GREEN HYDROGEN FOR A CLEAN STEEL INDUSTRY?
Part 3

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1. Preamble

1.1. This part 3 of the article *'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[1]) 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 has 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:

[1] 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 other 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.

<u>4. Comparisons with other recent cost estimates and financing considerations</u>

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.

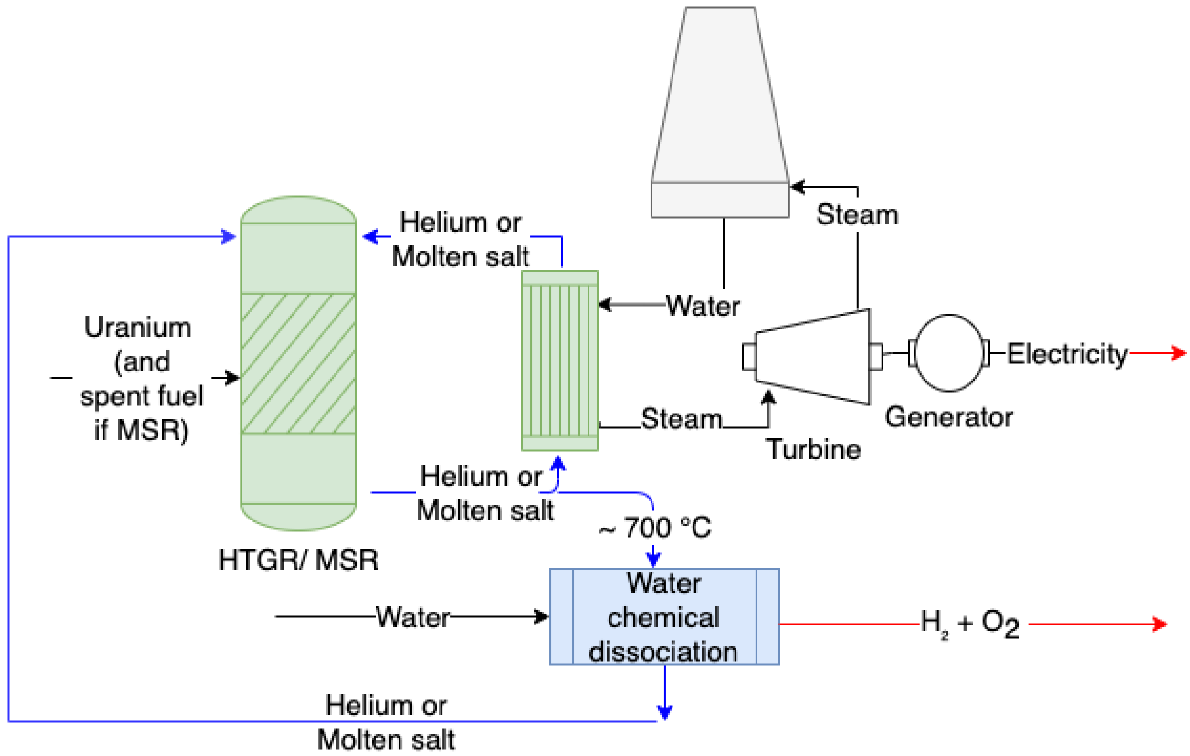
5.3. Even if the ultimate goal is to reach a net-to-zero CO_2 emission, does it make sense to decarbonise the steel industry with green hydrogen? The obvious answer should be negative, at least on the basis of the available data and the technology as per today. By looking at those huge numbers, we can 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	166 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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