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Net-zero emission opportunities for the Iron and Steel industry at a global scale

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ABSTRACT
We use a bottom-up prospective model to explore how the iron and steel industry can decarbonize its activity by combining bioenergy with carbon capture and storage technologies.

Keywords: Negative emission technologies, bioenergy, CCS, energy modelling, steel industry

1. INTRODUCTION

According to the latest IPCC Assessment Report, achieving the objective of limiting temperature increase to 1.5°C will require the massive roll-out of solutions to reduce CO2 emissions and remove CO2 from the atmosphere. For the industry sector, which represented around 25% of global CO_2 emissions in 2018 (IPCC 2021), the decarbonization pathway is particularly complex. The improvement in energy efficiency might be overcompensated by the increase in production and emissions would further increase. This is especially the case for the iron and steel industry (ISI), which is responsible for 7% of global emissions in 2019 (IEA 2020a). Notably, steel is a very important product for the energy transition because most low-carbon technologies depend on it. The decarbonization pathway for this sector becomes more challenging as part of its CO_2 emissions coming from production processes are inevitable (Suopajärvi et al. 2017).

The current options to produce steel are very polluting. Around 70% of the world's steel production is based on the blast furnace-basic oxygen furnace (BF-BOF) technology that relies heavily on the use of coke for iron reduction (World Steel Association 2020). Coke production is a high CO_2 emitting process but is also vital for iron production through the BF-BOF route because it shows the most suitable characteristics to produce high-quality iron. Hence, it is difficult to replace it with other materials (Yang, Meerman, and Faaij 2021). Many efforts have been made to reduce energy consumption and emissions in the BF-BOF route, however further reductions within the current technologies are hard to achieve as they are really mature (Remus et al. 2013). The remaining steel production comes from the electric arc furnace route (EAF) based on steel scrap (23%) and from the direct reduction of iron coupled with an EAF (DRI-EAF) (7%). The production based on the EAF using steel scrap replaces most of the use of coal by electricity which significantly reduces emissions. However, steel production cannot fully rely on steel scrap as its availability cannot cover the increasing steel demand, and because some of the steel scrap does not present the required characteristics to produce high-quality steel end-products. On the other hand, DRI-EAF uses natural gas as the main iron reducing agent, producing up to 60% fewer emissions compared to the BF-BOF route. This might be a good alternative to produce less polluting steel in regions having access to natural gas. However, it is not feasible that DRI-EAF will completely replace BF-BOF steelmaking, as there are some locations where BF-BOF is clearly the less costly route (MIDREX 2018). New steel producing technologies shifting to the direct use of coal (HISARNA or COREX) or natural gas (ULCORED) could allow the reduction of emissions however they might not be commercially available before 2030. There is also the possibility to shift the use of natural gas to hydrogen decreasing even further the emissions. This option requires a very low price for electricity to keep the competitiveness of the industry. Complete neutral carbon steel producing technologies (ULCOWIN, ULCOLYSIS) relying on the electrolysis of iron ore to produce steel might be available by the middle of the century. The transition to new steel producing technologies would be affected by economic aspects as they are more expensive. In this sense, the use of the BF-BOF route might still play an important role in the production of steel in the future, which requires additional efforts to reduce emissions.

Subsequently, to further reduce CO_2 emissions in this sector, it is possible to integrate carbon capture and storage (CCS) and/or utilization (CCU) technologies into the different steel production routes. Another option consists of replacing part of the fossil fuels with biomass products. Charcoal can replace some of the coke used in the BF, nevertheless, complete replacement of coke is not possible because charcoal does not feature the same physical properties as coke. On the other hand, most of the use of coal can be replaced by charcoal, and biomethane can completely replace natural gas (Mousa et al., 2016). Finally, the CO_2 captured can be utilized by mineralizing steel slags, a by-product of BF-BOF. Thus, options appear very promising for decarbonizing the ISI, although the study of these options combined together, and on a global scale, has received little attention, although the use of bioenergy with CCS or CCU (resp. BECCS and BECCU) may offer negative emissions (NE). Indeed, as biomass is considered carbon neutral, by capturing and storing CO_2, the latter can be subtracted from the atmosphere (they are thus commonly referred to as Negative Emission Technologies (NETs)).

In this sense, the objective of this work is to analyze the role of NETs in decarbonizing the ISI. To what extent could NETs contribute to this target? What would be the most cost-efficient technologies? How do NETs interact with other decarbonization options available for this sector? Depending on biomass potentials, which regions of the world are the most likely to rely on NETs? These are the questions we will investigate in this paper.

2. METHODOLOGY

2.1 The TIAM-FR model

This analysis is carried out with TIAM-FR, the French version of the TIMES Integrated Assessment Model (TIAM). TIAM is the global version of the TIMES family models developed under the Energy technology System Analysis Program (ETSAP). TIMES is a generator of partial equilibrium techno-economic models representing the energy system of geographical area – or regions, on a long-term horizon. Thus, TIAM-FR is a bottom-up model describing the world energy system disaggregated into 15 regions. For each of them, the model depicts year-by-year the energy system with a detailed description of different energy forms, technologies, and end-uses, constituting the Reference Energy System (RES) (Figure 1). TIAM-FR allows evaluating and discussing the different perspectives of energy systems evolution with respect to the envisioned objectives and pathways.

The structure of the model enables us to consider variations across the 15 regions regarding their socio-economic properties (cost of capital, labor, and energy), energy demand projections and their commercial routes. Several thousand existing and alternative technologies described by their techno-economic parameters are connected into this RES for all sectors of the energy system (industry, commercial, residential, agriculture, transport). Technologies are also characterized by the energy carriers and materials they consume, the energy services they provide, and the GHG they emit. Driven by end-use demands, the model aims to supply energy services at a minimum discounted cost by choosing the most strategic investments to operate the energy system, dealing with several environmental and technical constraints. Besides, the model is equipped with a climate module allowing accounting for every GHG emitted by the energy system and calculates the impact on temperature elevation in the atmosphere. This type of modelling offers the opportunity for each region to explore the possible energy pathways in the long-term through different scenarios, i.e., consistent assumptions on the trajectories of the energy system.

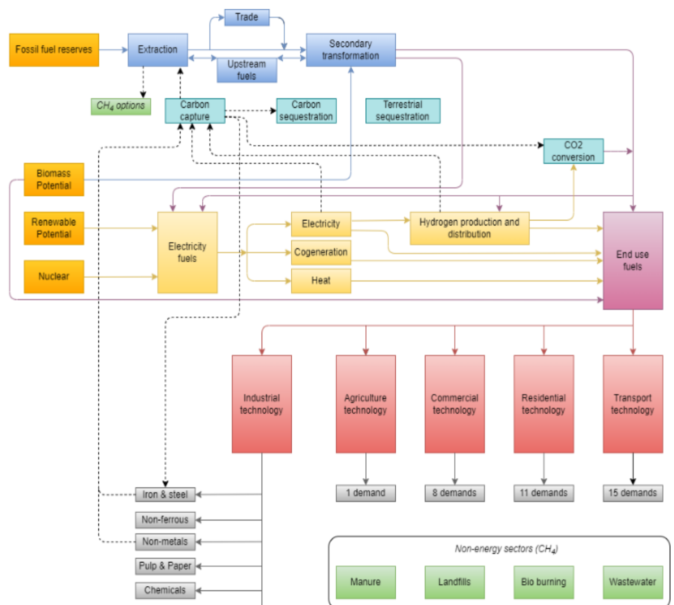

Figure 1: Simplified representation of the energy system (RES) for each of the regions in the TIAM-FR model

The modelling of the ISI includes the different decarbonization options presented previously and developed in the following paragraphs.

2.2 Modelling of iron and steel technologies and potential biomass use

The energy consumption of the base year (*i.e.* 2018) relies on the energy balances of the steel industry from the IEA database (IEA 2020b). The different iron and steel technologies that are developed through the modelling horizon have been represented in the TIAM-FR model with their respective energy and materials consumption based on (ETSAP n.d.; Griffin, Hammond, and Norman 2013; Keys, Hout, and Daniëls 2021; Sikström 2013). Economic parameters have been based on (ETSAP n.d.; Keys, Hout, and Daniëls 2021; Kuramochi et al. 2012; Vogl, Åhman, and Nilsson 2018; West 2020; Wörtler et al. 2013). With the different techno-economic parameters represented in the model it is possible to calculate the emissions of each steel producing route as well as the levelized cost of materials (see Table 1). The emissions and the levelized cost of CO_2 avoidance are in coherence with the data presented by (Yang, Meerman, and Faaij 2021).

Iron producing routes	**CO_2 emissions (kt)**	**Levelized cost of steel ($/t)**	**CO_2 avoidance cost ($/$CO_2$ avoided)**
BF-BOF	1653	590	
BF-BOF CCS	401	694	83
BF-BOF TGR	1861	777	
BF-BOF CCS TGR	774	852	69
COREX	2907	665	
COREX CCS	1231	727	37
HISARNA	1355	628	
HISARNA CCS	256	724	87
MIDREX	785	584	
MIDREX CCS	412	615	83
ULCORED	586	557	
ULCORED CCS	224	588	84
ULCOWIN	289	706	
ULCOLYSIS	28	696	
DRI-H2	101	791	
DRI-H2 INT	280	742	
SCR-EAF	149	630	

Table 1: Characteristics of the candidate technologies

Table 2 presents a summary of the different potentials (found in the literature) to substitute fossil fuels with bioproducts for the different iron and steel producing routes. In general, charcoal can substitute only a small share of the use of coke as it does not present the same strength and porosity. On the other hand, charcoal and biomethane are perfect substitutes to coal and natural gas respectively. Raw biomass cannot be used directly in any of these processes as it presents high moisture content. It is also important to notice that biogas or syngas produced directly from anaerobic digestion and gasification cannot be used directly in the ISI as they do not present the same chemical composition as natural gas, so purification and upgrading are required beforehand. The model can freely choose the amount of bioproducts (any combination between 0% and the maximum substitution potential) that can replace fossil fuels for each technology and in any period from 2030 to 2100. Before 2030, charcoal can be consumed in Brazil as around 20% of its steel production is based on this commodity (SINDIFER 2020), and in Norway that uses some charcoal in the steel industry. The use of bioproducts in the rest of the regions is made possible starting from 2030. The harvesting potentials of the different bioproducts (wood, agriculture residues, organic waste, etc.) are taken from (Kang 2017).

Process	**Availability date**	**Fossil fuel use**	**Bioproduct substitution**	**Maximum substitution potential**	**Reference**
Coke oven	2018	Coal	Charcoal	0%-5%	(Mousa et al. 2016)
Pelletization	2018	Coal	Charcoal	0%-100%	(Nwachukwu, Wang, and Wetterlund 2021)
Sintering	2018	Coke	Charcoal	0%-40%	
Blast Furnace / with CCS (including the Top Gas recycling option)	2018	Coke	Charcoal	0%-6%	(Suopajärvi et al. 2017)
		Coal	Charcoal	0%-100%	
		Natural gas	Biomethane	0%-100%	
Direct Reduction of Iron (MIDREX) / with CCS	2018 / 2025	Natural gas	Biomethane	0%-100%	(Tanzer, Blok, and Ramírez 2020)
COREX / with CCS	2020	Coal	Charcoal	0%-100%	(Norgate et al. 2012)
		Coke	Charcoal	0%-45%	
HISARNA / with CCS	2030	Coal	Charcoal	0%-100%	
ULCORED / with CCS	2030	Coal	Charcoal	0%-100%	(Tanzer, Blok, and Ramírez 2020)
		Natural gas	Biomethane	0%-100%	
ULCOWIN	2050	Natural gas	Biomethane	0%-100%	
		Coal	Charcoal	0%-100%	
Cupola	2018	Natural gas	Biomethane	0%-100%	
EAF	2018	Coal	Charcoal	0%-100%	(Yang, Meerman, and Faaij 2021)
		Natural gas	Biomethane	0%-100%	
DRI-H2 integrated steel plant	2030	Coal	Charcoal	0%-100%	(Tanzer, Blok, and Ramírez 2020)
		Natural gas	Biomethane	0%-100%	
Final production of steel	2018	Natural gas	Biomethane	0%-100%	(Tanzer, Blok, and Ramírez 2020)

Table 2: Possible uses of biomass in the ISI in TIAM-FR

2.3 Scenarios

The analysis of the role of NETs in decarbonizing the ISI will be carried out through four different scenarios.

The first run consists of a reference scenario (REF), without any specific decarbonization plans targeted. This allows having an initial vision on the role of the different steel assets to satisfy steel demand, and to capture the efforts needed to reduce emissions in the future. Also, this scenario enables us to identify whether biomass products can be developed in the absence of specific policies favoring its use.

The next scenarios consist of limiting the atmospheric temperature increase to 2°C and 1.5°C by 2100 (respectively entitled 2C and PA, in reference to the Paris Agreement). Solving these scenarios, the model might require massively deploying alternative technologies in all sectors including the ISI, so it is possible to analyze the contribution and roles of different decarbonization options (CCS, CCU, NETs). As these scenarios constrain all sectors of the economy, the model is free to maintain a certain level of emissions in the ISI which might be eventually offset by negative emissions generated in other sectors (e.g. power sector, DAC), as long as this paradigm is the most cost-effective. The underlying assumption behind this paradigm is that economic sectors could buy negative emissions.

The final scenario (IS0) forces the iron and steel industry to achieve carbon neutrality by 2050 in a world where temperature increase is limited to 1.5°C by 2100. Through this ambitious target, it will be possible to analyze more deeply the potential contribution of NETs in ISI, as the model has to compensate the residual CO_2 emissions released by fossil-based processes or by the residual emissions of carbon capture assets.

Through the analysis of these different scenarios, it will be assessed how the different decarbonization options would interact with each other and with the rest of the energy system in order to reach the proposed decarbonization objectives, and how NETs could further contribute to face the current climate challenge.

All scenarios are consistent with an SSP1, based on a recent post-COP26 study (Climate Resource 2021), projecting the demand for commercial steel to be multiplied by 2.5 by 2100.

3. Results

To capture the challenges underlying the decarbonization of the ISI at the global scale, we first analyze the emissions of CO_2 in each scenario until 2080 (Figure 2). In the REF scenario, we first notice that the emissions of CO_2 are steadily increasing and are multiplied by more than 3, which denotes the huge efforts to be accomplished by this industry to become carbon neutral in 2050. The emissions of CO_2 from ISI represent roughly 5% of the cumulative CO_2 emitted over the century, which guides the world towards 2,8°C temperature elevation by 2100. To lower global warming either to 2°C or 1°5C, the efforts engaged by the ISI can be appreciated with the figure below.

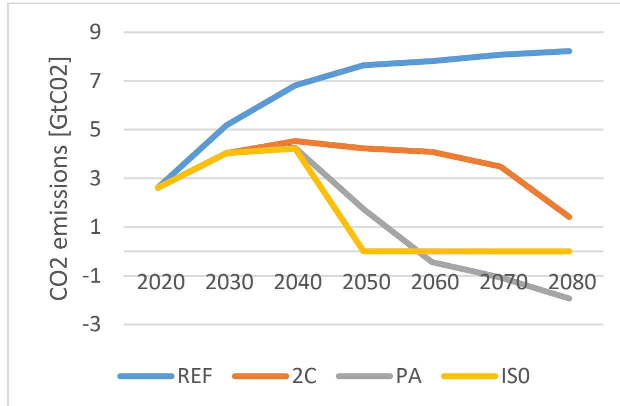

Figure 2: CO_2 emissions of the ISI according to the scenarios

Comparing the PA and ISI0 scenarios reveals that it is more cost-effective to delay the carbon neutrality of ISI to 2060 and further compensate the CO_2 emitted before, rather than investing massively and rapidly between 2040 and 2050 to become carbon negative.

In terms of technology, these ambitions are achieved mainly thanks to CCS and hydrogen processes, as **Error! Reference source not found.** shows. Notably, even in a REF scenario, the DRI process becomes cost-competitive and penetrates the world steel production mix significantly, with a cost of hydrogen of roughly 1.2$/t$H_2$ starting from 2040. In the other scenarios, the industry heavily deploys carbon capture units, that avoid CO_2 emissions from BF and Hisarna processes either to store it or enhance it into gaseous and liquid fuels. From 2050 onwards, roughly 2Gt (resp. 3,5 Gt) of CO_2 are captured from the ISI in a 2C scenario (resp. PA and IS0).

In the pivotal period of 2040, one can appreciate the huge technological efforts required for the ISI to become carbon neutral, which replaces and equips almost all BF processes with BF-CCS processes in the IS0 scenario. The transition is more progressive in the PA scenario, in which the industry prefers to delay the roll-out of some CCS assets but will generate more negative emissions (NE) than the IS0 scenario in the last decades. These NE are achieved by combining bioenergy from charcoal and CCS. In a 2C scenario, the ISI starts using charcoal as a

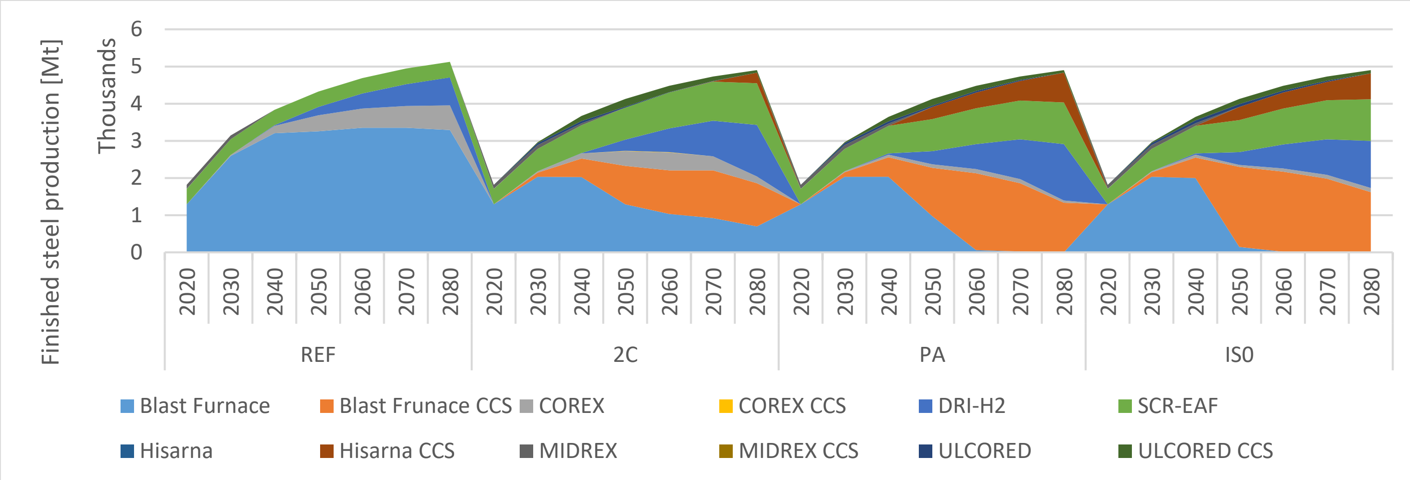

Figure 3: Finished steel production from different processes over time through the 4 scenarios

substitute to coal and coke from 2030 with shares below 10%, but in the more constrained scenarios (PA and IS0), between 40 and 50% of coal is replaced by charcoal. We notice a big difference between the PA and the IS0 in the shares of charcoal and coke used, as Figure 4 below shows, necessary to offset the CO_2 emitted during the 2040-2060 period (Figure 2).

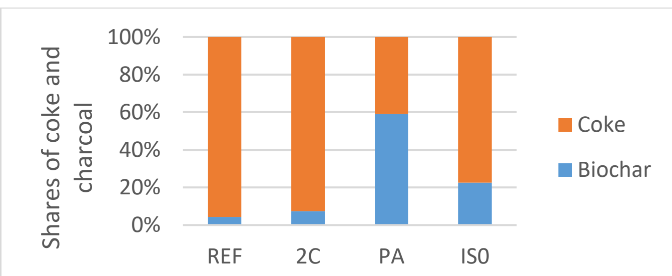

Figure 4: Average shares of charcoal and coke used globally

Thus, there is a trade-off between achieving carbon neutrality of the ISI in 2050 (IS0) or delaying it to 2060 (PA); the first requires a massive deployment of CCS assets but a moderate charcoal use, while the other prefers a more progressive penetration of CCS but a massive use of bioenergy in the future.

Although there is no specific policy in the REF scenario biogas is used in high proportions only in India and Africa which have low or expensive access to natural gas resources but affordable biomass potentials. For those regions biogas is used as a perfect substitute to natural gas in existing assets. In the more constrained scenarios, biogas is used as a reducing agent combined with CCS to generate minor NE in MIDREX processes by less than 2% of the total amount of NE at the global level. According to the IS0 scenario, negative emissions from the ISI are generated unequally around the globe. The USA, Western Europe and Africa are the regions relying the most on charcoal by up to 85% to compensate the emissions of other regions such as Japan and Western Europe using only 40% of charcoal roughly in 2050, due to the higher cost of biomass in these regions.

4. Discussion

The latter statement underlines a major assumption made in this modelling that is the global ISI is united to become carbon neutral by 2050 and agrees that industries of some regions would generate more NE than they require to offset the emissions of others. This involves that a global carbon market is set up. Besides, the emissions of CH_4 and N_2O were not considered in achieving carbon neutrality but those would constrain even more the ISI. If all GHG were considered, we would expect an even greater role for negative emissions in the ISI.

5. CONCLUSION

The ISI can achieve its decarbonization by midcentury under the condition to be able to massively use charcoal and invest in CCS units, which would roughly double the production costs of steel. To reach global decarbonization objectives the cooperation of different regions is required.

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