GREEN HYDROGEN FOR A CLEAN STEEL INDUSTRY?

Complete article

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Preamble

This article consists of three successive parts which were published in the SEII Newsletter issues of respectively September 14, 2021, April 20, 2022 and October 22, 2022 thanks to the few specialized papers and privileged information available on this recent topic during 2021 and 2022. The references are listed at the very end of the document.

Part 1

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.

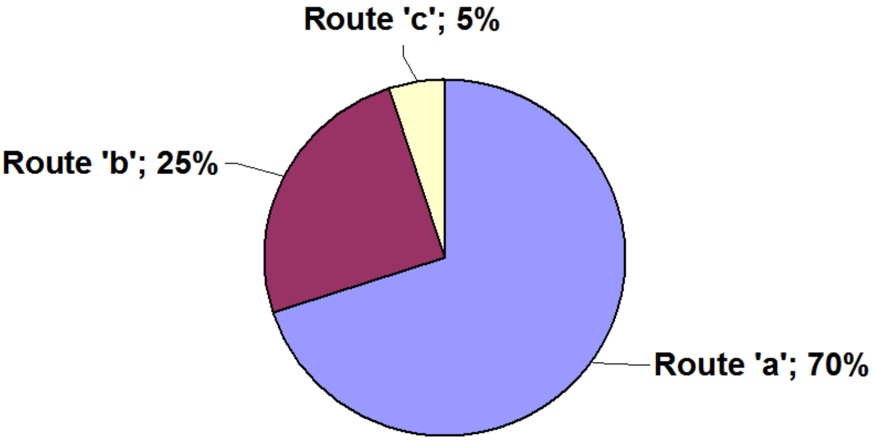
For electricity production, a surprising enthusiasm for green hydrogen has been rapidly growing to further develop renewable energy sources (wind, solar), but also to compensate for their inevitable intermittency. However, controversy from several energy experts has appeared to oppose the very poor technical 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:

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

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

  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):

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

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).

Part 2

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?

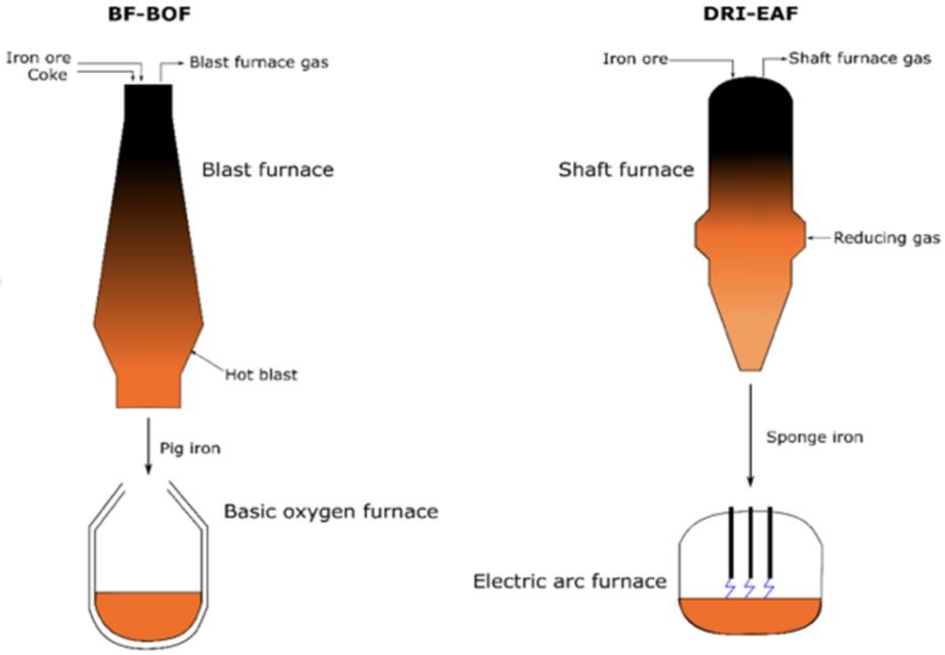
The reasons for issuing a second article on the same subject are the following:

- 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 European 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).

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.

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[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.

7.3. 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.

Part 3

1. Preamble

1.1. This part 3 of the article *'Green Hydrogen for a clean steel industry?'* is the follow-up of the two previous parts, which were published in the SEII Newsletter respectively on September 14, 2021 and on April 20, 2022.

2. Why a third article on the same subject?

2.1. Parts 1 and 2 had been dedicated to explore if green hydrogen could be technically envisaged decarbonising the steel industry in order to make 'clean steel' (or 'green steel'), i.e. steel produced with net-to-zero CO_2 emissions. It was demonstrated that the use of hydrogen – instead of carbon – as chemical reductant – would substantially change the iron-making processes by going from the conventional route 'a' (BF/BOF[2]) towards the innovative route 'c' (DRI/EAF).

2.2. The significant consequences of such a transition were analysed in terms of new iron-making facilities to be built as well as of the huge amounts of green hydrogen and electricity from renewable sources which would be required in case of the steel plants respectively for Europe (the EU 27, in the frame of the Green Deal) and by extension for the world.

2.3. In the conclusions of part 2, the cost estimates for decarbonising the steel industry have been briefly approached. Therefore, the present part 3 is intended to go further in this cost estimate both at the European level as well as at the world level, on the basis of limited available data as per today, in order to achieve/to target a net-to-zero CO_2 emission by 2050. In particular, the CAPEX estimates as published by the steel world leader producer Arcelor Mittal (part 2, para 6.2.) for their European steel plants will be referred to. In addition, as far as possible, all costs related to such a challenging transition will be taken into account as it is (or should be) currently the case for the energy sector (LCOE = Levelized Cost Of Energy).

3. Tentative cost estimate

3.1. The following figures for the production tonnage and the iron-making processes involved in the substitution of BF/BOF route 'a' for the green H_2 based DRI/EAF route 'c' will be assumed for this cost estimate exercise:

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[2] See Part 1 for the definition of the acronyms.

Steel production (27)

- EU 27: 166 million t/y (2020)
- World: 1,860 million t/y (2020)

Estimated Percentage of route ‘a’ (BF/BOF)

- EU 27: 60% (which means that the production of 100 million t/y is involved)
- World: 70% (which means that the production of 1,380 million t/y is involved)

Note: the above factor (60 or 70%) is a fairly average gross estimate but it may significantly vary at lower values at a country or at a company level.

3.2. On the basis of the ArcelorMittal – hereafter abbreviated as AM – cost estimates for their European steel plants to converting the ironmaking/steelmaking facilities from route ‘a’ to route ‘c’ (part 2, para 6.2.), the following tentative extrapolations have been calculated respectively for the EU steel industry and for the World steel industry.

AM figures

- AM – Europe steel production: 45 million t/y (2018)
- AM – World steel production: 96 million t/y (2018)
- AM-Europe route ‘a’ percentage: 60%
- AM-World ’route ‘a’ percentage: 70%

  AM-Europe cost estimate range for new steelmaking facilities (DRI/EAF): €30 to 40 billion (announced projects are in the € 1,000 – 1,300 /ton CAPEX range) (17)

- AM-Europe cost estimate range for associated clean energy infrastructure (lower end with blue hydrogen and higher end with green hydrogen): €40 to €200 billion

EU 27 and World figures

The following figures are based upon the above AM data and have to be considered as orders of magnitude. For coherence purposes, the percentage factor of route ‘a’ (0.6 or 0.7) is applied on the above total tonnages – which are global – in order to calculate the tonnages actually concerned by the conversion from route ‘a’ towards route ‘c’:

- Cost estimate range for the EU 27 new steelmaking facilities (DRI/EAF) (crude steel):

  (166 × 0.60)/(45 × 0.60) × € 30–40 billion = € 111–148 billion

- Cost estimate range for EU27 associated clean energy infrastructure (lower end with blue hydrogen and higher end with green hydrogen):

(166 × 0.60)/(45 × 0.60) × € 40–200 billion = € 148–738 billion

- Cost estimate range for worldwide new steelmaking facilities (DRI/EAF):

  (1,860 × 0.70)/(96 × 0.70) × € 30–40 billion = € 1,240–1,653 billion

- Cost estimate range for worldwide associated clean energy infrastructure (lower end with blue hydrogen and higher end with green hydrogen):

  (1,860 × 0.70)/(96 × 0.70) × € 40–200 billion = €1,653- 8,267 billion

3.3. Therefore, on the basis of the above calculations, the total cost estimate ranges for decarbonising the steel industry would be respectively:

- EU 27 steel industry: € 111–148 billion + € 148–738 billion = € 259–886 billion

  note: this means that an investment of € 2,590–8,860 would be needed per ton of steel (capacity figure), as resulting from € 259–886 billion/100 million tons

- World steel industry: € 1,240–1,653 billion + € 1,653–8,267 billion = € 2,893–9,920 billion

  note: this means that an investment of € 2,096–7,188 would be needed per ton of steel (capacity figure), as resulting from € 2,893–9,920 billion/1,380 million tons.

The above investment figures per ton of steel (capacity figure) are huge compared to the average value of one ton of steel (ex-works price around € 1,000 to 1,500/ton) (28). It can also be noticed that those figures are rather coherent between the European level and the World level. It clearly appears that the infrastructure costs for green hydrogen will be more expensive (by ca a factor 10) compared to the costs for the new steelmaking facilities.

3.4. Consequently, at this stage and as long as the above extrapolation figures would make sense even though they cannot be very accurate due to missing or unknown exact data, it could be concluded that a massive financing would be necessary as:

- for the World level, it would be in the range of €1.24 and 9.9 **trillion**, respectively for the new steel facilities alone and for the same **plus** the associated clean energy infrastructure

- for the EU 27 level, it would be in the range of €111 and 886 **billion**, respectively for the new steel facilities alone and for the same **plus** the associated clean energy infrastructure

3.5. We do realise that for the sake of coherence, the above extrapolation should be referring to the same year instead of corresponding to periods before and during the pandemic. However, we believe that it would not bring any significant difference in the above 'large numbers', the main purpose of the present exercise being to appraise orders of magnitude of what would be the cost of decarbonising the steel industry based on green H_2.

It is interesting to address two other comments concerning the numbers given in part 2 para 3.4. which ones are used here above:

- the 160 million t/y tonnage for EU 27 is not weighted by the percentage factor of 0.6 but is actually very close to the 166 million t/y tonnage

- on the contrary, the 1.38 billion t/y tonnage for the World is actually weighted by the percentage factor of 0.7 and is very close to the 1.30 billion t/y, which amounts results from 1,860 × 0.7 billion t/y.

3.6. It is important to remind that the above cost estimates are limited to the CAPEX and do not include any OPEX, mainly the large amounts of green hydrogen and of electricity from renewable sources which will be necessary to operate the new steelmaking facilities. Maintenance costs are also not considered.

3.7. At this stage, the following comments could be addressed on the massive financing required if such a very challenging transition had to be implemented:

- thanks to the ongoing first pilot plants under development (i.e. green H_2 based DRI/EAF, instead of natural gas based DRI/EAF), it will be possible in the near future to get more accurate data about the actual cost estimate of such new steelmaking facilities from projects such as SALCOS/Salzgitter(D), H2Stahl/ThyssenKrupp(D), HYBRIT/SSAB-LKAB (SE) and H2Future/VOEST-ALPINE (A).

- however, it does not mean that the steel industry will be able to finance these new steelmaking facilities on its own without financial support from the national governments and the EU Institutions (for the European steel plants). Indeed, the steel industry does not have enough financial resources to do it alone without taking the risk of jeopardising its competitiveness in the world market and therefore its long-term survival in the steel business. In addition, the steel industry would inevitably need the financial support (subsidised prices for both consumables) from the national governments and from the EU Institutions (for the European steel plants).

- The above cost estimate range for associated clean energy infrastructure (lower end with blue hydrogen and higher end with green hydrogen) at the European level and the World level is very wide at this stage, and consequently is not that accurate, because it is very difficult to elaborate such calculations without defining the exact scope (perimeter) and all other local and national conditions to take into consideration.

3.8. As a massive financing would be required to implement such a very challenging transition, it is important to remind that, as mentioned in part 2 para 6.8., an alternative to this very expensive transition could be the so-called ‘smart carbon approach’ combining green hydrogen, electrification, waste carbon (like recycled plastics), CCU and CCS technologies, and consequently a net-to-zero steelmaking would be more realistic to reach and less expensive to achieve.

Indeed, the costs of the ArcelorMittal European plants to implement reach such a ‘smart carbon’ approach would be:

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

So as, the total cost estimate for such a ‘smart carbon’ approach would be € 30–55 billion for ArcelorMittal, to be compared to the € 70–240 billion mentioned in above para 3.2

note: this interesting ‘smart approach’ might appear rather complex to implement as it should combine various technologies, some being still under development at an industrial stage. However, more and more, it appears that the ‘smart approach’ (including some hydrogen) would result in ca 50 % of the CAPEX needed for the hydrogen route (17). Also, it has to be reminded that hydrogen steelmaking is still under development and some technological challenges are not yet solved. Probably the main reason to adapt the “smart carbon approach” is the fact that the transition can be implemented stepwise. It makes the strategy also more resilient for shocks and unexpected changes thanks to the combination of multiple solutions: when one of the five “tools” is too expensive, still four others can deliver.

3.9. This shows that the cost estimate for decarbonising the steel industry is not at all an easy exercise as it would deeply depend on which technology – DRI/EAF or ‘smart carbon approach’ – would be adopted and to which extent it would be applied, without excluding a possible combination of both approaches. It would also depend on how far the CO_2 emissions could have to be reduced, without necessarily reaching a net-to-zero target which seems unrealistic according to the above cost estimates.

3.10. Therefore, it is interesting to compare the results of the above ‘risky’ exercise to recent data which have been published on the same subject, but which are unfortunately very limited and poorly documented. This is the purpose of the next section.

4. Comparisons with other recent cost estimates and financing considerations

4.1. According to a recent paper of Deutsche Bank (DB) published in the periodic magazine of PRIMETALS Technologies (a world leader builder for the steel industry) (29), the following figures and considerations are given without any reference and without a clear definition of the scope (steel tonnage, region, countries) under consideration:

- ‘The CAPEX bill for the EU steel industry over the next 10 years could reach USD 20 billion’. Note: this would be in line with likely a 20 % reduction of direct emissions (17).

- ‘For the EU steel countries, more than one € trillion would be needed for the coming decades with €279 billion from the private steel sector and the remaining finance would have to come from the EU budget and from the national governments’

- ‘DB recommends proceeding with special financial instruments such as green-bond issuances and sustainability linked bonds (SLB)’ such as recently announced respectively by US STEEL (USA) and JSW (JINDAL STEEL WORKS) (India).’

The first comment looks totally underestimated whereas the second one looks to comply more with our cost estimates for the new steel facilities. Without any explanation, the financing to be supported by the private sector is quantified and DB claims that this transition would need a huge contribution from the EU budget and from the national governments. Not surprisingly, this is also the position of the German steel industry as clearly addressed in the Stahl+Eisen Magazine for several months (30).

4.2. International Agency for Energy (IEA) has projected a cumulative need for investment of around USD 1.5 trillion by 2050 without – to our knowledge – a clear definition of the scope (steel tonnage, region, countries) (10). This cost estimate looks to comply more with our cost estimates for the new steel facilities.

4.3. TENOVA (another world leader builder for the steel industry) has published a recent exhaustive general paper (31) about how ‘US Steelmaking became a green industry’ but it purposely does not cover the cost estimate for such a transition. Instead, their paper emphasises the importance of steel recycling, which is a well-established and significant advantage for the US steel industry to reduce CO_2 emissions and it suggests that the Carbon Tax as well as the ETS should be taken into account for the cost estimate.

<u>5. Tentative conclusions.</u>

5.1. From the above development, it clearly appears that a massive financing would be required to implement such a transition from the conventional route ‘a’ (BF/BOF) towards the innovative route ’c’ (DRI/EAF). Indeed, as shown in para 3.3, the total cost estimate ranges for decarbonising the steel industry would be respectively:

- EU 27 steel industry: € 111–148 billion + € 148–738 billion = € 259–886 billion, which means an investment of € 2,590–8,860 per ton of steel (capacity figure)

- World steel industry: € 1,240–1,653 billion + € 1,653–8,267 billion = € 2,893–9,920 billion, which means an investment of € 2,096–7,188 per ton of steel (capacity figure)

5.2. Such huge investments are not affordable for the steel producers. Therefore, a very high contribution from the national governments and from the European institutions (for the European steel plants) would be imperative.

5.3. Even if the ultimate goal is to reach a net-to-zero CO_2 emission, does it make sense to decarbonise the steel industry with green hydrogen? The obvious answer should be negative, at least on the basis of the available data and the technology as per today. By looking at those huge numbers, we can wonder if the EU Authorities have anticipated or just ignored what would be the actual costs for achieving that goal by 2050 such as foreseen in the ‘Green Deal’.

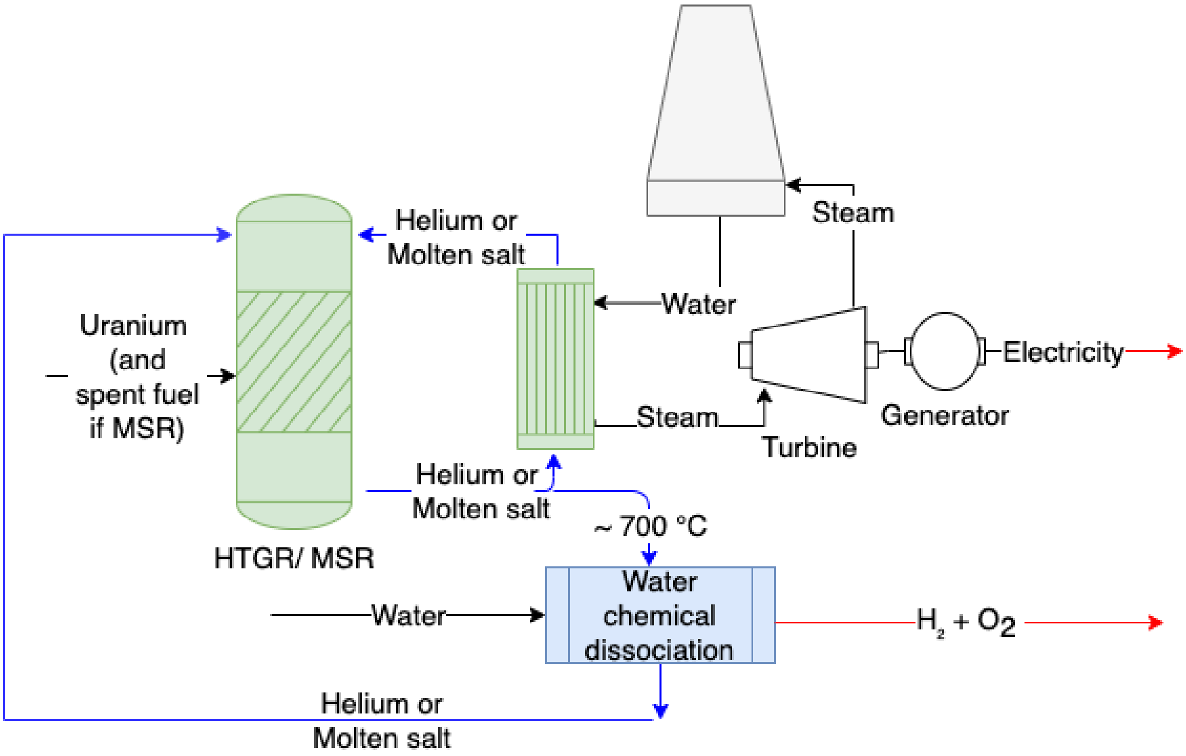
5.4. Maybe a part of this challenging transition from route ‘a’ towards route ‘c’ could be achieved by a limited number of appropriate steel plants or alternately, the ’smart carbon

’approach could be privileged instead as a more affordable solution, without excluding a possible combination of both approaches.

5.5. Unless other innovative technologies like CIRCORED (DRI process with a fluidized bed instead of the shaft furnace) under development by METSO-OUTOTEC (FL) (32) and hydrogen plasma under development by VOEST-ALPINE (A) (33) would be more appropriate and more affordable, it looks that it is irrelevant to promote the green hydrogen as the solution for decarbonising the steel industry.

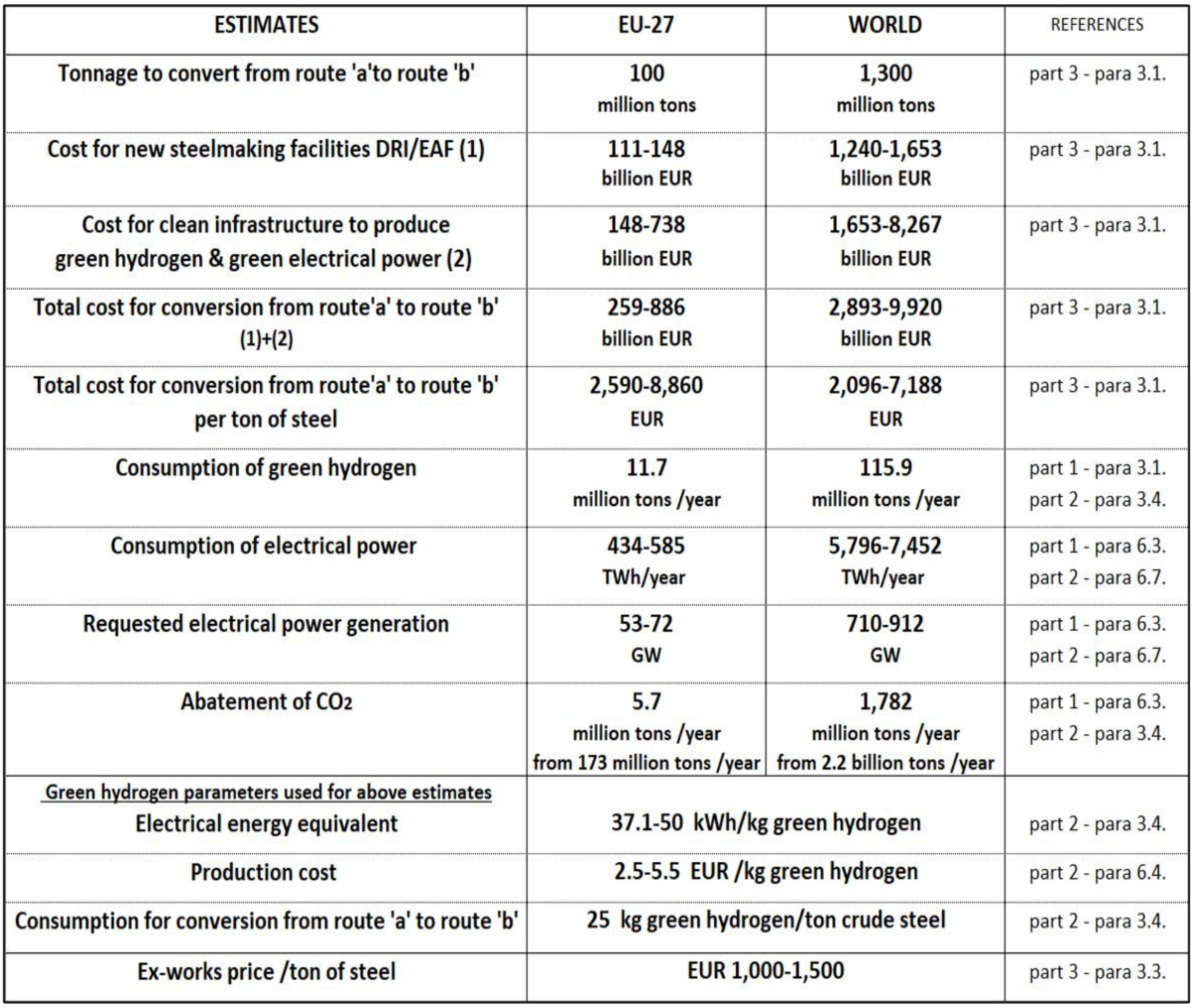
6. Perspectives

6.1. Finally, instead of the green hydrogen, a totally different approach based on hydrogen and electricity produced from a nuclear plant could be explored. Indeed, as per part 1 para 7.2. by taking into account the requested huge amount of green hydrogen and electricity from renewable sources, advanced Generation IV high-temperature gas cooled nuclear reactors (HTGR) as well as molten salt reactors (MSR) should be seriously considered. The following diagram (34) shows that hydrogen (‘pink’ hydrogen, i.e. from nuclear source) can be produced by thermally splitting the water molecule through the high coolant temperature of these new types of Generation IV nuclear reactors.



6.2. Surprisingly, a paper of DUAL FLUID ENERGY (D) dedicated to a new generation of nuclear reactors to contribute to the decarbonization of the steel industry has been published recently in the Stahl+Eisen magazine (35). Also, another paper on ‘Nuclear Hydrogen for Green Steel Production’ was given by THORIUM ENERGY ALLIANCE (USA) at the last AIST 2022 Conference (36): this is the first time that such an approach is openly proposed in the American Iron & Steel Technology annual conference.

Executive Summary for Main Data



ESTIMATES	EU-27	WORLD	REFERENCES
Tonnage to convert from route 'a'to route 'b'	100 million tons	1,300 million tons	part 3 - para 3.1.
Cost for new steelmaking facilities DRI/EAF (1)	111-148 billion EUR	1,240-1,653 billion EUR	part 3 - para 3.1.
Cost for clean infrastructure to produce green hydrogen & green electrical power (2)	148-738 billion EUR	1,653-8,267 billion EUR	part 3 - para 3.1.
Total cost for conversion from route'a' to route 'b' (1)+(2)	259-886 billion EUR	2,893-9,920 billion EUR	part 3 - para 3.1.
Total cost for conversion from route'a' to route 'b' per ton of steel	2,590-8,860 EUR	2,096-7,188 EUR	part 3 - para 3.1.
Consumption of green hydrogen	11.7 million tons /year	115.9 million tons /year	part 1 - para 3.1. part 2 - para 3.4.
Consumption of electrical power	434-585 TWh/year	5,796-7,452 TWh/year	part 1 - para 6.3. part 2 - para 6.7.
Requested electrical power generation	53-72 GW	710-912 GW	part 1 - para 6.3. part 2 - para 6.7.
Abatement of CO_2	5.7 million tons /year from 173 million tons /year	1,782 million tons /year from 2.2 billion tons /year	part 1 - para 6.3. part 2 - para 3.4.
Green hydrogen parameters used for above estimates Electrical energy equivalent	37.1-50 kWh/kg green hydrogen		part 2 - para 3.4.
Production cost	2.5-5.5 EUR /kg green hydrogen		part 2 - para 6.4.
Consumption for conversion from route 'a' to route 'b'	25 kg green hydrogen/ton crude steel		part 2 - para 3.4.
Ex-works price /ton of steel	EUR 1,000-1,500		part 3 - para 3.3.

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