GREEN HYDROGEN FOR A CLEAN STEEL INDUSTRY?
Part 2

By Ir Bernard MAIRY, S.E.I.I. Executive Director and member of AIST & AIST-DRI Committee (USA), of VDEh Stahl Institut (DE) and of BNS (BE)

1. Preamble

This second part of the article *'Green Hydrogen for a clean steel industry?'* is the follow-up of the first part, which was first published in the SEII Newsletter on September 14, 2021. However, please note that this first part was then inadvertently not completely displayed, as the main arguments developed in para 6, as well as the title of para 7 and the numbering of references were missing. In the meantime, these missing items have been duly integrated as you will have seen in the SEII Newsletter of March-April 2022 (the corrected version can also be found on the Communications/Publications page of the SEII website (www.seii.org)).

Therefore, it would be highly recommended to the interested people to have read the correct part 1, in particular this missing essential para 6, in order to get a fairly good understanding of the core subject developed in this second part. We do apologize for the inconvenience.

2. Why a second article on the same subject?

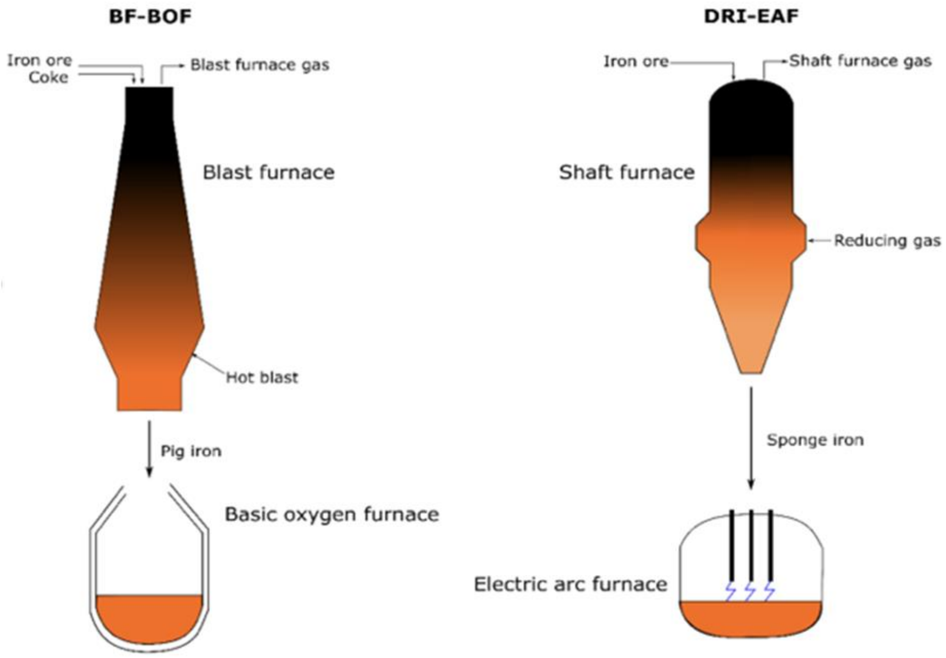
The reasons for issuing a second article on the same subject are the following:

- The question addressed to the steel industry is a very complex and vast challenge, which cannot be answered without elaborate and long considerations.
- Several new industrial DRI projects have been decided during the last few months (please refer to route **c** as per part 1).
- Since last September, a very elaborated and detailed exploratory technical paper has been presented on the subject by the first worldwide steel leader during the last AIST Conference in Nashville (USA) (16)(17).
- Several interesting communications from the main American and German steel companies have been reported by specialized steel magazines published by AIST and Stahl & Eisen (18)(19)(20).

3. Recent paper published by the first worldwide steel leader

3.1. The Howe Memorial lecture presented at the last AIST Steel Conference (16) analyses in depth challenges and opportunities to convert the steel industry towards carbon neutrality by 2050. The main possible technological steps are described and quantified as well as the constraints to achieve such a goal, by considering a certain number of assumptions, in particular with regard to green hydrogen, in terms of production, storage and distribution to the steel plants.

3.2. Its main conclusions can be summarized as follows: the carbon direct avoidance (CDA) technologies using green hydrogen instead of natural gas for the route **c** (DRI/EAF) should be further developed because of the major beneficial impact to be expected for reducing CO_2 emissions. Actually, based on current experiences and taking into account metallurgical constraints, for both the existing BF/BOF plants and the DRI gas plants, at least 25 kg H_2/ton of steel could replace coal and natural gas. In addition, a 'smart carbon'approach, wider than the SCU technologies (which cover CCS and CCU), should be based on a flexible combination of carbon and hydrogen inputs, from renewable sources and from waste resources as well as on the production of highly valuable chemicals with CCU (carbon capture and use), CCE (carbon capture and export) and BECCS (bioenergy CCS).



The 2 main production pathways to produce iron and steel (16)

3.3. It would be a much too long exercise to overview in further details this multi-solutions exhaustive approach. However, like in the German paper referred to in part 1, this paper underlines the technical feasibility and the limits of using green hydrogen as reductant instead of natural gas for the DRI process (route '**c**') and instead of carbon (coke – in a limited range) for the blast furnace (BF) process (route '**a**'). The impacts of such a technological transition on CO_2 emissions, as well as on costs (CAPEX and OPEX), are also evaluated.

3.4. Although both papers are coherent for the major aspects, they do not necessarily converge towards similar calculation or estimation results. Indeed, they do not start from the same assumptions for several variables or unknown values and they do not consider the same scenarii in terms of steel tonnage coverage and distribution of processes between route '**a**' (BF/BOF), route '**b**' (EAF/Scraps) and route '**c**' (DRI/EAF) as shown hereafter:

- For a 160 million tons/year of steel production on a **European scale** and after conversion to green hydrogen with the consumption of 11.7 million tons/year, on the basis of 37.1 kWh/kg hydrogen, the required electrical supply would be 434 TWh/year (see para 6.3 in part 1). This scenario would allow achieving a CO_2 abatement of 166 million tons/year down to 5.7 million tons/year.

- For a 1.38 billion tons/year of steel production on a **worldwide scale** and after potential consumption of 34.5 million tons of green hydrogen/year in existing BF and DRI plants – on the basis of 25 kg hydrogen/ton crude steel and of 50 kWh/kg hydrogen – the required electrical supply would be 1,725 TWh/year. This scenario would allow achieving a CO_2 abatement of 402 million/year from almost 2.2 billion tons/year.

- Whereas for 1.38 billion tons/year of steel production on a **worldwide scale** and after full conversion to green hydrogen with a total consumption of 115.9 million tons/year, the required electrical supply would be 5,796 TWh/year. This scenario would allow achieving a CO_2 abatement of 1,782 million tons/year from almost 2.2 billion tons/year. Actually, another electrical supply of 1,656 TWh/year is needed to operate the EAF's, the DRI's facilities, and downwards the rolling & finishing lines. The total electrical supply amount would be 5,796 + 1,656 = 7,452 TWh/year (16).

3.5. Consequently, as neither paper is considering the same scenarii (steel tonnage coverage and distribution of processes), it is not easy to compare them at first glance. So, 37.1 kWh/kg hydrogen is the lowest (optimistic) reference in the industry for high temperature electrolysers (> 600 °C) whereas 50 kWh/kg hydrogen is based on benchmark figures of today commercial electrolysers. However, at least both papers emphasize the highly technical challenges and underline the very high costs (CAPEX and OPEX) which should be requested to achieve such a transition towards a net-zero steelmaking.

Note: for what concerns the costs for the green hydrogen strategy, it is not clear if all related costs are actually duly levelized.

4. Recent decisions for investing in subsidised brand new DRI industrial plants

4.1 While both papers are trying to identify and to quantify the requested amounts of resources (green hydrogen, blue hydrogen, electrical power) and all associated costs in order to reach such a transition goal, several orders for brand new DRI industrial plants have been recently announced, all with substantial subsidies from the States where these will be located.

4.2. For example, in case of ArcelorMittal Ghent (BE), the new DRI steelmaking facility will have a capacity of circa 2 million tons DRI/year for a cost of around €1.1 billion including two EAF's (21). In general, the amount of public subsidy is not always clearly mentioned but could range from 25 to 50% of the investment cost. These facilities would be designed to be capable of operating with a significant amount of hydrogen as reductant (maximum still to be proven by the demo R&D plants mentioned in para 5.1. in part 1)

4.3. These projects concern several plants of ArcelorMittal such as Hamilton (CND), Hamburg (DE), Sestao (ES), Ghent (BE), Dunkerque (FR), Eisenhüttenstadt (DE) and also Essar/Algoma (CND).

5. Recent echoes from the German and the American steel industries.

5.1. In Germany, very few papers (except (1)) have been published on technical feasibility and economic affordability of such a transition based on green hydrogen. For quite a long while, most of the German steel leaders have been enthusiastic for such a transition, which would allow them to produce 'green steel' as requested by their customers.

5.2. However, according to recent press releases in the German steel magazine, the same leaders have been changing their mind and are 'throwing out incantations' towards the German and the Commission political decision-makers in order to get their financial support (for both CAPEX and OPEX) and to develop all necessary preferential regulations, while at the same time, they do not mention the huge impact that such a costly transition would have on the taxpayers. Nevertheless, in the very last issue of the German Steel magazine, according to its editorial, there could be a big change in the attitude of the German Steel Industry so as to reconsider the nuclear energy to secure a **stable** (also low cost & no CO_2 emission) and a **huge amount of electricity** needed to achieve the 2050 transition. A clear reference is even made to the Netherlands, which recently decided to build two new nuclear reactors (18).

5.3. On the contrary, the situation of the American steel industry is totally different from the European one as their steelmaking processes are based on 75% route '**c**' (EAF/Scrap) and 25% route '**a**' (BF/BOF), which is much different from the European steel industry, which is based on 40% route '**c**' (EAF/Scrap) and 60% route '**a**' (BF/BOF). Consequently, their CO_2 emissions are around 1.0 ton CO_2/ton hot metal, to be compared to 1.8 ton CO_2/ton hot metal for the European steel industry, which is a huge difference. In addition, the American approach to reduce their CO_2 emissions already includes several DRI plants (using natural gas, not hydrogen green or blue)(17).

5.4. Ironical comments have been addressed during the last AIST conference by the CEO of Cleveland-Cliffs – the #1 steel producer in America – against the unrealistic transition strategy imposed by the European Commission to the European steel industry (net-zero steelmaking in 2050) (19). Another paper (20) emphasises that when converting from BF/BOF process to H_2DRI/EAF process, a minimum amount of carbon is unavoidable – for metallurgical reasons – to melt steel scraps and the DRI products in the EAF's.

5.5 Finally, a vast scrap market that sustains the EAF/Scrap route is available in North America, which results from domestic recycling of steel products (like used cars) locally produced or from imported steel and steel-supply intensive products (17). This perfectly illustrates another significant and virtuous advantage, which is the circular economy widely already practised by the American steel industry. Indeed, it has to be reminded that recycling steel scraps in EAF's (as well as in BOF's and to some extent in BF's) is already a current practice which contributes efficiently to the circular economy and to the reduction of CO_2 emissions.

6. Tentative conclusions.

6.1. Based upon the above considerations, the net-zero steelmaking target by 2050 as imposed by the European Commission to the European steel industry appears to be an extremely difficult challenge to achieve, if not unrealistic as long as it should only rely on green hydrogen.

6.2. The first most significant solution would be the conversion of the BF/BOF route towards the DRI/EAF route by using green hydrogen (produced from renewable sources) as reductant instead of natural gas. However, this solution still has to be proven technically feasible and economically affordable. Indeed, it would require big investments in such new steelmaking facilities as well as huge amounts of renewable electricity sources to produce the huge requested volumes of green hydrogen. Indeed, a 25% CO_2 reduction of the ArcelorMittal Europe plants by 2030 would request USD 10 billion to be invested (22). This figure does not include external costs for green hydrogen production (infrastructure and transportation), nor the operating costs (green hydrogen supply and green electricity supply). Also, the costs of the ArcelorMittal Europe plants to reach carbon neutrality through such an innovative DR/EAF route would be as follows:

- 30 to €40 billion for the new steelmaking facilities.
- 40 to €200 billion for clean energy infrastructure (lower end with blue hydrogen and higher end with green hydrogen) (23).

6.3. Such a transition does not look affordable without substantial public funding, not only for implementing these new steelmaking processes, but also for building the whole infrastructure required to produce green hydrogen from renewable sources and to transport it to the steel plants. This concerns the CAPEX aspect.

6.4. Concerning the current operating costs (OPEX), advantageous market prices for green hydrogen would be mandatory through subsidies in order to support the higher operating costs related to the consumption of green hydrogen, otherwise the European steel industry would not stay competitive and could not provide affordable steel products to the market. The following question could then be raised: wouldn't the European steel industry have to switch from a private business (EU State Member contribution to the steel industry is prohibited since a long time) towards a public business?

6.5. Moreover, the huge amount of electricity and the huge volumes of green hydrogen required would not allow to convert the whole European steel industry in that direction. Indeed, for comparison purposes, as mentioned in a recent publication (24) about hydrogen as electricity vectors, even if all technologies for producing green hydrogen (electrolyse, compression, liquefaction and storage) and its conversion to **electricity** existed at power levels up to some MW, scaling up these technologies to produce, transport and distribute huge volumes of hydrogen would be limited to technical and economic reasons. The same conclusion – to our opinion – could be raised for producing, transporting and distributing green hydrogen as **reductant** for the steel industry.

6.6. The IEA's net-zero scenario by 2050 anticipates around 35 million tons hydrogen/year in the steel industry (16). This number matches the amount of 25 kg hydrogen/ton crude steel given in para 3.4. This shows that hydrogen supply in 2050 will be insufficient to completely rebuild the steelmaking facilities towards full hydrogen conversion.

6.7. All the above developed approach is based on green hydrogen from renewable sources. However, it is obvious that low cost and stable electricity from nuclear plants (conventional or new generation reactors such as SMR's) could also be supplied to advanced powerful (around 100 MW) electrolysers for water electrolysis purposes. By considering such a **nuclear-based electricity supply**, the total electrical supply amount of 7,452 TWh/year as mentioned in para 3.4 would require a total of 912 nuclear reactors (each of 1 GW, 92% load charge for 24 × 365 = 8,760 hours, each producing 8.16 TWh/year). This would be a huge move to consider. As another alternative approach for producing significant and pilotable amounts of hydrogen (25), advanced high-temperature gas-cooled nuclear reactors (HTGR) or molten salt reactors (MSR) could be envisaged in the near future[1], as already suggested in para 7.2. in part 1. We could perhaps speak here about **'nuclear hydrogen'** to avoid any confusion with hydrogen generated from electrolysers powered by electricity from renewables or from nuclear plants.

6.8. While exploring the above challenging solutions, it is already possible to envisage operating blast furnaces with a limited injection of hydrogen at a smaller scale to replace partly carbon (coke), as well as a combination of other innovative technologies like CCS, CCU, CCE and BECCS, as long as they are technically feasible and economically affordable. Therefore, thanks to such a 'smart carbon approach' combining hydrogen, electrification, waste carbon (like end-of-life plastics), CCU and CCS technologies, a net-zero steelmaking would be more realistic to reach and less expensive than the full innovative DRI route (16) (23)(26). Each could indeed contribute to 20%, could be applied in parallel and could generate some additional value (like flexibility, waste valorisation, chemical productions) to reduce the costs of the transition (17). Here, the costs of the ArcelorMittal European plants to reach carbon neutrality through such a Smart Carbon approach would be as follows:

- €15 to €25 billion for the new steelmaking facilities.
- €15 to €30 billion for clean energy infrastructure (leveraging mainly bioenergy and CCS; this range could be much higher if green hydrogen was fully leveraged) (23).

[1] The researchers of the ISPRA Common Research Centre of the European Commission have considered that the production of hydrogen from water can only be economical by thermally slitting the water molecule and not by electrolysis, and this can be done precisely with these new type of nuclear reactors (1), nowadays called AHS (Advanced Heat Systems) by INL.

7. Perspectives

7.1. Besides the steel industry, other energy-intensive heavy industries also have to face the challenge of reducing their CO_2 emissions. It is the case for the cement and the glass industries, which represents, together with the steel industry, more than 18% of the total 25% emissions usually attributed to the industry (excluding the petrochemical industry).

7.2. It has to be noted that the coupling of the chemical sector (plastic and organic waste) with the steel sector in a circular economy is a huge opportunity for the reduction of CO_2 emissions.

7.3. If the SEII readers are interested, we could consider other newsletters respectively dedicated to the cement, the chemical and the glass industries.

7.4. Then, after publication of such newsletters as introduction materials, we could organise a set of lunch-conferences (or evening conferences), each presentation being dedicated to one of these energy-intensive industries and each given by an expert in the matter.

References:

(1) Dr-Ir Samuel FURFARI: The Hydrogen Utopia
(2) Proceedings IEEE Oct.2006, p1835, Ulf BOSSEL
(3) Alisha GIGLIO, HATCH, AIST March 2021 Recent Sustainability Development in the Iron and Steel Industry
(4) World Crude Steel production – Industry Statistics. AIST March 2021
(5) Tksteel, Stahl& Eisen Jan+Feb/2021, Erste Direktreduktionanlage mit Einschmelzer
(6) Dr-Ing Hans-Bodo LUNGEN, Stahlinstitut VDEh, private communication
(7) MIDREX : private communication
(8) Dr-Ing Hans-Bodo LUNGEN, Stahlinstitut VDEh,Schlüsselwege zur CO_2-Minderung der Stahlindustrie, Stahl+Eisen, March 2021
(9) EUROFER EU-28 Steel Statistics & Decarbonation Industrial Projects: website
(10) IEA International Energy Agency, 2019 Hydrogen Report
(11) Peter MARCUS & John VILLA, Strategic Insights from WSD, AIST Issue of July 2021
(12) ArcelorMittal press release July 29, 2021
(13) UK Energy System Modelling: Net Zero 2050. National Nuclear Laboratory 2021
(14) Ch.HEINE, Revue ELECTRICITE, n°164, June 1977
(15) CEA e-den, Energie nucléaire du futur : quelles recherches pour quels objectifs ? November 2005
(16) Carl De MARE, Howe Memorial Lecture, AIST Issue of September 2021
(17) Carl De MARE, private communication
(18) Stahl & Eisen March thru November/2021, various press releases from the German steel producers
(19) Lorenzo GONZALVES, Cleveland-Cliffs Inc, AIST Issue of September 2021
(20) Sara A. HORNBY, GSB USA, Hydrogen-Based DRI EAF Steelmaking: Fact or Fiction?
(21) ArcelorMittal Ghent, 'STAAL in je buurt', December 2021
(22) ArcelorMittal website, Second Group Climate Action Report, July 29, 2021
(23) Carl De MARE, AIST European Forum, October 14, 2020
(24) Manfred WANNER, MPI Max Planck Institut, Plasma physik , The European Physical Journal Plus, May , 28, 2021
(25) Molten Salt Reactors and Thorium Energy. Direction Thomas J.DOLAN. Woodhead Publishing Series in Energy . Elsevier 2021.

(26) SMART: Steelmaking with Alternative Reductants, Steel Orbis, February 25, 2022