steel is produced in carbon coke-fired blast furnaces because China is still a developing economy and has limited availability of ferrous scrap. However, as products and infrastructures reach end-of-life in the coming years, it is likely that the increasing availability of ferrous scrap and China's climate neutrality targets to 2060 will support a gradual shift from primary steel production to electric arc furnace technology[17]. This shift will have a significant impact on scrap demand both in China and around the world. If China decides to convert even 15% of its installed full-cycle capacity to electric arc furnaces, it alone would achieve a scrap demand of about 220 million tons per year. Scrap is already a scarce resource and must, therefore, be carefully managed. This leads to primary steel production being considered a necessary process. Indeed, depending on scrap imports exposes the entire national steel industry and many key sectors in our country's economy to high risks and uncertainties.

4 The DRI technology

The aim of this work is to identify a possible conversion plan for the hot area of the Taranto steel site that would allow the continued production of primary steel with technologies that are compatible with climate neutrality goals to 2050. This paper also considers the social implications of reconversion, particularly in terms of employment, and the support mechanisms and public interventions needed.

Currently in Taranto, primary steel is produced through the BF - BOF (Blast Furnace - Basic Oxygen Furnace) process (Box 1). However, the only solution in which investment is consistent with the long-term decarbonization path is the total reconversion of the Taranto steel plant with Direct Reduced Iron (DRI) technology and electric arc furnaces (EAF). By means of this process, it is possible to obtain a low-carbon iron product from ore without the transition of the metal to a liquid state. Currently, one of the most popular processes is based on the *MIDREX* technology, which uses a mixture of carbon monoxide and hydrogen as the reducing agent, obtained by reacting natural gas with carbon dioxide:

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$

[16] "Steel Statistical Yearbook 2020 concise version", *World steel association.*
[17] "Clima: Xi promette Cina a emissioni zero entro il 2060", *Ansa,* 17 November 2020.

The reducing gas is preheated and fed into a furnace at a temperature of 750°C to 900°C. Iron ore is also charged in the furnace and the following overall reactions take place:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$
$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

The resulting product is then supplied as raw material to electric arc furnaces, where the scrap is melted by electricity and natural gas (in the future, hydrogen) burners, and primary steel is thus produced (Figure 5).

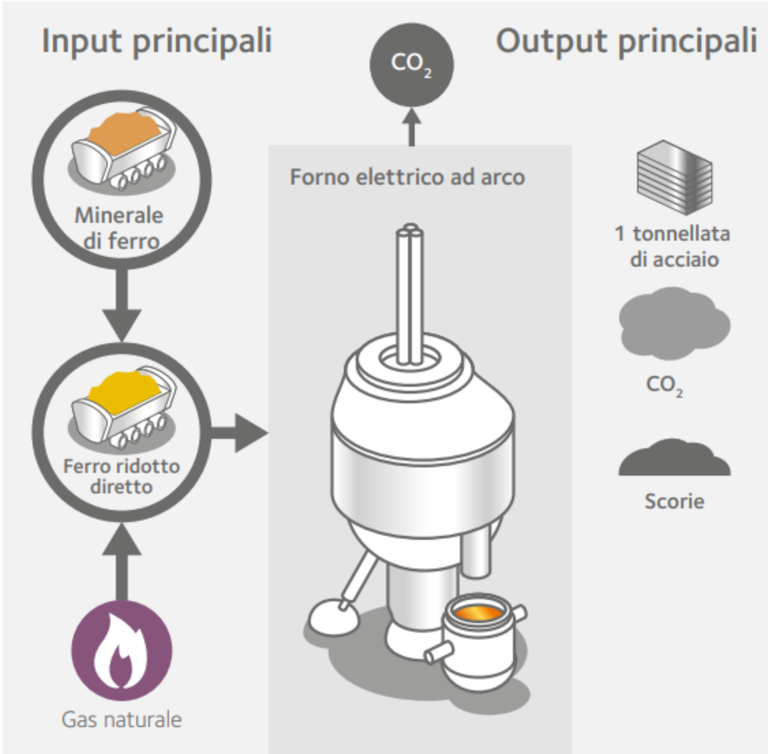

Figure 5 - Steel production with DRI technology and electric arc furnace[18].

During the DRI production process with natural gas, the hydrogen in the reducing gas contributes to the reduction of 66% of iron ore, while the remaining 34% is reduced by carbon monoxide, which then gives rise to CO_2[19]. For iron ore reduction, however, only hydrogen can be used, and with green hydrogen, CO_2 emissions related to primary steel production can be abated. From a technical point of view, therefore, DRI makes it possible to produce steel with a quality fully comparable to the product of full-cycle mills, since steel is derived directly from ore reduction and its quality does not depend on scrap sorting processes. Natural gas DRI technology makes it possible to eliminate coal-fired blast furnaces, significantly reducing the emission contribution. Only with the subsequent switch to green hydrogen, however, primary steel can be produced in a manner fully compatible with the 2050 climate goals.

[18] "Azione per il clima", *ArcelorMittal,* May 2019.
[19] Dati *Politecnico di Milano*.

Box 1
The BF – BOF technology

The BF - BOF (Blast Furnace - Basic Oxygen Furnace) process is the one most widely used for primary steel production and consists of the following stages:

1. Preparation of raw materials (iron ore and coal). The iron ores are sent to sintering and pelletizing plants to obtain agglomerates of the appropriate size. The agglomerates are then crushed and cooled and CO_2 is an emission from the sintering plants. The coal undergoes distillation, a gaseous chemical separation process that takes place at a temperature of 510°C to 1˙010°C, in the absence of oxygen. This produces coke, which is then mixed together with iron ore and heated to a temperature of 1˙000 to 1˙300°C;
2. Production of pig iron. Iron ore, coke and limestone are loaded into the blast furnace and hot air is fed in from below. The air reacts with the coke, forming carbon monoxide (CO):
$$C + O_2 \rightarrow CO_2$$
$$CO_2 + C \rightarrow 2CO$$
Carbon monoxide is the reducing agent for separating the iron in the ores, according to the following overall chemical reaction:
$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$
This produces liquid pig iron, which is an alloy with a carbon content of more than 2,11%.
3. Steel production. To obtain steel, a material with a carbon content of 0,005% < C < 2,11%, pig iron is fed into the basic oxygen furnace, along with a certain amount of scrap (with a cooling function) and is converted to steel by a jet of oxygen. The latter reacts with the carbon in the pig iron and carbon dioxide is formed: this reduces the carbon content and produces steel.

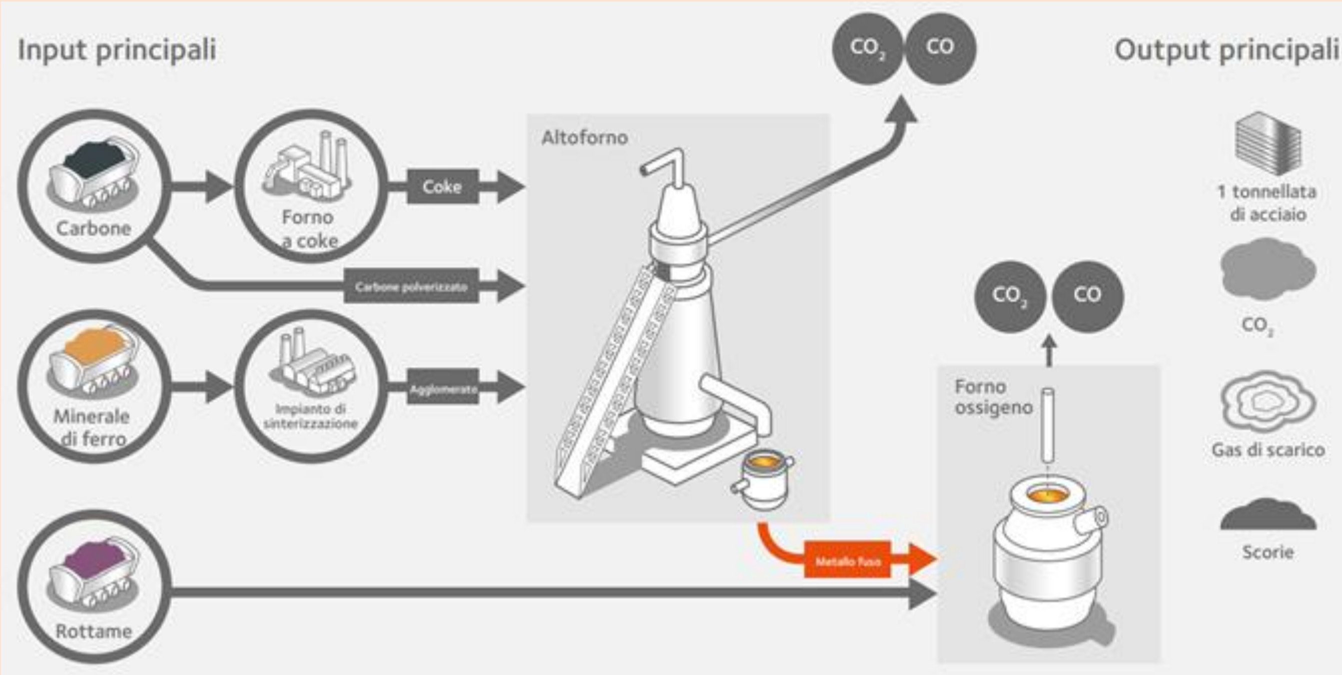

Figure 6 - Steel production with full cycle[20].

[20] "Azione per il clima", *ArcelorMittal,* May 2019.

In the full-cycle process, coal has multiple functions: it is one of the 'ingredients' to produce the steel alloy, it is the source of the reducing chemical species for the production of pig iron, it is used as an energy source for heat generation and it has a structural function for supporting the material loaded into the blast furnace. Full cycle steel production is particularly emissive in terms of gaseous pollutants, dust and greenhouse gases. In 2020 3,4 million tons of steel were produced at the Taranto steel mill, emitting 8,3 million tons of CO_2 into the atmosphere.

4.1 Best practice examples

In Europe many large steel producers are already investing in projects that aim to develop hydrogen DRI technology on a large scale. In 2016 *SSAB*, *LKAB* and *Vattenfall* started the *HYBRIT* (*HYdrogen BReakthrough Ironmaking Technology*[21]) project, a joint venture with the goal of developing the replacement of coal with hydrogen in the steelmaking process. A year ago, the first tests for green steel production began at the Lulea steel mill in northern Sweden. The first batches of green steel have been sent to the *Volvo Group* to design prototype vehicles made from this steel and the goal is to develop hydrogen DRI technology on an industrial scale by 2026. The joint venture also announced that a green hydrogen DRI plant will be built in Gaellivare, Sweden, with a production capacity of 1,3 Mt of steel per year, which will start operation in 2026 and reach an output of 2,7 Mt/year in 2030[22].

In 2019 *ArcelorMittal* launched a 65 million € project to experiment green hydrogen steel production in Hamburg, Germany[23]. DRI technology has been used at this plant since 1971, based on the use of natural gas. Now the goal is to produce 100 kt per year of steel using grey hydrogen first and then gradually switch to green hydrogen.

With the *H2FUTURE* project[24], funded by the European Union in 2019, the production of green hydrogen on an industrial scale is being studied for later use in the steel industry. To this end, At the Voaestalpine plant in Linz, Austria, has been built the largest pilot plant for the production of hydrogen for the steel industry, with a 6 MW electrolysis capacity[25]. Total funding for the project is 18 million euros. Initial tests are having positive results.

4.2 The local pollution problem in Taranto

The DRI process is characterized by a 'shorter' production line than the classic full-cycle process, with no need for coking and agglomeration plants, which have the greatest environmental impact. During these processes, in fact, emissions of toxic and carcinogenic substances are formed with very significant local pollution and health effects. When evaluating solutions for the reconversion of the Taranto plant, therefore, the broader environmental objectives that need to be pursued on the area must also be considered. This approach, especially in the context of Taranto, is inescapable: the steel plant is the emblem of a production model that characterized the country's industrial development at a time in history (the post-war period) when the health and environmental component was completely ignored in the planning of investments, including public ones. In defining the location of

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[21] Progetto HYBRIT.
[22] "HYBRIT: SSAB, LKAB and Vattenfall to begin Industrialization of future fossil-free steelmaking by establishing the world's first production plant for fossil-free sponge Iron In Gällivare", *SSAB,* 24 March 2021.
[23] "Azione per il clima", *ArcelorMittal,* May 2019.
[24] Progetto H2FUTURE.
[25] "H2FUTURE", *Voestalpine.*

production hubs, logics more related to the socioeconomic context than to the environmental and health context were valid. Such an approach, over the years, has led to many of the environmental emergencies on a national scale: just remember the Augusta area in Sicily, Marghera in Venice or Brindisi, just to name a few. Taranto, then, is an emblematic case: an industrial area that is comparable in size to that of the built-up area and is close to it, located in a fragile environmental context (just think of the morphological conformation of the coast in that stretch), for years at the center of legal battles and citizen protests for the pollution it generates. According to the findings of the latest Control at the *ArcelorMittal* strategic steel plant of national interest in Taranto by *ISPRA*, the emissions channelled from the hot area alone amount to:

- 3,1 thousand tons per year of dust;
- 257,7 kt per year of substances considered carcinogenic and/or toxic to reproduction and/or mutagenic;
- 1 kt per year of inorganic substances that occur as dust (such as, for example, cadmium, mercury and thallium).

The *ISPRA* Control also reports that the peculiar problem of the plant is the significant amounts of diffuse emissions that the steelmaking process causes. In addition to air pollution, the broader effect on all environmental compartments must be considered, even considering the concentration of receptors in the immediate vicinity of the plant area. It is evident how much, even if the environmental interventions already planned are carried out to minimize the impacts on the territory, the process itself, with the massive use of coal, determines inevitable environmental and health consequences that a replacement of the technology could, instead, radically solve.

Table 2 shows the emissions of climate-altering gases and pollutants from the Taranto steel plant.

Table 2 - Greenhouse gas and pollutant emissions from the Taranto steel mill in 2018[26].

		u.o.m.
Carbon dioxide (CO_2)	10'763,3	kt
Carbon monoxide (CO)	73,4	kt
Nitrogen oxides (NO_X)	5,2	kt
Sulfur oxides (SO_X)	4,6	kt
Particulate matter (PM10)	0,3	kt
Non-methane volatile organic compounds (NMVOC)	0,2	kt
		u.o.m.
Ammonia (NH_3)	37,8	t
Chlorine and inorganic compounds (HCl)	19,4	t
Florus and inorganic compounds (HF)	8,1	t
Benzene	8	t
Zinc and compounds (Zn)	4,3	t
Cyanides (CN)	3,8	t
Chromium and compounds (Cr)	1,4	t
Nickel and compounds (Ni)	0,7	t
Lead and compounds (Pb)	0,6	t
Cupper and compounds (Cu)	0,3	t
Naphthalene	0,2	t
Arsenic and compounds (As)	0,1	t
Cadmium and compounds (Cd)	0,1	t
		u.o.m.
Mercury and compounds (Hg)	21	kg

[26] "ArcelorMittal Italia", *European Industrial Emissions Portal*.

4.3 The scale of intervention

On average, primary steel plants aimed at producing flat products, such as the Taranto plant, have higher capacities than electric arc furnaces. Typically, annual production capacities are between 4 and 8 million tons. For the Taranto plant, which was designed and built for a production of 12 Mt/year[27] (of which 9,5 Mt was produced on site and the rest imported to the plant in the form of semi-finished products[28]), it is assumed that it will reach 8 Mt/year of steel production at full capacity. This production level makes it possible to take advantage of economies of scale, which has always been the strength of the Taranto plant, to keep production and rolling capacity in balance, to take advantage of the service area and logistics, and to optimize employment levels. Compared to the 2020 output, the production level can grow gradually, as assumed, for example, by the *Invitalia - ArcelorMittal* agreement[29] (Figure 7).

Figure 7 - Trend of primary steel production in Italy since 1990. Shown in purple is the 2021 - 2025 production level of the Taranto plant agreed between Invitalia and ArcelorMittal[30].

4.4 Current costs of DRI technology

Natural gas DRI technology is a proven and established solution that is already being used by some steel plants, especially in the Middle East, where companies have access to cheap natural gas. In the context of decarbonizing primary steel production, however, the use of natural gas should be seen as a transitional fuel, as it still involves the emission of a certain amount of greenhouse gases (albeit significantly reduced compared to the use of coal). The reliance on gas is motivated by the timing of conversion, which involves the closure of coal-fired blast furnaces and necessitates waiting for the development of appropriate technologies to produce the required amounts of hydrogen and the increased penetration of renewables in the national power system. DRI technology has a strategic interest from this perspective because it allows this transition to be made with modest plant interventions, since

[27] "Proposta di soluzione tecnica per il rilancio dello stabilimento di Taranto", *Federmanager,* May 2020.
[28] Data *Politecnico di Milano*.
[29] "AM InvestCo Italy S.p.A.", 12 January 2021.
[30] "Rapporto esercizio 2020 Allegato-1.2 Materiali prodotti in stabilimento", *Minister of Ecological Transition.*
"La siderurgia italiana in cifre", *Federacciai*.
"AM InvestCo Italy S.p.A.", 12 January 2021.

optimization is primarily related to operational and product quality aspects rather than basic plant engineering.

The use of green hydrogen, on the other hand, is still at an experimental stage, mainly because of the high investment in the infrastructure required to produce sufficient electricity from renewable energy sources and because of the still rather small size of electrolysers.

Based on the considerations outlined in the previous paragraphs, it is assumed that, when fully operational, the Taranto plant can reach a production of 8 Mt of steel per year. Hydrogen should be produced on-site, given the complexity and safety issues related to its transportation. The necessary electricity is assumed to be supplied from the grid and, based on this assumption, it is, therefore, not necessary to provide a dedicated system for power generation in Taranto, where it will, indeed, be possible to take advantage of the overproduction of renewables with storage systems. Investments in renewables are, therefore, not directly related to the Taranto steel plant, but will have to be integrated into the broader context of decarbonization of the national electricity system. Consideration may, however, be given to exploiting the large impermeable and roofing areas already present in the steel plant for the possible installation of photovoltaic systems.

The investments required to convert the Taranto plant from coal-fired blast furnaces to natural gas-fired DRI concern direct reduction units, electric arc furnaces and pelletizers for iron ore processing. The direct reduction units cost €1,8 billion to produce 8 million tons of steel per year[31]. For the electric arc furnaces, an investment of €0,5 billion is estimated, assuming reuse of some already very efficient auxiliary equipment at the plant. The pelletizer, costing 220 million euros, must also be built for steel production from DRI. A total investment of 2,5 billion euros is obtained, to which are also added the costs related to the decommissioning of the existing blast furnaces and those related to the plant adaptation resulting from the layout change.

For the subsequent transition from natural gas to green hydrogen, electrolysers and hydrogen storage systems are needed, so that the continuous operation of the plant can be guaranteed. Considering that 0,06 tons of hydrogen are needed to produce one ton of steel, at steady state, 0,5 Mt of hydrogen per year must be produced, resulting in a requirement of 56,4 tons of hydrogen per hour, assuming continuous operation of the electrolysers. Behind the assumption of a specific electrical requirement of the electrolysers of 52 MWh/t hydrogen and a price of this technology of 1 million euros per MW, this results in an investment of 2,9 billion euros[32].

Even with continuous operation of the electrolysers, a steel plant requires storage of a certain amount of hydrogen to ensure safety and continuity of operation. For a large steel plant, it is necessary to store an amount of hydrogen corresponding to five working days, which for Taranto is equivalent to 6,8 kt of hydrogen once the production target of 8 Mt of steel per year is reached[33]. Considering that tanks cost between €500 and €600/kg and that compressors cost €1˙500/kW, an investment of €5,3 to €5,9 billion is needed for hydrogen storage systems[34]. This results in an additional investment of between €8,2 and €8,9 billion being required for the transition from natural gas to green hydrogen. Table 3 summarizes the investments needed to convert the Taranto plant from coal-fired blast furnaces to green hydrogen DRI technology.

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[31] Data *Politecnico di Milano*.
[32] Data *Politecnico di Milano*.
Hypothesis *IEA*.
[33] Bhaskar, Abhinav; Assadi, Mohsen; Somehsaraei, Nikpey, Homam; "Decarbonization of the Iron and Steel Industry with Direct Reduced of Iron Ore with Green Hydrogen", *energies,* 9 February 2020.
[34] Data *Politecnico di Milano*.

Table 3 - Investment needed to convert Taranto steel from coal-fired blast furnaces to green hydrogen DRI technology (current costs).

Investment needed [billion €]	
DRI unit	1,8
EAF unit	0,5
Pelletizers	0,2
Subtotal to switch from coal to natural gas	**2,5**
Electrolyzers	2,9
Hydrogen storage	5,3 – 5,9
Subtotal for switching from natural gas to green hydrogen	**8,2 – 8,9**
Total	**10,7 – 11,3**

The Levelized Cost of Production (LCOP) of one ton of steel with green hydrogen DRI technology is currently estimated to be €669/ton. In the case of natural gas DRI, the LCOP is between 490 and 600 €/t depending on the price of natural gas. With coal-fired blast furnaces, there is a LCOP of €580 to €592 per ton of steel. However, by 2030 the CO_2 price is set to increase, from 58 €/t today to about 68 €/t[35]. Combined with the drop in the price of electricity from PV (LCOE assumed to be 37,8 €/MWh, down from 56,7 €/MWh today[36]), this results in a drop in the cost of production with green hydrogen DRI to 543 €/t. This solution turns out to be the most cost-effective since a LCOP of 607 €/t will be associated with natural gas DRI technology, which for coal blast furnaces goes up to 609 € per ton of steel produced.

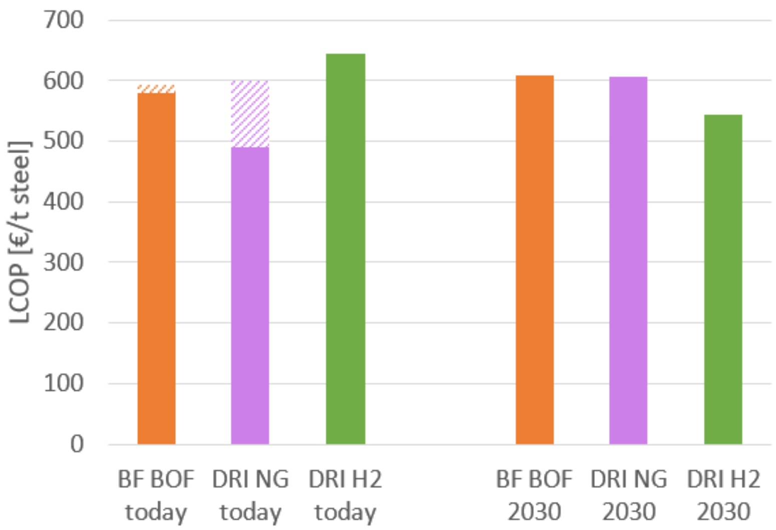

Figure 8 - Levelized Cost Of Production (LCOP) of steel today and in 2030 with coal blast furnaces, natural gas DRI technology, and green hydrogen, respectively. The current price ranges in the BF BOF and natural gas DRI cases are since a natural gas price of both €15.4/MWh (average 2019) and €63.6/MWh (average August, September, and October 2021) was considered. For the current BF BOF and gas DRI estimates, an electricity price of 40 €/MWh was assumed. In the hydrogen DRI case, electricity is assumed to be produced through a photovoltaic system, thus with a price of 56.7 €/MWh. By 2030, an electricity price of 37.8 €/MWh is assumed for all three technology solutions. Finally, a useful life of the plants of 20 years and a discount rate of 10 percent is assumed.

35 "Spot Market", *eex*.
Scenarios PRIMES.

36 Such LCOE refers to electricity produced by photovoltaic, assuming: plant useful life of 20 years, discount rate of 10%, 1600 kWh of energy produced per kW, CAPEX of 600 €/kW, OPEX of 25 €/kW and a connection cost of 1,5 million € for a 30 MW plant ("Renewable Energy Report", *Politecnico di Milano*, May 2019). For 2030 a discount rate of 5% has been assumed (assuming that it is guaranteed by SACE), 1600 kWh of energy produced per kW, CAPEX of 500 €/kW and OPEX of 21,3 €/kW ("Renewable Energy Report", *Politecnico di Milano*, May 2019; "Più pulita, intelligente e conveniente: come cogliere le opportunità della transizione energetica in Europa", *Energy Union Choices*; "PV LCOE in Europe 2014 - 30", PhotoVoltaic Technology Platform, 30 June 2015 and data from *Politecnico di Milano*).

The National Recovery and Resilience Plan[37] recognizes that steel is one of the sector where hydrogen can assume a relevant role in the perspective of progressive decarbonization. In this regard, in Mission 2 Component 2 (M2C2) "Renewable Energy, Hydrogen, Grid and Sustainable Mobility," an investment of only two billion euros is planned for the use of hydrogen in hard-to-abate sectors (cement, glass, paper, ceramics and steel). For steel, it is intended to promote the study of hydrogen DRI pilot plants, electric furnaces for melting the DRI-derived pre-melt and reheating furnaces for subsequent rolling processes. However, of the total two billion euros planned, it is not specified how much is allocated to the development of hydrogen DRI technology.

4.5 The costs of DRI technology in the medium term

Currently, green hydrogen DRI technology is characterized by high costs, which are particularly affected by the prices of hydrogen production and storage systems. In the coming years, however, costs for green steel production are expected to decrease, mainly due to the supposed decrease in electrolyser prices, improved efficiency of these technologies and economies of scale. Assuming that 37 kWh of electricity will be required to produce one kilogram of green hydrogen in 2030 and that the cost of electrolysers will fall to 0,5 million euros per MW, this results in an investment of 1 billion euros for electrolysers[38].

Hydrogen storage tank prices are also expected to fall to €375 to €490 per kg of hydrogen, resulting in an investment of €2,5 to €3,3 billion[39]. Thus, we have that the extra investment needed for the switch from natural gas to hydrogen will be between €5,5 and €6,2 billion, about 30% less than that obtained with current prices. Table 4 summarizes the investment needed to convert the Taranto plant from coal-fired blast furnaces to green hydrogen DRI technology with prices to 2030.

Table 4 - Investment needed to reconvert Taranto steel from coal blast furnaces to green hydrogen DRI technology (costs to 2030).

Investment needed [billion €]	
DRI unit	1,8
EAF unit	0,5
Pelletizers	0,2
Subtotal to switch from coal to natural gas	**2,5**
Electrolyzers	1
Hydrogen storage	4,4 – 5,2
Subtotal for switching from natural gas to green hydrogen	**5,5 – 6,2**
Total	**7,9 – 8,7**

4.6 The impact on employment

There are currently 8˙200 people employed at the Taranto plant, including 5˙000 in the hot area[40]. The adoption of DRI technology generates a downsizing of the employment level because, as fewer plants are needed for steel production, fewer people are also needed to run these plants. The current low production volumes and plant modifications mean that the current workforce is surplus to the actual needs of the plant if converted to DRI. The literature shows that a DRI + EAF plant needs 227 to 400 workers to produce one million tons per year

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[37] "Piano Nazionale di Ripresa e Resilienza". PNRR.pdf (governo.it)
[38] Hypothesis *Hydrogen Europe*.
[39] Gorre, Jachin; Ruoss, Fabian; Hannu Karjunen; Schaffert, Johannes; Tynjälä, Tero; "Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants In dynamic operation", *Applied Energy*, 2020.
[40] "Proposta di soluzione tecnica per il rilancio dello stabilimento di Taranto", *Federmanager,* May 2020. Bentivogli, Marco; "Contro i cialtroni dell'acciaio", *FIM-CISL*, 27 November 2019.

of steel, which translates into a total workforce of 1˙816 to 3˙200 people, with a redundancy of 1˙800 to 3˙184 workers[41].

By producing the necessary hydrogen on-site, there is potential for the creation of a hydrogen supply chain. In the *Preliminary Guidelines of the National Hydrogen Strategy*[42], the Italian government envisions the installation of about 5 GW of electrolysis capacity by 2030, double the amount needed for the reconversion of the Taranto steel plant. From these *Guidelines*, it is estimated that in Taranto the employment impacts, solely related to hydrogen production, could be about 100 thousand temporary jobs during the construction phase and 50 thousand permanent ones. The high investment required by hydrogen DRI technology is, therefore, offset by multiple benefits, such as the reduction of greenhouse gas and pollutant emissions and the creation of a local hydrogen supply chain, with positive repercussions on employment.

Training courses will be needed for workers to interface with the new technologies, including both DRI units and electrolysers. Resources from the Just Transition Fund[43], a €17,5 billion fund to support the territories most affected by the decarbonization process, could be used for the eventual training of workers.

5 CO_2 capture

Several redevelopment projects at the Taranto plant have already been presented over the years, some of them based on the use of Carbon Capture and Storage (CCS). These facilities are used to capture carbon dioxide originating from the use of fossil fuels and certain industrial processes. Once captured, the CO_2 can be stored in special containment sites or it can be used as a raw material for the production of products such as, for example, plastics, cement or fuels (CCU, Carbon Capture and Utilization). The latter examples, however, do not involve industrial-scale realizations since most CO_2 utilization processes are at an experimental scale.

With the natural gas DRI process, an almost pure CO_2 stream is achieved. This allows for its easy capture, for CO_2 utilization or eventual storage, if significant potentials emerge. However, the main issue is the decommissioning of the coal-fired blast furnaces and the switching to natural gas DRI, which in itself already enables a 55% reduction in CO_2 emissions and aligns the primary steelmaking process with long-term decarbonization.

By maintaining the coal-fired blast furnaces and installing a CCS plant, emissions can be reduced by 50%, with electricity consumption of 1,5 MWh/t steel. With a production of 8 million tons of steel per year, 9,8 Mt of CO_2 would still be emitted, in addition to substantial pollutant and dust emissions (Figure 9). It is, therefore, crucial, to point out that even using CCS to abate climate-changing emissions from coal-fired blast furnaces would not be possible to do so completely, there would be much higher operating costs than in the case of DRI, and, most importantly, the operating costs and environmental risks of a coal-based process would not come to an end, as desired for the Taranto area.

[41] "Proposta di soluzione tecnica per il rilancio dello stabilimento di Taranto", *Federmanager,* May 2020. Marescotti, Alessandro; "L'occupazione crolla con l'acciaio green", *Peacelink,* 22 July 2021.
[42] "Strategia Nazionale Idrogeno Linee Guida Preliminari", *Minister of Economic Development.*
[43] "Just Transition Fund", *European Parlament,* 20 September 2021.

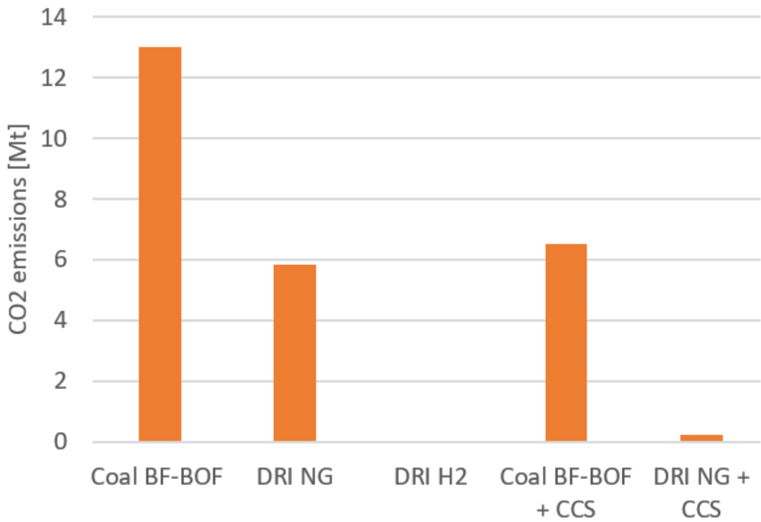

Figure 9 - Estimated CO2 emissions at the Taranto steel mill as a function of technology diversion, assuming production of 8 Mt of steel per year

6 Conclusions

The revival of primary steel production in Italy passes through a reconversion of the hot area of the Taranto plant. Effective production transformation is possible and in line with economic and environmental objectives on a local and global scale, in the medium and long term. Public resources and, in particular, those of the Recovery Fund, must be directed toward DRI technology, as it is the only one that guarantees steel production in a manner compatible with long-term decarbonization goals. Continuing to invest in carbon-intensive supply chains, which are contrary to the goals that the country and the European Union have set, seems counterintuitive. For action to be effective, a coordinated action plan must be developed with all stakeholders in the sector, compatible with the long-term climate neutrality vision and containing explicit targets for 2025 and 2030.

A rapid transition to green steel depends on the availability of large amounts of clean energy and infrastructure. The reconversion of the industry and the steel sector pass, necessarily, through a successful transition of the electricity sector to renewables. Policies to support investment in green hydrogen infrastructure are, at this moment in history, crucial for advancing large-scale processes and bringing down their costs.

The ingredients of this strategy should include investment aid and stimulating demand for green steel, leveraging public procurement and encouraging the same behaviour in the private sector, with particular reference to the downstream supply chains of primary steel production. Indeed, there are industrial partnerships in the automotive sectors, such as the one between *SSAB* and *Volvo*, that could also be promoted in the electromechanical and construction sectors. Such partnerships could be guaranteed by the state with instruments such as, for example, contracts for difference, so that the buyer could purchase green steel at a price that is competitive with that of steel from coal-fired blast furnaces. The cost surplus would be paid to the producer by the state.