Technologies and challenges for sustainable steel production: an overview

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Abstract: The steel sector, being one of the most environmentally polluting, will have to radically renew itself in the next years in order to meet the European climate and energy targets defined within the Paris Agreement. The traditional production method, based on the blast furnace, is the most widespread in the world but also the most polluting. In recent years, new unconventional technologies that make it possible to produce steel with limited or no Greenhouse Gas emissions have been developed. However, the application of these alternative sustainable technologies is hampered by technical, economical, organisational and regulatory barriers.

Nowadays, there is no clear defined business path for steelmakers to limit their environmental impact, especially because the transition from the traditional technologies to green ones involves large investments. Moreover, companies struggle in identifying most promising technologies from a systemic economic, social, and geographical perspective, as certain solutions seem suitable for some but not for others, given the different availability of energy resources, raw materials, and financing. For these reasons, steel producers are in a situation of great uncertainty, not even receiving specific direction from policymakers, who could provide helpful guidance with a better organised framework of incentives and constraints.

The aim of this article is to provide an overview of the most recent available technologies for the sustainable production of steel, presenting the advantages and disadvantages of each, based on a critical review of the extant literature. This research aims at supporting companies from a managerial and strategic point of view in understanding the conditions under which it is more economically, geographically, and socially advantageous to adopt these technologies for producing green steel, outlining at the same time the most common barriers.

Keywords: Steel; Steelmaking; Green steel; Decarbonisation; Sustainable production

I. INTRODUCTION

Steel is one of the most important materials in modern society but, at the same time, steelmaking is one of the most greenhouse gases emitting production processes. Indeed, currently, the steel industry is responsible for about 7% of all anthropogenic CO_2 emissions and steel production is predicted to grow by 25–30% [1]. Given that, there is a clear need to adopt new production methods with lower environmental impact.

The Paris Agreement defined a new climate strategy that lays the foundations for the future, recognising in particular the need to limit global warming to well below 2, preferably to 1.5 degrees Celsius compared to pre-industrial levels [2]. For this to be achieved, it is necessary to invest in production methods that limit greenhouse gas emissions.

In recent years, a number of methods are being developed to produce steel while reducing CO_2 emissions. The application of these technologies, however, faces several challenges that need to be overcome. The main issue nowadays is that these technologies are not competitive on the market, since the currently adopted, well consolidated traditional steel production methods are cheaper than the more advanced sustainable ones. It is therefore necessary to create an economically-sustainable steel value chain, triggered by an increased demand for green steel (i.e., steel produced with low emissions).

The aim of this article is to provide an overview of the most promising available technologies to produce steel and green steel through a critical literature review, in order to understand whether there are conditions under which the implementation of some technologies is less hindered than the application of others. This should lay the groundwork for a deeper understanding about the main barriers that still prevent from the adoption of these technologies, in order to provide steel companies with a clearer perspective to support the transition of the steel sector towards more sustainable production paradigms.

The manuscript is organised as follows: the two most common methods for steel production are described in

Section 2, followed by the methodology adopted during the research that is presented in Section 3. Section 4 deals with the main decarbonisation method for steel production encountered in the corpus of articles which are then discussed in Section 5. Conclusion and future work are addressed in the last Section.

II. ROUTES FOR STEEL PRODUCTION

In this section, the most common methods for steel production are briefly outlined and a comparison between them is made in terms of diffusion and CO_2 emissions is reported.

A. The two main steel production methods

To date, the most common processes for steel production are:

- The Blast Furnace (BF) - Basic Oxygen Furnace (BOF) route ('integrated route') by which steel is produced from iron ore.
- The scrap - Electric Arc Furnace (EAF) route ('secondary route'), by which steel is produced from the recycling of scrap.

The integrated route consists in the production of steel from coke and sinter which, together with pellets and lump ore, are loaded into the upper part of the Blast Furnace, while, from the lower part, hot air is blown. Pulverised coal is also injected into the BF which, reacting with the hot air and coke, leads to the formation of CO, a reducing gas that allows the reduction of iron oxide, thus extracting oxygen from the iron ore. Due to the high temperatures reached inside the furnace the iron ore melts, resulting in hot metal together with slag. After being purified the hot metal obtained is then fed into the BOF together with a share of selected steel scrap. Here, limestone and other fluxes are added, oxygen is injected, and molten steel is produced [3].

On the other hand, the secondary route consists in melting the scrap in an electric furnace by running an electric current through it, often together with a small amount of natural gas or coal to form a protective foam of slag [4].

B. Comparison between the two main production methods

With both the production methods presented, steel production involves a share of direct emissions, associated with the production process, and a share of indirect emissions resulting from electricity and imported heat generation.

In particular, producing a tonne of crude steel via the integrated route directly emits around 1.2 t CO_2 and indirectly emits, on average, 1.0 t CO_2 at the BF - BOF stages, when coal injection is used (as happens in most cases). Scrap-based EAF production, on the other hand, results in only about 0.04 t CO_2/t of crude steel produced on a direct emissions basis and 0.3 t CO_2/t in indirect emissions [4].

Thus, while the integrated route has an impact on the environment mainly through direct emissions, the CO_2 produced by EAF depends mainly on indirect emissions, which themselves depend on the CO_2 intensity of electricity generation.

It would therefore seem clear that, in the perspective of a necessary reduction of greenhouse gas emissions, the most promising route should be the electric furnace one.

However, if we focus on global production worldwide, today this is mainly done by the BF/BOF process (72%), while only a minor part (28%) is produced by recycling scrap [5].

Table 1 reports data about steel production divided by production method and country. It shows the thousand metric tonnes of material produced and the percentage of the total in the specific country.

TABLE I
CRUDE STEEL PRODUCTION BY PROCESS

	BF/BOF		SCRAP/EAF		OTHER		TOT
	Mt	**%**	**Mt**	**%**	**Mt**	**%**	**Mt**
World	1341	72	523	28	10	0,5	1874
Asia	1093	81	252	19	3	0,2	1348
European Union	92	59	64	41			157
North America	39	32	81	68			120
C.I.S.	65	65	29	29	6	6	100
Middle East	2,5	6	42	94			44
South America	28	67	13	32	0,5	1	41
Other Europe	13,5	34,5	25,5	65,5			39
Africa	4	23	13	77			17
Oceania	4,5	76	1,5	24			6

The inequality between the integrated route and all the other technologies can be attributed to a wide number of factors, including for example a lock-in effect which stems from long investments in fossil-based technology [6] and the fact that many alternative technologies to the BF-BOF have not yet reached sufficient technological maturity, since most of them have not yet been tested on an industrial scale [7].

In particular, among the most recently developed alternatives, technologies and methods for producing green steel, i.e., limiting the CO_2 emissions, have been studied. Nevertheless, these methods are far from fully replacing traditional methods since several barriers currently prevent companies in their adoption. Moreover, scientific literature lacks contributions highlighting in a systematic way the potentials of these new technologies and claims for research studies in the field. To partially overcome this gap and to highlight why the integrated route is still so widely used, in the remainder of the paper a review of the technologies and methods for green steel production will be discussed.

III. METHODOLOGY

To provide an overview of the main technologies for green steel production and to give an idea of the barriers related to their application, we decided to adopt a critical review. The peculiarity of this method is that it goes beyond a mere description of the identified articles by including a degree of analysis in the study [8]. Given that there are already several roadmaps and projects exploring the different technologies in detail, the purpose of this research is not only to limit to a technical description of the green steel processes, but to perform a critical analysis able to identify the challenges and the barriers related to each of them, in order to understand whether there are similarities, recurrences or specificities.

The selection of articles used to perform the critical review was made using major publishers' databases and library services such as Scopus, Elsevier (i.e., Sciencedirect), Emerald and Springer. A set of keywords related to steel production and decarbonisation of the steel sector was first defined. These include, for example: "green steel", "steel production", "steel recycling".

Only articles written in English and published from 2017 to 2021 have been selected, in order to have a focused view on the most recent years, also considering that, the obstacles that might have existed a few years ago, are probably different from those of the last period.

Starting from a base of about 400 articles, after analysing the titles and abstracts, a group of approximately 100 was assessed to be relevant to the research. After reading them, 31 papers were selected to finally depict the overview of the sustainable methods for steel production, also highlighting the barriers related to them, either with regard to a specific technology, or more than one.

The list of all the articles considered is not reported in the text since it was considered more relevant to put the emphasis on critically reviewing the conceptual contribution of each research study of included literature, not on formal quality assessment, as suggested by Grant and Booth (2009) concerning the critical review methodology.

IV. MAIN DECARBONISATION METHODS

From the selected articles, it was possible to identify which decarbonisation methods in the steel sector are most widely discussed in the scientific literature, to understand the advantages and disadvantages of each and to point out what might be the main obstacles that are preventing the total replacement of the integrated route.

As shown in Figure 1, four methods mainly emerged. The graph also shows the number of articles dealing with each technology. Analysing the publication trend, there is a growing number of publications in the last three years.

It should be noted that some articles cover more than one technology, which is why these are counted in more than one category.

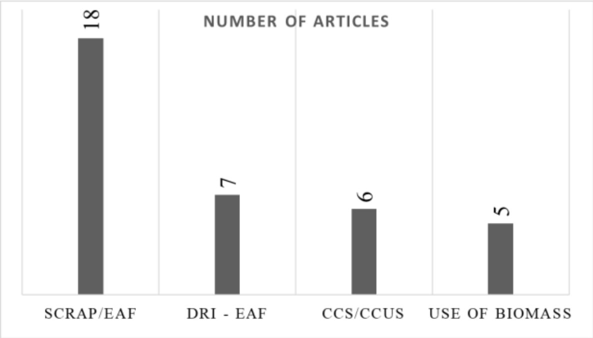

Fig. 1. Decarbonisation methods covered in the paper corpus

A. *Scrap - EAF*

As presented in Figure 1, the decarbonisation method most frequently discussed in the selected literature is the recycling of scrap in the EAF, i.e., the secondary route.

As mentioned in Section 2, this technology is already well established on the market and allows a large reduction in emissions compared to the integrated route, given that the GreenHouse Gas (GHG) intensity of the scrap-EAF route is mainly indirect, i.e., it depends on the amount of CO_2 emitted for the production of the electricity involved in the process. For this reason, this process can be GHG-free if supplied with decarbonized electricity [9].

However, the secondary route cannot be the only solution to the decarbonisation of the steel sector for a number of reasons that emerge from the articles analysed. The main motivation, which is mentioned in 14 of the articles considered (e.g. [10], [11], [12]) is that this production method, operating through scrap recycling, allows a maximum degree of purity of the steel on the output strictly linked to the quality of the scrap fed into the EAF. On the contrary, production through the primary route, requiring iron ore as an input, allows a very high degree of purity that can be obtained [13].

Since high-quality scrap is not always available, the secondary route would not be able to answer the whole demand for the high-purity (and therefore high-quality) material, thus always requiring a share of primary steel to obtain it. Moreover, with a 100% Scrap - EAF production, the concentration of tramp elements in the scrap increases with each recycling cycle, so that a system based solely on this method would lead to highly contaminated steel [11].

Another aspect of this same problem is that the chemical composition of scrap is not easy to monitor or predict, as it often comes from different sources [14].

For these reasons, this process seems to be more convenient to produce low quality steel, as for example structural steel, that does not need high alloy purity compared to other products such as automotive products or electrical equipment which are more sensitive to a reduced secondary steel quality through contamination [15].

On the other hand, in countries such as Europe, where there is a high demand for products less tolerant to tramp elements (e.g., flat steel), it could be useful to improve the sorting of the scraps where possible, in order to obtain a better quality on the output [16], which, however, is often complicated.

B. DRI (Direct Reduction of Iron) - EAF

Ironmaking with DRI (Direct Reduced Iron) method consists in reducing iron ore removing oxygen from iron by a chemical reaction with a hot reducing gas. The hot DRI can either be fed right to the EAF or be compacted as Hot Briquetted Iron (HBI), which allows better storage and transportation. The DRI or HBI is then fed into an EAF, to obtain liquid steel from solid iron. Scrap may still be added to improve the operational performance of the EAF [17]. The potential of this technology, which is already available on an industrial scale, is that it makes it possible to use natural gas as a reducing gas in a first stage, and then to switch to hydrogen (having Hydrogen based Direct Reduced Iron, H-DRI) once it will be available in sufficient quantities.

Given that iron ore remains solid throughout the DRI-production process, making it difficult to remove impurities, the DRI quality is closely related to the quality of iron ore inputs [18]. In the steelmaking phase, DRI–EAF method allows to decide on the amount of scrap to be fed together with DRI in the electric furnace, as in the case of the integrated route. For these reasons, if high quality iron ore is used and low quantities of scrap are included, it is possible to achieve high quality material with this production method, as opposed to secondary production which, as mentioned, is strongly influenced by the quality of the scrap.

As well as the secondary route, when hydrogen is used as a reducing gas, this production method has CO_2 emissions that mainly depend on the power grid emission intensity, implying that a switch from the BF/BOF route to H-DRI would reduce emissions in most of Europe today, given the averagely low grid emission intensities [19].

An example of the application of this technology, which uses hydrogen as a reducing gas, is HYBRIT, a project born from the collaboration of SSAB, LKAB and Vattenfall, three Swedish companies specialized respectively in processing raw material to steel, mining iron ore and producing electricity. The production site resulting from this collaboration does not use fossil fuels for pellet production and produces hydrogen with electrolysis through fossil-free electricity. The only direct fossil carbon load comes from the consumption of graphite electrodes and from carbon added in the EAF melt shop [20].

C. Carbon Capture Use and/or Storage (CCUS)

In contrast to the previous method, which fits into the category of Carbon Direct Avoidance (CDA), as it aims to avoid the formation of CO_2 during the production process, Carbon Capture Storage (CCS) or Carbon Capture Use (CCU) methods fall into the category of Process Integration (PI), since they only have the objective of limiting CO_2 emissions, without rethinking the method of steel production.

Value chains that may involve use and/or storage of CO_2 in various combinations are often referred to as "CCUS" (Carbon Capture Use and/or Storage).

Specifically, CCS consists of the capture, compression, and long-term storage of CO_2 underground. Considering that the storage of CO_2 typically has no commercial value, CCS generally has the sole objective of climate change mitigation [21].

CCU, on the other hand, is a method that allows to capture and utilize the CO_2 by converting it into products of commercial value e.g., for the chemical industry [22]. The use of CO_2 can thus be seen as a means to improve the financial viability of conventional CCS projects.

One of the main advantages of CCUS is that it can be used in conjunction with other decarbonisation technologies [4]. This allows the possibility of a smoother transition towards decarbonisation as it makes it possible to invest deferred over time.

On the other hand, one of the main difficulties connected with this technology is the high costs and energy required for CO_2 capture and compression. The higher energy demand could result in higher fuel combustion, which would increase fine particulate matter ($PM_{2.5}$) and nitrogen oxide (NO_x) emissions. Ammonia (NH_3) emissions could also more than triple due to the use of amine-based absorbers for CO_2 capture [9].

Despite having the potential to substantially reduce CO_2 emissions in many industrial sectors, the application of this decarbonisation method, to date, is mostly limited to the power sector. The main reason for this is the lack of a convincing business model in which economic revenues, funding sources, asset ownership and risk management are conveniently shared among the stakeholders. [21].

An example of an application of this decarbonisation method in the steel sector is ENERGIRON, which combines direct reduction with CO_2 capture. In this technology the selective elimination of CO_2 though chemical absorption is highly efficient and low energy consuming due to the high operation pressure [23].

D. *Use of biomass*

Another useful process integration method to reduce CO_2 emissions discussed in the selected articles is the use of biomass.

Regarding the application in EAF, biomass can be used as a partial or total substitution of coal and natural gas with charcoal and biogas produced from pyrolysis of biomass. The char is used as injectable powder or charged in the basket [24].

When applied in the integrated route, biomass can replace a part of coal in the coking ovens, substitute at least half of the solid fuel used in the sinter plant mix or used in the BF as a substitute of pulverised coal [25].

Since the assumption that charcoal consumption produces net-zero emissions is only possible if planted timber is used [26], one of the main concerns connected with this production method is the need for large areas of cultivable land in the vicinity of the production area: for example, producing 500 tons of hot metal using bio-coke requires over 400 km^2 [27].

Moreover, since it is not economically convenient to transport the harvested woody material over long distances, the introduction of a new large wood consumer is likely to have a strong impact on the regional level by increasing local woody feedstock prices [28].

However, the most important issue resulting from this decarbonization method is the economic one since the purchase of fossil fuels remains cheaper than the use of alternative feedstock. An increase in carbon taxes and a decrease in biochar production costs would be definitely needed to improve the situation [29].

Reviewing the literature, it has been possible to find that a number of studies based on the use of this decarbonisation method have been conducted in recent years, including the Short Term CO_2 Mitigation for Steelmaking (SHOCOM), a project in the frame of the European Research Fund for Coal and Steel (RFCS), which demonstrated that replacement of part of top-charged coke with charcoal reduces CO_2 emissions from the BF by 9-12%, resulting in more CO_2 savings compared to using biomass in the coke oven [30]. Moreover, the GREENEAF, which is also a RFCS project, demonstrated the feasibility of using char from biomass as a substitute of coal into the EAF [24].

V. DISCUSSION

In the previous Section, the main decarbonisation technologies covered in the corpus of articles were briefly described with the aim of clarifying their features and outlining some challenges that are not allowing their development on a large scale to understand how to overcome them.

It should be noted that this review of technologies is not intended to be exhaustive, as there are also other methods to decarbonise steel production that are discussed in technical reports but are not particularly covered in the scientific literature, probably due to the still relatively low Technology Readiness Level (TRL) or for low diffusion, as for example alkaline iron electrolysis or molten oxide electrolysis [4].

For each of the technologies presented in this article, some of the main barriers or challenges have also been identified. They are summarised in Table II.

TABLE II
SUMMARY OF THE MAIN BARRIERS FOUND DIVIDED BY TECHNOLOGY

TECHNOLOGIES			
SCRAP - EAF	**DRI - EAF**	**CCUS**	**Biomass**
Not all steel grades can be produced [10]	Need for reducing gas (e.g., green hydrogen) [31]	High operative costs (capture and compression) [21]	Need for large areas of arable land nearby [26]
Need for high quality input materials (improvement in sorting of scrap) [16]	Need for high quality iron ore (pellets) [13]	Environmental risk (leakage during transport and storage) [32]	Impact on local woody feedstock prices [28]
Need for low CO_2 emission electricity [9]	Need for low CO_2 emission electricity [9]	Emission of other pollutants (e.g., NH_3) [9]	
Risk of downcycling high valuable materials [33]	Need for hydrogen transport and storage infrastructure [34]	Need for CO_2 transport and storage infrastructure [32]	
		Lack of a convincing business model [21]	

Concerning the technologies that employ scraps, some aspects have already been discussed about the need for more electrical energy (in medium – long term renewable energy) and the variable grade of steel produced in the EAF, depending on scrap quality. In addition, another matter in which it is easy to incur with this production method is the downcycling: when valuable alloying elements end up in steel products where they are unessential, they cause economic and environmental harm (Compañero et al., 2021). Therefore, the technologies for sorting and cleaning of scrap need to be improved.

Hence, it could be concluded that the main problem with scrap recycling is related to the quality of the input and output materials: despite being a very relevant issue, currently it does not significantly hamper the application of this technology, which is why the EAF is already quite widespread.

Since high quality steel is often required and the scarp availability will not cover the full demand of steel, technologies such as H-DRI or CCUS will be needed, also used complementarily, to produce steel from virgin iron. As in the case of scrap recycling, their application also requires more electricity compared to the integrated route, in one case for the compression of CO_2 and in the other for the production of hydrogen through electrolysis if it is decided to produce it on site.

It is therefore clear that the availability of renewable energy will be a key in the transition to decarbonization of the steel sector, whatever technology is chosen.

On the other hand, the application of H-DRI and CCUS, besides the need for high quality input materials in the case of H-DRI [35] and environmental risks in the case of CCUS [32], also need for additional infrastructure, for the transport and storage of hydrogen in one case, and for CO_2 in the other.

For this type of technologies, a significant role is played by policymakers, which can promote these projects with funding and incentives, or they can hinder them, as in the case of CCS, which is not legally allowed in some countries due to social concerns [22].

Another aspect for which policymakers are likely to be key players through the setting of incentives is the deployment of greater market demand for green steel which will be crucial for the diffusion of these new technologies [36].

Finally, the development of new business models which imply the offering of a bundle of green technologies and services by steel solutions providers could also help to stimulate the demand for green steel. In this sense, however, the whole supply chain should be considered, which would be different for each technology (e.g., hydrogen supply chain for H-DRI, scrap collection and sorting supply chain for secondary production, etc.).

Indeed, for the development of the discussed technologies, which involve many different stakeholders, it is essential to find favourable conditions throughout the whole supply chain and the local industrial ecosystem. The HYBRIT project, discussed in Section 4, is a good example of this: Sweden has a unique situation with overcapacity in electrical power in the northern part of the country, vicinity to iron ore mines, good access to biomass and steelworks, and a strong network between industry, research institutes, and universities [20]. All these conditions allowed this project to find fertile ground for the H-DRI application, but this same technology would probably have had less success elsewhere.

As pointed out throughout the article, for the implementation of each technology, difficulties of a different nature are encountered. It is therefore likely that in the future steelmakers will choose different decarbonisation methods depending on the environmental, social and economic conditions of their specific case, according to the barriers presented above. The clearest example of this is the use of biomass, which, requiring proximity to large amounts of arable land, can certainly not be applied everywhere, demonstrating that certain barriers might be difficult to overcome for some, but less for others.

In general terms, a smooth change which might be suitable for companies that want to switch from primary route to a greener technology, could be to adoption of DRI in a first phase, which could compete, together with existing BF, for iron production. Once sufficient capacity is obtained to fully switch to the DRI, BF could be eliminated. In a second phase, BOF could be replaced with EAF to fully switch to the H2-based DRI method. Then, the adoption of green electricity could allow to further reduce the environmental impact of the plant.

VI. CONCLUSION

In order to meet the Paris Agreement's demands, it is necessary that the steel sector embark on a path towards reducing its greenhouse gas emissions.

This review has shown that there is not only one possible route to decarbonisation for steelmaking, but that each route has different requirements that need to be covered for the application of the specific technology. The analysis shows that one technology may be preferred to another depending on geographical location, the possibility of building infrastructure, the availability and the cost of raw materials, the local regulations, the resulting operating costs or the quality of the output materials requested from the market.

As mentioned above, this article is only an overview of the main decarbonisation technologies in which the main barriers related to each of those technologies have been briefly discussed. To make the study more comprehensive, further research could concern the systematic investigation of these barriers, not limiting to those that relate purely to the technologies.

Starting from this base, it would be possible to come up with strategies to overcome these barriers, such as the development of new business models. This, would be capable of providing the definition of a portfolio of services and product-service solutions with a high innovative content that technology suppliers can offer to steelmakers. Thanks to this, new technologies for green steel production should be more competitive on the market.

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