GREEN HYDROGEN FOR A CLEAN STEEL INDUSTRY?
Part 1

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1. Green Hydrogen, a new star for the Steel Industry?

1.1. Since the end of 2019/early 2020, the so-called green hydrogen has become a new star in the ongoing debate for the decarbonation objectives. This debate mainly concerns electricity production, transportation and more recently energy-intensive industries. Green hydrogen is generated from renewable-based electricity and water electrolysers, whereas grey hydrogen refers to conventional steam methane reforming without the capture of the CO_2 produced, and blue hydrogen with partial or total CO_2 capture; these last two items are not considered in this paper.

For electricity production, a surprising enthusiasm for green hydrogen has been rapidly growing to further develop renewable energy sources (wind, solar), but also to compensate for their inevitable intermittency. However, controversy from several energy experts has appeared to oppose the very poor technical efficiency – 28% resulting from: 0.80 (electrolyser) x 0.70 (compression + transportation + storage) x 0.50 (fuel cell) = 0.28 for renewable-based H_2) – and the challenge of high-power water electrolysers, as well as the anticipated high costs of such a new type of electricity production (1)(2).

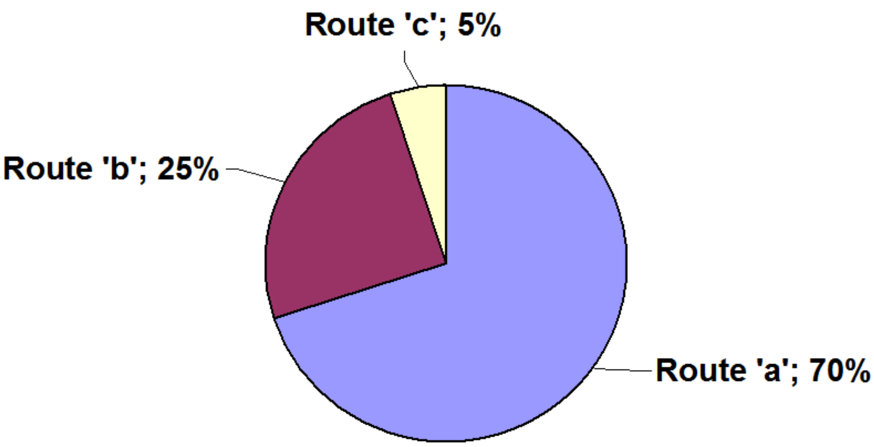
1.2. The present paper is dealing with the possible use of green hydrogen in the steel industry, one of the most energy-intensive heavy industries, actually not as an energy vector but as an alternative reductant. This would go towards substantially reducing CO_2 emissions, specifically in the upstream iron – and steelmaking processes (the downstream processes like rolling and finishing are not considered hereafter).

2. The Steel Industry, a big player

As a preliminary to appraise the importance of the steel industry, some typical specific figures have to be recapped (3)(4):

- At the end of 2020, the total world crude steel (CS) production was close to 1.9 billion metric tons/y.
- The world steel production is responsible for 7 to 8% of the global CO_2 emissions, i.e. around 2.6 billion tons CO_2/y.

- The upstream iron and steel productions are mainly based on **three routes** (the percentages are worldwide; see also figure below):
  - **a.** Integrated route: Blast-Furnace (BF)+Basic-Oxygen Furnace (BOF) = **70%**
  - **b.** Scrap-based Electric Arc-Furnace (EAF) = **25%**
  - **c.** Direct reduction of Iron Ore (DRI) + Electric Arc-Furnace (EAF) = **5%**



3. Green Hydrogen to replace Carbon as Reductant?

3.1. The use of green hydrogen as reductant would concern routes '**a'** and '**c'** (route '**b'** is disregarded as being a melting process and therefore will not be further discussed). For routes '**a'** and '**c'**, the following simplified chemical reactions are prevailing (5)(6):

- Route '**a'** (BF+BOF) based on coke (distilled coal) and mostly injected coal as reductant:

  In short, then in more details:

  $Fe_2O_3 + 3CO \Rightarrow 2Fe + 3CO_2$

  $Fe_2O_3 + 3C \Rightarrow 2Fe + 3CO$

  Indirect reduction in BF:

  $3\ Fe_2O_3 + CO \Rightarrow 2\ Fe_3O_4 + CO_2$

  $2\ Fe_3O_4 + 2\ CO \Rightarrow 6\ FeO + 2\ CO_2$

  $6\ FeO + 6\ CO \Rightarrow 6\ Fe + 6\ CO_2$

  Direct reduction in BF:

  $FeO + CO \Rightarrow Fe + CO_2$

  $CO_2 + C \Rightarrow 2\ CO$

  $FeO + C \Rightarrow Fe + CO$

Note: actually, from top to bottom of the BF, successive reductions from Fe_2O_3 to Fe_3O_4 and FeO and then to Fe are taking place thanks to CO generated by coke and coal combustion.

- Route '**c**' (DRI) is currently based on methane (CH_4) as reductant (5)(6):

  $Fe_2O_3 + 3/4\ CH_4 \Rightarrow 2\ Fe + 3/4\ CO_2 + 3/2\ H_2O$

3.2. For route '**a**' (BF), the use of hydrogen to replace carbon as reductant would be rather limited to a few % H_2 in the natural gas (up to an estimated 30–35 kg H_2/t hot metal) injected in the tuyeres (mostly to control raceway adiabatic flame temperature (RAFT) and to control H_2 content in top gas; the coke rate of a BF is much lower in the operating mode with coal injection than that with natural gas, coke oven gas or oil injection) (6). Basically, coke has to support the massive burden of loaded materials like iron ore lumps, sinter lumps, pellets and coke (bell coke and nut coke) all over the whole height of the furnace body as well as to allow, of course, the above-mentioned solid-gas chemical reactions.

Whereas for route '**c**' (DRI), hydrogen could technically replace up to 100% (for metallurgical reasons; however, a bit less than 100% should be appropriate to avoid impacting the slag behaviour in EAF) on the basis of the following chemical reaction (5):

$$Fe_2O_3 + 3H_2 \Rightarrow 2\ Fe + 3H_2O$$

Such a reaction would take place at a very high temperature (above 1,000 °C) in a vertical shaft furnace charged with iron ore green pellets or lump ores (7). However, full H_2 DRI production would require 84 kg H_2/t steel, both for reduction and for heating purposes.

3.3 By comparing both above routes, it appears that the DRI route would offer more potential for the use of hydrogen as reductant than the BF route. Besides, the DRI route with hydrogen would match the so-called CDA technological EU objective (CDA stands for *Carbon Direct Avoidance*), which will introduce the next considerations.

4. The EU Decarbonation Challenge imposed to the Steel Industry

As the EU Commission has decided to take the lead in the decarbonation challenge (although the EU only represents around 9 to 10% of the global world CO_2 emissions) (1), very ambitious targets have been defined for the EU steel industry which can be summarised as follows: the total CO_2 emissions of the steel industry should be reduced, by 2050, from 298 million tons CO_2 in 1990 down to respectively 60 million tons CO_2 for an 80% mitigation level and 15 million tons CO_2 by 2050 for a 95% mitigation level (8). For this estimate, it is assumed that the total EU steel production will stay at the 2015 level, i.e. 166 million tons/y. This scenario will be a huge step to get over.

5. Industrial Demonstration Projects funded by the EU

5.1. Consequently, it is not surprising that several demonstration projects have been recently started in the steel industry with EU financial funding in the frame of the so-called *Smart Carbon Usage* (SCU) and *Carbon Direct Avoidance* (CDA) technologies (9).

These technologies are key options to achieve the CO_2 mitigation of the EU steel industry. More precisely, SCU includes the so-called CCS (Carbon Capture & Storage) and the CCU (Carbon Capture & Usage) technologies. CDA actually concerns the route '**b**' (scrap-based EAF) and the route '**c**' (DRI+EAF) as previously mentioned.

The demonstration industrial projects concern the following steel companies (3)(8)(9):

- BF route: *Thyssen Krupp* (DE)
- DRI route: AG der Dillinger Hüttenwerke (DE), ArcelorMittal Hamburg (DE), ThyssenKrupp (DE), Salzgitter (DE) and SSAB/LKB (SE).

Note: for Smart Carbon Usage, other Demo projects are ongoing respectively at *Thyssen Krupp* with Carbon2chem and ArcelorMittal with Igar/Steelanol: Carbon2chem needs huge amounts of H_2 (110 kg/ton CS) besides the 10 kg coming from the process gases, while Igar/Steelanol requests ca 60 kg H_2/ton hot metal to produce the required amount of ethanol (6).

5.2. As it appears, most of these companies are located in Germany, which for years has been seeking a very exclusive and expensive development of renewable energy sources (wind+solar) with lignite/coal/gas power plants (as back-up) for electricity generation.

6. Substantial Consequences in case of scaling up of existing or new Steel Plants

6.1. In case of success of these demo plants – from a technical and economic standpoint – a scaling-up could be envisaged on existing installations or on brand new facilities. The next step would consist in switching progressively from the BF/BOF route towards the DRI/EAF route, where hydrogen would mainly replace methane as reductant. This would represent a very challenging breakthrough for the EU steel industry.

6.2. Indeed, switching from the BF/BOF route towards the DRI/EAF route would request massive amounts of green hydrogen and CO_2-free electricity from renewable sources (wind + solar), as well as massive financial resources in order to achieve the above-mentioned EU decarbonation targets. These targets would also include the use of CO_2-neutral carbon based fuels (biomass) and/or the application of CCU and CCS technologies for carbon-based iron ore reduction routes (route '**a**'). According to a recent German study, the demand for electricity, only for such a clean EU steel industry, could rise in 2050 to a level of around 450 to 500 TWh, that is to say 4.5 to 5 times the total forecast for Belgian electrical consumption by then (6)(8).

6.3. Such an estimate is actually a difficult exercise because of its high complexity (14). For the sake of argument, this would correspond to the following simplified assumptions (8):

- Total crude steel production: 160 million tons/y (100 million tons/y for the BF-BOF route and 60 million tons/y for the scrap-based-EAF route)
- Total electric energy required for green H_2 generation for switching from the BF-BOF route towards the DRI-EAG route: 381.90 TWh
- Total electric energy required from the grid for operating the DRI-EAF route, as well as the associated CCS & CCU technologies (as end-of-pipe processes): 51.98 TWh
- Total of these two electricity demands: 433.88 TWh, which is rather close to the above 450 to 500 TWh estimated as per above.

By doing so, the total CO_2 emissions would decrease from 173 million tons/y through the BF-BOF route down to 5.7 million tons/y through the DRI-EAF route.

6.4. Consequently, assuming that the above estimate is likely, an energy amount of 381.90 TWh/y would allow producing 11.4 million tons of green hydrogen (based on 483.88 kJ or 33.6 kWh/kg hydrogen needed to produce two moles H_2 from water electrolysis (1)). This production – which is more than 15% of today's world hydrogen production – would cost 28 to €63 billion/y (on the basis of 2.5 to €5.5/kg green hydrogen) (1)(10).

7. Tentative conclusions and perspectives

7.1. For conclusion purposes, the following question could be addressed, i.e.: would such a huge breakthrough technological scenario make sense to achieve a clean steel industry?

More specifically:

- Would it be technically appropriate and financially/economically affordable for the steel industry without massive EU funding (11)(12)? Indeed, besides the high operating costs (OPEX), the investment costs (CAPEX) for such a breakthrough technological change would be tremendous and much time would be required for such a transition to take place in the steel industry.

  Note: if EU funding could be justified for R&D purposes for elaborating and testing such demo plants, any EU funding, however, contributing to the capital costs for building a brand new DRI/EAF plant, as well as to the operating costs related to green hydrogen as feedstock, would not be acceptable according to the EU regulations and the free trade obligations (EU TFEU articles 107(1) & 107(3)).

- Are renewables the best suited energy source to produce huge amounts of green hydrogen for switching towards the DRI/EAF route with green hydrogen?

  Note: while EAF's are rather flexible processes allowing load shedding services to the grid, the DRI process is a baseload process that must run 24/7 and hence, be fuelled with a continuous flow of hydrogen.

Therefore, two solutions consist in: 1° overdesigning electricity production with massive hydrogen storage capacity (with its obvious consequence on hydrogen cost) or 2° building gas power plants to compensate for solar & wind intermittency (with an increase in CO_2 emissions).

7.2. As an **alternative scenario** to the requested huge green hydrogen production, wouldn't it be more relevant to envisage producing large amounts of green hydrogen – without the intermittency issue – through a nuclear-based approach (13). Indeed, water steam pyrolysis could be provided by **advanced high-temperature gas cooled nuclear reactors** (**HTGR)** with helium as reactor coolant and heat vector, or by **molten salt reactors** (**MSR**) providing heat sources in a temperature range between 600 and 1,000 °C? The pyrolysis of water at high temperature would be obtained through specific thermochemical reactions involving chemical products to be recycled (14). Such Gen-IV-type reactors for electricity & heat production are presently under development in many G20 countries (12). On top of the operational compatibility (dispatchable energy production), advanced reactors could be installed right next to consumption points, greatly cutting down on transport and distribution costs. However, such a nuclear approach would obviously depend on the energy policy of the country concerned.

Note: the DRI technology has been growing despite the CO_2 issue related to methane as reductant, but would be boosted by the use of green hydrogen as reductant provided the answers to the above questions could receive a positive reply. This technology is currently provided by two main builders, respectively MIDREX (USA) and TENOVA(AR)&DANIELI (Italy).

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, Plasmaphysik, The European Physical JournalPlus, 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