The role of biomethane and hydrogen towards a climate friendly steel production in Italy

Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

The role of biomethane and hydrogen towards a climate friendly steel production in Italy

To cite this article: Michel Noussan *et al* 2025 *J. Phys.: Conf. Ser.* **3143** 012029

The role of biomethane and hydrogen towards a climate friendly steel production in Italy

Michel Noussan[1], **Viviana Negro**[1], **Alessio Riorda**[1] **and David Chiaramonti**[1]

[1]Department of Energy, Politecnico di Torino, Torino, Italy

E-mail: michel.noussan@polito.it

Abstract. Steel production is an important sector in Europe, with more than 125 million tonnes of annual output in the continent, and Italy is the second country per steel output (21 Mt) after Germany (34 Mt). At the same time, the steel industry is responsible for around 5% of greenhouse gas emissions in the EU, representing one of the most critical segments for the decarbonization of industry. This work will present an analysis of the potential role of hydrogen and biomethane in supporting the decrease of steel emissions, through their integration with the steel production process. The paper anlyses and discusses the potential role that both biomethane and hydrogen could have for the decarbonization of the Italian steel sector, comparing their estimated demand in the sector with their supply levels based on official national strategies and scenarios and available estimates from the literature. The results show that depending on the technological solution that is adopted, biomethane and hydrogen could complement the contribution of renewable electricity for the decarbonization of the steel sector. The demand of biomethane remains lower than the expected supply, but attention must be paid on the competition with other sector and the distribution of production plants across the country. The potential hydrogen demand could instead be significant, especially on the medium term, and the choice of this solution should be carefully supported by a coherent strategy to scale-up its availability. The results of this work may support researchers and other stakeholders dealing with similar topics, as they will provide useful indications that can be integrated into energy system modelling and decarbonization scenarios at national level.

1 Introduction

Steel production is one of the most energy and carbon intensive industries around the world. Recent estimates of the iron and steel industry energy consumption reach about 7% of global energy supply, and the greenhouse gas (GHG) emissions of the sector are in a range of 7-9% of global emissions [1]. Thus, finding suitable solutions to decrease GHG emissions of this industry is crucial to reach the challenging targets ahead to limit climate change.

The global steel production reached more than 1.8 billion tonnes, with a significant increase in the last decade, while the European production has shown a declining trend (136.3 Mton in 2022, down from 177.4 in 2012), as the one seen in Germany (36.8 Mton in 2022, down from 42.7 in 2012) and Italy (21.8 Mton in 2022, down from 27.3 in 2012), the two largest countries for steel production in the continent [2]. The production data for 2022 may have also been affected by the very high energy prices resulting from the energy crisis caused by the Russian invasion of Ukraine.

Considering production technologies, 71% of global crude steel production takes place in blast furnaces-basic oxygen furnaces (BF-BOF) and 29% in electric (arc) furnaces (EAF) [3]. The production technologies and energy sources are at the basis of the emission intensity of steel production, with average direct emissions of 1.7 tonnes of CO_2 per tonne of steel in BF-BOF and 0.07 tonnes of CO_2 per tonne of steel in EAF [3], although indirect emissions vary depending on the source of electricity.

Many literature works have considered specific solutions to decarbonize steel production, and others have evaluated also alternative scenarios with a wider perspective. Some scholars have also considered the specific situation in Italy. Mapelli et al. [4] compare the performance of different technologies to decarbonize the steel production in Italy, with a detailed analysis of the potential contribution of hydrogen, biomethane and carbon capture and storage. While the authors present a comprehensive evaluation of impacts including GHG emissions, water consumption, electricity consumption and soil use, they do not present estimates of total volumes at the national level. Monteleone et al. [5] present the results of a LCA of the cast iron production in Italy based on the operational data of ten real foundries located in the north of the country. While their analysis is not directly focused on the steel sector, it provides some interesting insights in a similar sector, highlighting the challenges of decarbonizing industrial segments dealing with iron and steel, such as the need to intervene on a well consolidated production process without altering the product quality.

The steel sector is one of the most promising for the application of hydrogen to decarbonize the process when direct electrification with EAF is not possible. Recent studies have evaluated the potential contribution of hydrogen to decarbonize the steel industry in different countries around the world, such as Kenya [6], Bangladesh [7] and Malaysia [8]. Each country has very specific conditions that can be crucial in determining the success of hydrogen for the decarbonization of the sector, including the type of steel route (i.e. from primary ore or recycled scrap) and the availability of renewable resources for the production of green hydrogen. Biomethane has also been proposed as an alternative to natural gas in the steel sector, both as reducing agent and to supply the required heat throughout the entire process. Biomethane, when coupled with carbon capture and storage, could also represent an option to reach climate-positive steel production [9, 10], with different levels depending on the capture rate and the type of feedstock that is used to produce it.

In addition to technological developments, it is important to highlight that research works have also addressed other dimensions that are crucial for the development of green steel, such as the acceptance by the public of supporting green hydrogen in the steel industry [11] or the long-term economic and social sustainability when considering public funding and incentives to green steel [12].

This work focuses on the potential contribution of hydrogen and biomethane in decarbonizing the steel sector in Italy. Starting from real data of natural gas and electricity consumption in the sector, we estimate the potential contribution of low-carbon electricity, hydrogen and biomethane to lower the climate impact of the industry. The analysis also provides a comparison of the expected biomethane demand with the current forecast of biomethane supply deployment at the national level. A similar analysis is also presented for hydrogen, although the supply potential in the literature is less detailed.

The results can be of use for both researchers and policy makers to evaluate the potential allocation to the steel sector of a share of renewable electricity, hydrogen and biomethane, also taking into account the other applications that can require it.

2 Methodology

This section presents the methodology applied into the analysis, together with the main assumptions at the basis of the definition of two alternative scenarios.

2.1 Steel production in Italy

Considering Italy, the national steel production in the last decade, with an average value of 23.5 Mt per year, shows a predominant share (around 85%) of secondary steel coming from the melting of scrap through the technological process based on the electric arc furnace (EAF), while the remaining 15% is represented by primary steel produced through the integral Blast Furnace-Basic Oxygen Furnace (BF-BOF) cycle, which uses ferrous minerals in the only currently operational plant, the Acciaierie d'Italia in Taranto [13]. These figures are very different compared to the global and the European shares, as in both these cases the BF-BOF process represents the majority of the total steel output. The total steel demand in Italy in 2022 has reached 28.96 Mton, including national production and imports.

In this analysis, in a decarbonization perspective, the BF-BOF is assumed to be substituted with a direct reduced iron (DRI) process, that could use natural gas, hydrogen or biomethane as energy inputs, as further described below. An alternative option could be to evaluate carbon capture, storage and utilization (CCUS) options to mitigate GHG emissions. However, at this stage, the first option seems to be more promising based on the strategies of different industries in Europe as well as at the EU level [14]. CCUS solutions allow in general for emissions reductions that are lower than those that can be reached through the DRI option, due to a number of reasons related to the distribution of emissions in a steel factory as well as to the capture rates that can be reached. Moreover, in Italy the availability of geological storage for CO_2 is quite limited compared to other European countries. For these reasons, the current analysis will not consider CCUS technologies, which will be evaluated in a future work.

The layout of the DRI process is represented in Figure 1, where the current technology based on the use of natural gas as reducing gas and for other energy applications in the process is represented on the left side. Two possible alternatives are possible to substitute the natural gas, either with hydrogen (flows represented in blue color) or with biomethane (flows represented in green color). There are currently no DRI steel plants in Italy, but this technology could represent a possible alternative to the BF-BOF process in Taranto to produce steel from iron ore.

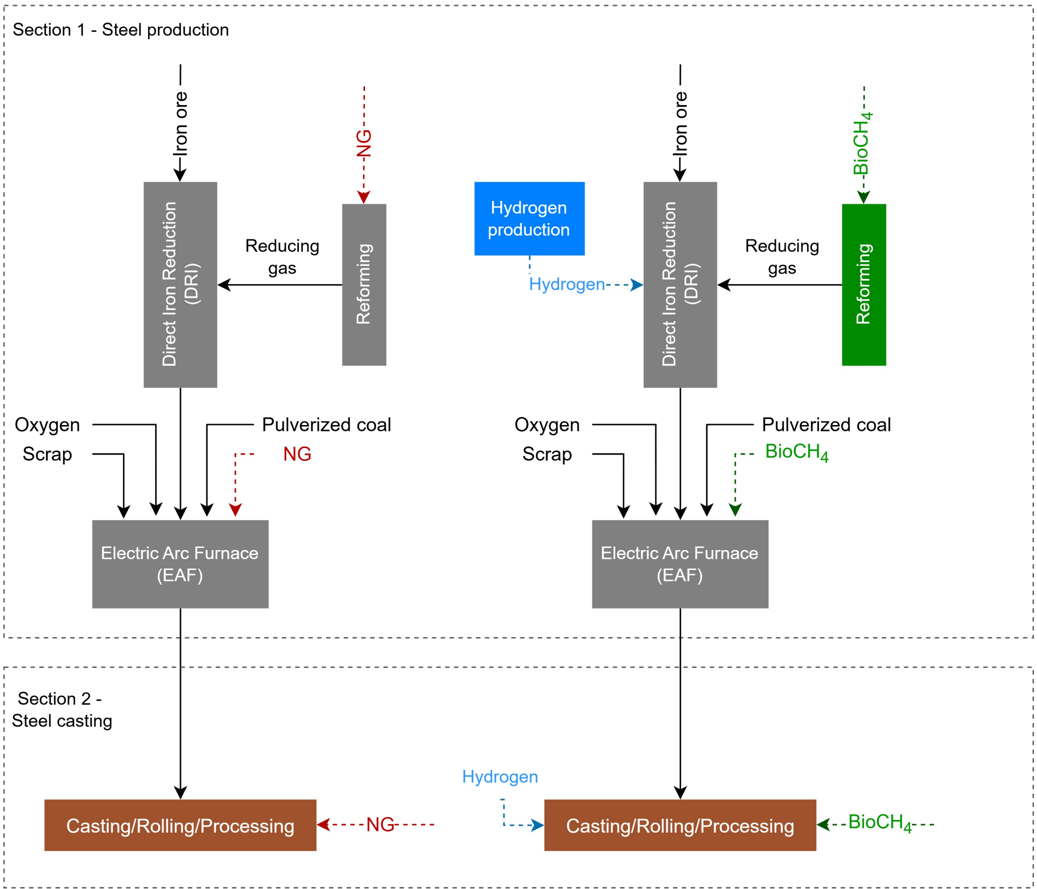

Figure 1: Scheme of the DRI process and the substitution of fossil natural gas with hydrogen (blue color) or biomethane (green color).

A similar shift can be considered for the EAF process, as represented in Figure 2. Also in this case, the state-of-the-art technology based on the use of fossil natural gas is compared with the substitution with hydrogen (flows represented in blue color) or with biomethane (flows represented in green color). Only a few studies address the direct utilization of hydrogen in the EAF, which concludes the necessity for further investigation of its potential impact on the other reactions [15]. For this reason, in the present study, as far as EAF is concerned, hydrogen is considered to be integrated only in the steel casting process (section 2).

Specific values on energy consumption in the three different configurations considered in this study are reported in Table 1, based on data from [16].

Considering the current share of steel production in Italy, i.e. 85% from EAF and 15% from BF-BOF, each tonne of steel would require on average 0.844 GJ (234 kWh) of natural gas and 1.643 GJ (457 kWh) of electricity. These values are significantly lower than the average indicators published by the Italian association of steel producers [13], which are around 640 kWh of natural gas and 785 kWh of electricity

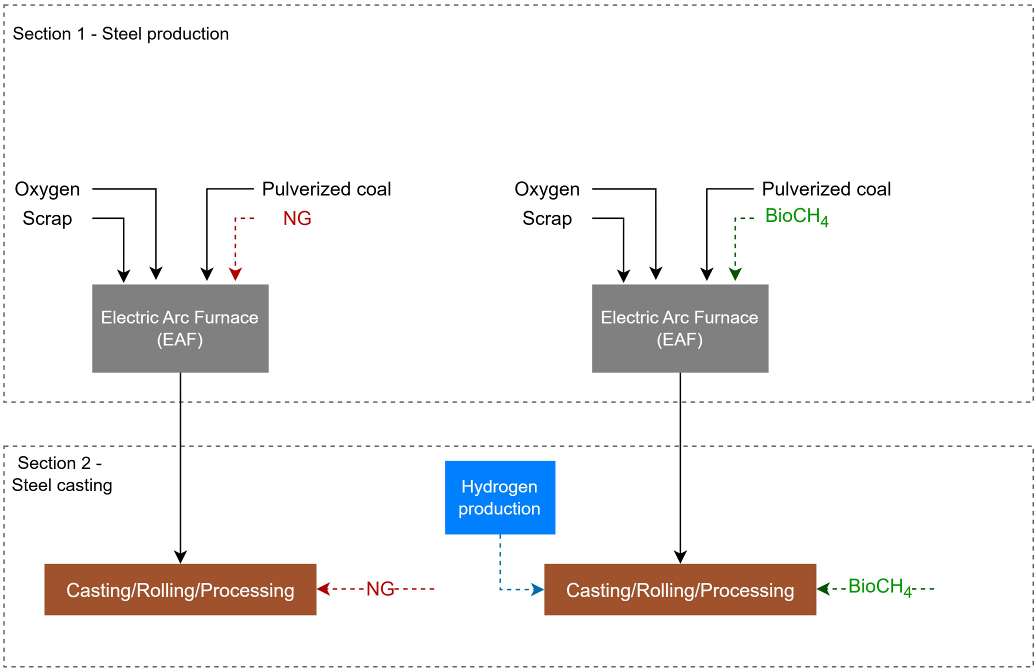

Figure 2: Scheme of the EAF process and the substitution of fossil natural gas with hydrogen (blue color) or biomethane (green color).

Table 1: Energy consumption of natural gas, electricity and hydrogen per tonne of steel output in the different steel production processes considered in this study (data from [16]).

Energy Consumption (GJ/t)	BF-BOF	EAF	DRI–NG	DRI–H2
Natural gas	2.530	0.546	11.292	3.573
Electricity	0.875	1.779	4.173	4.173
Hydrogen	-	-	-	7.321

per each tonne of steel produced. This difference could be related to the auxiliary energy consumption of the different processes in the sector that are not directly related to the aspects analyzed in the work by Zhang et al. [16].

Given the fact that the aim of this work is to estimate the overall energy consumption of steel production in Italy, we believe that actual data from national statistics may be more accurate. Thus, we have chosen to use the data from [16] to estimate the differences across technologies, but we have also included the additional energy consumption obtained by the difference with the national indicators by allocating it as an additional consumption that is not depending on the specific steel production technology. This would allow our final estimates to be in line with the historical evolution of the energy consumption of the sector, although without being able to properly allocate this consumption to the processes that cause it. The additional energy consumption considered for all the processes is thus 0.845 GJ/t of natural gas and 1.643 GJ/t of electricity.

These data have been used to calculate the total energy demand by type of energy carrier (e.g. renewable electricity, biomethane and green hydrogen) that could be expected in Italy with a fully decarbonized steel sector by 2040. The results have been compared with the estimated total demand of these carriers in the official scenarios developed by SNAM and Terna [17].

The analyzed scenarios aim at evaluating the potential contribution of biomethane and hydrogen to decarbonize the steel sector in Italy. The first scenario assumes that the share of steel currently produced by the BF-BOF process will be substituted by a DRI process based on hydrogen (and on a minor share of biomethane). In the second scenario the DRI process is based on biomethane.

In both scenarios the electricity demand and natural gas demand of both the EAF and DRI will be supplied by low-carbon electricity from RES and biomethane respectively.

In this perspective, both the use of electricity and hydrogen on site would not lead to any direct GHG emissions, nor to any other indirect emissions if electricity is produced only from renewables or nuclear. Conversely, the use of biomethane would lead to carbon-neutral direct emissions, under the assumption that the combustion emissions are compensated by the carbon dioxide absorbed during the lifetime of the biomass that is used as input in the anaerobic digestion. Indirect emissions associated to biomethane strongly depend on the type of feedstock that is used, and they can also show negative values for some feedstocks (and in particular when using manure, thanks to the avoided methane emissions thanks to substituting alternative manure disposal).

Considering direct emissions, there are no difference in the two considered scenarios, as they are both proposing zero-carbon or carbon neutral fuels. However, the analysis also incorporated an evaluation of indirect emissions to shed light on the differences across the evaluated options, based on the evolution of both electricity and biomethane mix, as better described below.

2.2 Electricity production

An important share of the indirect emissions of the steel sector are related to the generation of the electricity that is consumed by the industry, between 15 and 19 TWh in the last five years [13].

This value should be compared to the total electricity demand in Italy, which is around 312 TWh in 2024 [18]. National generation in the same year reached 261 TWh, of which 49% from renewable energy sources (RES), while the remaining 51 TWh have been imported. This significant level of low-carbon generation from renewables has contributed to a continuous decrease of the GHG intensity of electricity in Italy in the last decades. As a result, the estimated emission intensity of electricity production in Italy in 2024 reached 215.9 g/kWh, down from 327.2 g/kWh in 2014 and 497.3 in 2004 [19].

Compared to the current electricity production from RES (128.7 TWh in 2024 and 113.4 TWh in 2023 [18]), future scenarios estimate a significant increase, mostly led by a massive increase of solar and wind capacity. The official scenarios [17] estimate a range of electricity generation from RES between 201 and 227 TWh in 2030, and between 293 and 335 TWh by 2040 (on a total electricity demand of 347-362 TWh in 2030 and 404-439 TWh in 2040).

Such a significant increase in RES generation would significantly benefit the indirect emissions of the steel sector, further reducing its indirect carbon footprint compared to the current situation. While a 100% use of renewable electricity in steel production through guarantees of origin or other mechanisms, the use of grid electricity would lead to a non-zero amount of indirect emissions. Based on the data on electricity mixes provided by [17] and on emission factors presented in [19], we have estimated GHG emission factors of electricity of 101.1 g/kWh for 2030 and 69.1 g/kWh for 2040. These emission factors will be used to estimate the indirect emissions of the two alternative scenarios with respect to the evolution over the years.

2.3 Hydrogen supply

The future evolution of the Italian energy system may include different levels of hydrogen use, depending on its success in providing a cost-effective solution to decarbonize final uses. Hydrogen may be of particular interest in the industry and transport sectors, and it could also contribute to long-term electricity storage.

Official national estimates for hydrogen use in Italy [17] show a significant variability across scenarios. Nation-wide levels for 2030 are estimated in the range from 3.9 to 8.4 TWh, with 1.4-3.8 TWh used in the industrial sector. A significant increase is foreseen for 2040, with national demand varying from 58.9 to 91.9 TWh, of which 16.3-24.9 TWh in industry. The use of hydrogen in the steel sector is mentioned in the document, but without an explicit estimation of the penetration level or the required volumes.

Finally, it is important to highlight that the maximum national production capacity of green hydrogen is estimated at 11.9 TWh by 2035 and 18.4 TWh by 2040. Thus, the scenarios with a higher demand are based on the assumption of a significant level of green hydrogen import, that may reach 80% of the total demand [17]. This would in turn require both the availability of long-distance transport infrastructure as well as excess generation capacity in other countries, and both aspects would need that green hydrogen can be produced and transported at an affordable cost for final users.

For the analysis of indirect emissions, as discussed for electricity, the production of green hydrogen with 100% renewable electricity would not lead to any indirect emission. However, when considering hydrogen production from electrolyzers fed by grid electricity, GHG emission factors for hydrogen in 2024, 2030 and 2040 would be 332 g/kWh, 156 g/kWh and 99 g/kWh respectively (considering conversion efficiency levels of 65%, 65% and 70% respectively).

2.4 Biomethane supply

Biomethane is being seen as a potential solution to decarbonize many applications that are hard to electrify, as a direct substitute of fossil natural gas. The latest estimate (2023) of biomethane supply in Italy reach a level of 2.5 TWh, mostly reached thanks to a dedicated incentive for the development of new biomethane plants and the conversion of existing biogas-to-electricity plants.

National official scenarios [17] estimate biomethane demand to increase to 22.4-46.8 TWh by 2030 (equivalent to 2.3-5.0 billion cubic meters), based on the significant number of biogas plants that are currently operating for power generation and may shift towards biomethane upgrading. Industry will represent the lion's share of biomethane demand, with 64%-78% of the total demand, mostly due to the need of decreasing emissions to comply with the EU ETS. National biomethane supply is expected to increase to 44.4-101.0 TWh by 2040 (corresponding 4.7-10.4 bcm), mostly driven by its use in other final sectors (buildings and transport), as the use in industry compared to 2030 values remains very limited in most of the scenarios considered. In the most optimistic scenarios a marginal share of synthetic methane is included in the total.

Recent studies evaluate the total national potential of biomethane in Italy. A report from Gas for Climate [20] estimates the biomethane potential in Europe, including estimates at country level, and the 2030 potential from agricultural residues and sequential cropping in Italy is set to 5.5 bcm. The report also includes a comparison with other estimates, that have a higher value of 6.5 bcm, with an additional potential of 1-1.5 bcm when considering the organic fraction of municipal solid waste. The long-term potential, considering production capacity in 2050, estimates around 8.2 bcm from anaerobic digestion, mostly from sequential cropping, and also 5.2 bcm from thermal gasification (mostly from forestry residues and municipal solid waste). Different feedstocks may have a direct impact on GHG emissions over the supply chain, and thus in the effectiveness of biomethane in representing a low-carbon alternative to fossil gas.

Based on these potential levels, we have considered different feedstock mixes to estimate potential emissions over the supply chain of biomethane. Emission factors have been calculated based on recent studies that have addressed biomethane development in Italy [21], comparing the different mixes in the current situation, in 2030 and 2040, also accounting for the different electricity mixes at national level that contribute to different processes along the supply chain. The resulting GHG emission factors for biomethane are equal to -10.9, -3.7 and -0.9 g/kWh for 2024, 2030 and 2040 respectively. The negative emissions are due to the emission credits associated with the use of manure, thanks to the avoided methane emissions that would have occurred for the manure disposal.

3 Results

The objective of the analysis is to present an estimate of the potential contribution of biomethane and hydrogen to support steel decarbonization, together with the role of renewable electricity. Also, and estimation of indirect emissions in the two scenarios is presented, to evaluate the contribution of each technology as well as the crucial role of the electricity and feedstock mixes.

3.1 Energy consumption

The estimated energy consumption in the different scenarios is illustrated in Figure 3, with a level of detail per technology and energy carrier.

Figures clearly show the lower energy intensity of the EAF route, considering the fact that despite a slightly higher total energy consumption at the National level, it represents 85% of the steel output (20 Mt vs 3.5 Mt). However, most of its energy consumption is in form of electricity, while other routes have a minor share of electricity compared to their total energy consumption. Moreover, it is important to highlight other aspects, such as the fact that not all the types of steel can be produced though EAF, as well as the need for scrap as input that is not always available, in addition to the different economic and logistic aspects of the different routes.

Another significant trend that is noticeable in the chart is the substitution of the coal consumption when shifting from BO-BOF towards DRI, resulting in an important decrease of the GHG emissions of the sector. However, such a shift would require important investments in the process, as well as higher operating costs due to the shift to a higher-quality fuel (although with a decrease of the total energy consumption), and a detailed economic analysis would be needed to verify its feasibility.

These levels of consumption can be compared with the total supply of renewable electricity, biomethane and green hydrogen estimated in the National Scenarios by Terna and SNAM for 2040 [17]. The results of the comparison are presented in Table 2.

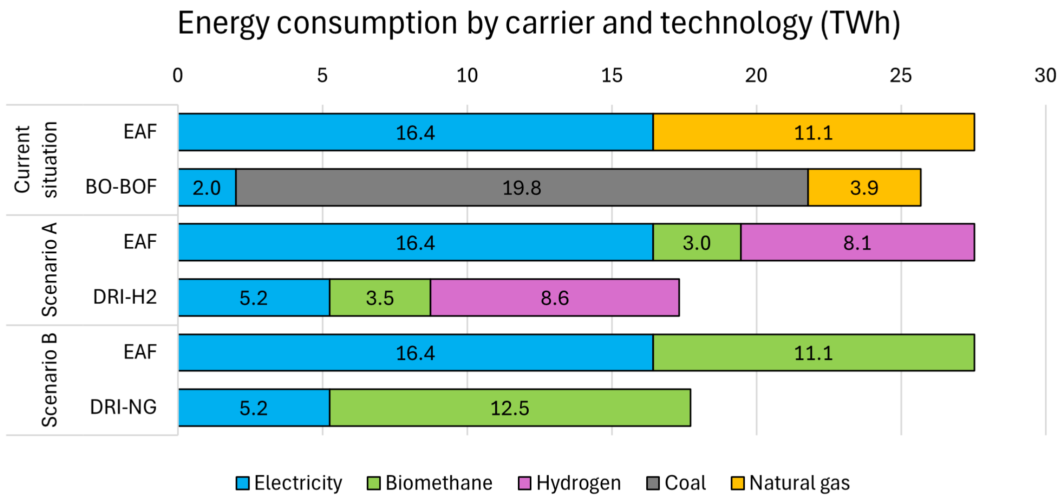

Figure 3: Energy consumption of the steel sector in Italy by energy carrier, technology and scenario. Values refer to total national steel production.

Table 2: Energy consumption of electricity, biomethane and hydrogen in the two scenarios compared with the National Scenarios (from [17]).

	Electricity from RES	**Biomethane**	**Hydrogen**
Scenario A	21.7	6.5	16.7
Scenario B	21.7	23.6	0.0
National supply in 2030 (min)	201.0	22.4	3.9
National supply in 2030 (max)	227.0	47.8	8.4
National supply in 2040 (min)	293.0	44.4	58.9
National supply in 2040 (max)	335.0	101.1	91.9

The total electricity consumption of the steel sector represents around 10% of the renewable electricity compared to 2030 figures, but decreases to around 7% when considering 2040 scenarios. Electricity demand remains the same compared to the current situation, under the assumption that the steel output is not changing, although a low-carbon steel production would required that all the electricity that is consumed is produced from RES. This would require additional investment in RES generation, as well as storage systems or other flexibility options to increase the production from RES at all times.

Considering biomethane demand, the scenario with the highest consumption would require slightly more than the lower generation in 2030 and around one quarter or one half of the total supply in Italy by 2040. The implementation of this scenario would require that a significant amount of the National biomethane production needs to be allocated to the steel sector. Thus, clear policy actions may be needed to ensure such an outcome. In the other scenario, biomethane demand would generally remain at a lower value, that is compatible with most of the national estimates for 2030 and 2040.

The hydrogen demand in the first scenario, which is the only one considering hydrogen, is the most critical in terms of comparison with the estimated national supply. In the short term, looking at 2030 figures, the total hydrogen demand would be between 2 and 4 times higher than the expected demand of green hydrogen in Italy (which is already considering both national production and imports). The situation would however improve by 2040, as hydrogen for steel would only represent 18%-28% of the national supply, mostly thanks to the very significant increase of hydrogen supply that is reported in the National scenarios [17]. In this case, the hydrogen demand would be balanced by a parallel decrease of biomethane consumption at a similar level.

3.2 GHG emissions

As already discussed above, the two scenarios are both resulting in net zero direct emissions, as both electricity and hydrogen do not emit carbon dioxide during their use, while biomethane combustion emissions are assumed to be carbon neutral due to the fact that they are compensated by the carbon dioxide absorbed by the biomass used to produce biomethane (however, indirect emissions over the supply chain are properly accounted).

Also, if electricity and hydrogen are produced from 100% renewable sources, they are also resulting in no indirect emissions (limiting the analysis to the operation of the system, i.e. neglecting building and decommissioning phases, that are beyond the scope of this work). On the other hand, if electricity for the steel plant and the hydrogen production is sourced from the national grid, the level of indirect emissions depends on the electricity mix that is used. The same applies to biomethane, whose indirect emissions over the supply chain depend on the type of feedstock that is used.

The chart in Figure 4 compares the effect of different electricity and feedstock mixes on the indirect emissions of the two scenarios considered in this work. The values clearly illustrate the crucial effect of the electricity mix in decreasing indirect emissions with increasing penetration of renewables over the years (leading to lower carbon intensity levels). As reported in the methodology section, we have estimated GHG emission factors of electricity of 101.1 g/kWh for 2030 and 69.1 g/kWh for 2040, compared to the current level of 215.9 g/kWh in 2024 [19]. Such a strong decrease is possible thanks to the massive deployment of solar and wind capacity that is planned under the current national decarbonization strategies.

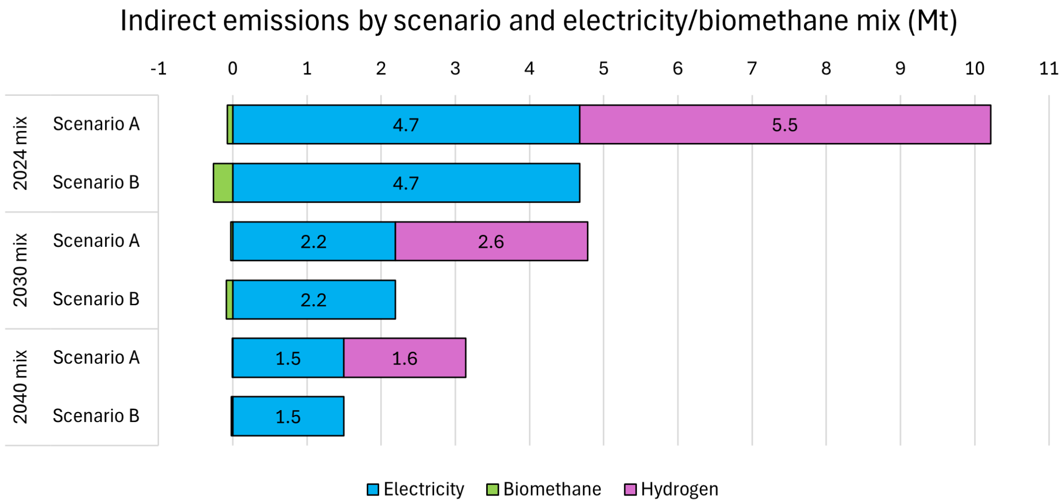

Figure 4: Indirect GHG emissions of the two analyzed scenarios, by energy carrier and with different electricity and feedstock mixes for Italy.

These levels of emissions can be compared to the current GHG emissions of the steel sector in Italy. Direct emissions account today for around 10-11 Mt of CO_2, based on official data [13]. Indirect emissions are not published, but we can estimate a total level of 5.8 Mt considering the emissions for electricity generation and the upstream emissions of natural gas and coal [22] consumed in the steel sector.

The results confirm the crucial importance of producing both electricity and hydrogen from renewable sources, as using the current electricity mix would lead to indirect emissions for the Scenario A that are roughly at the same level of the current direct emissions at the sector (and around 60% of the current direct and indirect emissions). Thus, to maximize the potential GHG savings, significant investments in pwoer generation from renewables in Italy are needed, especially when considering final applications that use hydrogen.

4 Discussion

The results of this paper provide a general estimate of the annual values of renewable electricity, biomethane and hydrogen demand that would be needed to decarbonize the steel sector in Italy. This annual national estimate is not considering additional temporal or geographical detail, assuming that these levels of energy demand could be provided on the supply side at an acceptable cost.

While the comparison of this demand with the estimated total demand of these energy carriers has mostly confirmed its suitability within a 2040 perspective, additional research should be needed to assess potential issues in delivering the energy carriers to the steel plants. Most of the sites are located in the Northern regions of Italy, especially Lombardy and Veneto, which may be in line with the geographical distribution of biomethane plants but may be less favourable for the production of renewable electricity and green hydrogen, as most of the solar and wind potential is located in Southern regions. Moreover, the temporal variability of those sources should be coupled with potential flexibility solutions to be matched with the operational load of the steel industries. Also, since national scenarios consider a significant share of green hydrogen import, dedicated transport infrastructure would be needed in the case that green hydrogen is not produced on site in the steel plants.

Another aspect that would require further investigation is related to the economic evolution of the sector, which is becoming more and more competitive at the global level. Its evolution will be affected by several aspects, including the national and international industrial policies of different countries, the effect of emission trading systems and other regulations (such as the carbon border adjustment mechanism), and also the dynamics of the many different final products that may impact the overall demand of the steel sector. For this reason, the total steel output may vary both in absolute terms as well as in terms of the share of each route, leading to different results compared to those presented in this analysis.

5 Conclusions

This work presented an analysis of the potential solutions for the decarbonization of the steel sector in Italy, assessing the required demand of renewable electricity, biomethane and green hydrogen in two different scenarios. Both scenarios confirm that the estimated demand of these three energy carriers remains marginal compared to their overall demand that is presented in the official National scenarios. However, these values remain higher than the current level of biomethane and green hydrogen produced in Italy, and in some cases also higher than the volumes estimated for 2030, confirming the importance of upscaling their supply chains to reach the required levels by 2040.

The two different scenarios compare the use of hydrogen or biomethane in DRI steel plants as an alternative to the current use of a BF-BOF plant. The results show that hydrogen could not substitute all the natural gas applications, as in some cases biomethane would remain a preferred option, but the use of hydrogen would significantly reduce the need for biomethane, making it available for other hard-to-abate applications. On the other hand, using high amount of hydrogen may require significant investments in generation and/or transport infrastructure, in addition to expanding power generation from renewables to support green hydrogen production.

The analysis of GHG emissions shows that both electricity and hydrogen used in the steel sector should be produced from renewable sources, as using the current or the future electricity mixes still causes a significant amount of indirect emissions, although at a much lower level compared to the current situation.

A future expansion of this analysis will incorporate the economic dimension, which is an important aspect to be addressed when evaluating different technological options. Such an analysis will need to consider several aspects that affect the evolution of the demand and supply of the steel sector at the international level, also incorporating a number of regulatory mechanisms such as the Emission Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM), that have an impact on the operation of steel plants in Europe and beyond.

Acknowledgments

This work was supported by the European Innovation Council (EIC) through the “H2STEEL project”, Grant number 101070741.

References

[1] Jinsoo Kim et al. “Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options”. In: *Energy Research Social Science* 89 (2022), p. 102565. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2022.102565. URL: https://www.sciencedirect.com/science/article/pii/S2214629622000706.

[2] Andrea Mio et al. *Il settore dell’acciaio in Italia: criticità ed opportunità*. https://www.wwf.it/uploads/Report-WWF-Settore-acciaio-1.pdf. Accessed: 2025-05-30. 2024.

[3] Süheyb Bilici et al. "Global trade of green iron as a game changer for a near-zero global steel industry? - A scenario-based assessment of regionalized impacts". In: *Energy and Climate Change* 5 (2024), p. 100161. ISSN: 2666-2787. DOI: https://doi.org/10.1016/j.egycc.2024.100161. URL: https://www.sciencedirect.com/science/article/pii/S2666278724000370.

[4] Carlo Mapelli et al. "Future Scenarios for Reducing Emissions and Consumption in the Italian Steelmaking Industry". In: *steel research international* 93.5 (2022), p. 2100631. DOI: https://doi.org/10.1002/srin.202100631. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/srin.202100631. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/srin.202100631.

[5] B. Monteleone et al. "A sustainability assessment of the foundry production process in Italy". In: *Sustainable Production and Consumption* 46 (2024), pp. 491–501. ISSN: 2352-5509. DOI: https://doi.org/10.1016/j.spc.2024.03.005. URL: https://www.sciencedirect.com/science/article/pii/S2352550924000666.

[6] Pietro Lubello et al. "Green hydrogen futures in LMICs: Opportunities for fertilizer and steel production in Kenya". In: *iScience* 28.4 (2025), p. 112298. ISSN: 2589-0042. DOI: https://doi.org/10.1016/j.isci.2025.112298. URL: https://www.sciencedirect.com/science/article/pii/S2589004225005590.

[7] Md. Sanowar Hossain et al. "A Comprehensive Study of the Hydrogen Energy-Based Green Steel Industry in Bangladesh: Prospects and Challenges". In: *International Journal of Hydrogen Energy* 135 (2025), pp. 316–338. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2025.05.041. URL: https://www.sciencedirect.com/science/article/pii/S0360319925022906.

[8] Soh Mian Yu et al. "Prospect of green hydrogen in Malaysian iron and steel industry: Techno-economic assessment and energy modelling using PyPSA-Earth". In: *Renewable and Sustainable Energy Reviews* 216 (2025), p. 115665. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2025.115665. URL: https://www.sciencedirect.com/science/article/pii/S1364032125003387.

[9] Carlos Andrade, Lucas Desport, and Sandrine Selosse. "Net-negative emission opportunities for the iron and steel industry on a global scale". In: *Applied Energy* 358 (2024), p. 122566. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2023.122566. URL: https://www.sciencedirect.com/science/article/pii/S030626192301930X.

[10] Daan Peters, Evelien Smit, and Leo Gray. "Biomethane for emission abatement by 2040, Marginal abatement costs compared to other renewables". In: *Common Futures* (2024), pp. 2023–11. URL: https://www.commonfutures.com/files/Common-Futures_Biomethane-for-emission-abatement-by-.pdf.

[11] Sven Alsheimer. "Does the public want green hydrogen in industry? Local and national acceptance of methanol and steel transitions in Germany". In: *Energy Research Social Science* 121 (2025), p. 103973. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2025.103973. URL: https://www.sciencedirect.com/science/article/pii/S2214629625000544.

[12] Per-Olov Johansson and Bengt Kriström. ""Green" steel investments in the EU: Pie in the sky?" In: *Resource and Energy Economics* 82 (2025), p. 101494. ISSN: 0928-7655. DOI: https://doi.org/10.1016/j.reseneeco.2025.101494. URL: https://www.sciencedirect.com/science/article/pii/S0928765525000181.

[13] Federacciai. *Rapporto di Sostenibilità 2023*. https://federacciai.it/wp-content/uploads/2024/06/Rapporo-di-Sostenibilita_2023.pdf. Accessed: 2025-05-30. 2024.

[14] Julian Somers. *Technologies to decarbonise the EU steel industry*. 2022. DOI: 10.2760/069150.

[15] Lilly Schulte, Alexander Reinicke, and Thomas Echterhof. "Application of hydrogen operated burners in the electric arc furnace". In: *IOP Conference Series: Materials Science and Engineering* 1309 (May 2024), p. 012011. DOI: 10.1088/1757-899X/1309/1/012011.

[16] Guiyan Zang et al. "Cost and Life Cycle Analysis for Deep CO2 Emissions Reduction for Steel Making: Direct Reduced Iron Technologies". In: *steel research international* 94.6 (2023), p. 2200297. DOI: https://doi.org/10.1002/srin.202200297. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/srin.202200297. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/srin.202200297.

[17] SNAM-Terna. *Documento di Descrizione degli Scenari 2024*. https://download.terna.it/terna/Documento_Descrizione_Scenari_2024_8dce2430d44d101.pdf. Accessed: 2025-05-30. 2024.

[18] Terna. *Rapporto Mensile sul Sistema Elettrico, Dicembre 2024*. https://download.terna.it/terna/Rapporto_Mensile_Dicembre_24_8dd358635ce3ac2.pdf. Accessed: 2025-06-05. 2025.

[19] ISPRA. *Fattori di emissione per la produzione ed il consumo di energia elettrica in Italia*. https://emissioni.sina.isprambiente.it/fattori-di-emissione-produzione-consumo-energia-elettrica/. Accessed: 2025-06-05. 2025.

[20] Sacha Alberici, Wouter Grimme, and Gemma Toop. *Biomethane production potentials in the EU - A Gas for Climate report*. https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_Biomethane-potentials_2022.pdf. Accessed: 2025-06-05. 2022.

[21] Michel Noussan et al. "The potential role of biomethane for the decarbonization of transport: An analysis of 2030 scenarios in Italy". In: *Applied Energy* 355 (2024), p. 122322. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2023.122322. URL: https://www.sciencedirect.com/science/article/pii/S0306261923016860.

[22] International Energy Agency. *Life cycle Upstream Emission Factors, 2023 (Pilot Edition) - Database documentation*. https://iea.blob.core.windows.net/assets/69b838f4-12ad-4f51-9155-9da6435b5d53/IEA_UpstreamLifeCycleEmissionFactors_Documentation.pdf. Accessed: 2025-05-30. 2023.