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## Assessing the role of negative emission technologies in the low carbon transition of the iron and steel sector

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### Abstract

The iron and steel industry (ISI) is responsible for 8% of global CO<sub>2</sub> emissions. Then it is urgently needed to find more sustainable pathways if the ISI aims to contribute to global environmental objectives. Many innovative clean alternative technologies, e.g. hydrogen-based steel production, are proposed to reduce the emissions in this sector, however, they are not available yet, and they do not completely reduce emissions; mainly due to process emissions and residual use of fossil fuels. Then replacing fossil fuels with biomass in combination with carbon capture and storage or utilization (CCS/CCU) could be a prominent solution to reduce the environmental impact as it is possible to produce negative emissions. Then, negative emission technologies (NETs) might help to compensate for the residual emissions of the sector. In this sense, through a bottom-up energy prospective modeling, this paper explores how NETs could contribute to the decarbonization of the ISI

*Keywords:* Biomass, Negative emission technologies, Bioenergy with carbon capture and storage, Iron and steel industry, Decarbonization, Long-term energy modeling, TIMES

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### 1. INTRODUCTION

The industry sector represented around 24% of global CO<sub>2</sub> emissions in 2018 [1], the decarbonization pathway is particularly complex. Indeed, industrial activities are expected to grow steadily in the coming years as their products are essential to human development. 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 around 7% of global emissions in 2018 [2]. 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<sub>2</sub> emissions coming from production processes are inevitable, so they cannot be avoided by simply replacing fossil fuels use with other renewable energies [3].

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 [4]. Coke production is a high CO<sub>2</sub> 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 [5]. 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 [6]. 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 [7]. 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<sub>2</sub> 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 [8]. Finally, the CO<sub>2</sub> 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. This is all the more surprising since 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<sub>2</sub>, 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.

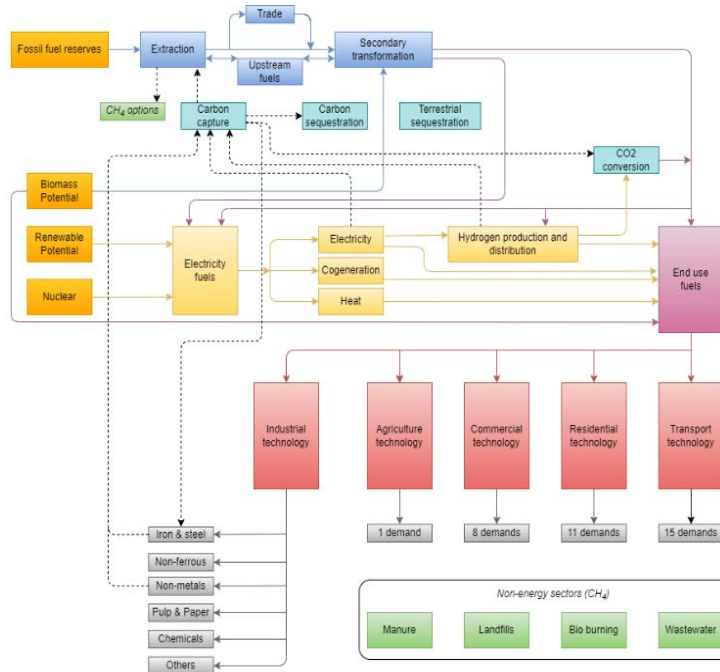


Figure 1: Simplified representation of the energy system (RES) for each of the regions in the TIAM-FR model

The modeling of the ISI includes the different decarbonization options previously mentioned. Accurate identification of emissions at each of the producing and consuming stages provides different roadmaps of the low carbon innovation options.

## 2.2. Modeling 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 [9]. 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 [10–13]. Economic parameters have been based on [11, 13–17]. With the different techno-economic parameters represented in the model it is possible to calculate the total energy consumption and the total emissions produced by each modeled route (see Table 1). The emissions and energy consumption are in coherence with the data presented by [5].

	CO <sub>2</sub> emissions by steel-producing technology	Energy requirements (PJ/t steel)	CO <sub>2</sub> avoided (with respect to BF-BOF)
BF-BOF	2145	19,83	100%
BF-BOF Bio	1584	19,83	-26%
BF-BOF CCS	752	20,60	-65%

BF-BOF CCS Bio	150	20,60	-93%
BF-BOF TGR	1979	20,51	-8%
BF-BOF TGR Bio	733	20,51	-66%
BF-BOF CCS TGR	567	21,24	-74%
BF-BOF CCS TGR Bio	-227	21,24	-111%
COREX	2960	32,66	38%
Corex Bio	1637	32,66	-24%
COREX CCS	322	33,29	-85%
COREX CCS Bio	-695	33,29	-132%
Hisarna	1362	17,28	-36%
Hisarna Bio	740	17,28	-65%
Hisarna CCS	161	18,12	-92%
Hisarna CCS Bio	-593	18,12	-128%
Midrex	857	19,67	-60%
Midrex Bio	62	19,67	-97%
Midrex CCS	157	20,08	-93%
Midrex CCS Bio	-580	20,08	-127%
Ulcored	688	18,07	-68%
Ulcored Bio	0	18,07	-100%
Ulcored CCS	286	18,48	-87%
Ulcored CCS Bio	-372	18,48	-117%
DRI-H2	243,06	14,19	-89%
DRI H2 Bio	30,76	14,19	-99%
DRI-H2 INT	206,66	18,27	-90%
DRI-H2 INT Bio	30,77	18,27	-99%
Ulcowin	53,28	15,19	-98%
Ulcowin Bio	0,00	15,19	-100%
Ulcowin CCS	28,00	17,70	-99%
Ulcowin Bio	0,00	17,70	-100%
SCR-EAF	174,25	6,67	-92%
SCR-EAF Bio	30,80	6,67	-99%

Table 1: List of the candidate technologies implemented in the TIAM-FR model with their respective CO<sub>2</sub> emissions, the levelized cost of materials produced by the technology and the cost of CO<sub>2</sub> avoidance.

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 [18, 19], and in Norway that uses some charcoal in the steel industry. The use of bioproducts in the rest of the regions would be made possible starting from 2030. The harvesting potentials of the different bioproducts (wood, agriculture residues, organic waste, etc.) are taken from [20].

Process	Availability date	Fossil fuel use	Bioproduct substitution	Maximum substitution potential
Coke oven	2018	Coal	Charcoal	0%-5%
Pelletization	2018	Coal	Charcoal	0%-100%
Sintering	2018	Coke	Charcoal	0%-40%
Blast Furnace / with CCS (including the Top Gas recycling option)	2018	Coke	Charcoal	0%-6%
		Coal	Charcoal	0%-100%
		Natural gas	Biomethane	0%-100%
Direct Reduction of Iron (MIDREX) / with CCS	2018 / 2025	Natural gas	Biomethane	0%-100%
COREX / with CCS	2020	Coal	Charcoal	0%-45%
		Coke	Charcoal	0%-45%
HISARNA / with CCS	2030	Coal	Charcoal	0%-45%
		Coal	Charcoal	0%-100%
ULCORED / with CCS	2030	Natural gas	Biomethane	0%-100%
		Natural gas	Biomethane	0%-100%
ULCOWIN	2050	Coal	Charcoal	0%-100%
		Natural gas	Biomethane	0%-100%
Cupola	2018	Natural gas	Biomethane	0%-100%
EAF	2018	Coal	Charcoal	0%-100%
		Natural gas	Biomethane	0%-100%

DRI-H2 integrated steel plant	2030	Coal	Charcoal	0%-100%
		Natural gas	Biomethane	0%-100%
Final production of steel	2018	Natural gas	Biomethane	0%-100%

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 (RF), 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 realize the efforts needed in order 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 economy, the model is free to maintain a certain level of emissions in the ISI which are 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.

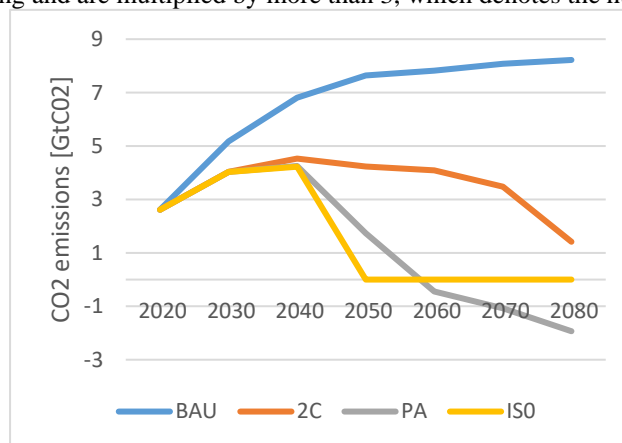
The final scenario (IS0) forces the iron and steel industry to achieve carbon neutrality by 2050 in a world where temperature increase is limited to 1.5°C by 2100. Through this ambitious target, it will be possible to analyze more deeply the potential contribution of NETs in ISI, as the model has no choice but to compensate the residual CO<sub>2</sub> 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 [21], projecting the demand for commercial steel to be multiplied by 2.5 by 2100.

## 3. RESULTS AND DISCUSSION

To capture the challenges underlying the decarbonization of the ISI at the global scale, we first analyze the emissions of CO<sub>2</sub> in each scenario until 2080 (Figure 2). In the reference scenario, we first notice that the emissions of CO<sub>2</sub> 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<sub>2</sub> from ISI represent roughly 5% of the cumulative CO<sub>2</sub> 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°C, the efforts engaged by the ISI can be appreciated with the figure below.

Figure 2: CO<sub>2</sub> emissions of the ISI according to the scenarios

Comparing the PA and ISO scenarios reveals that it is more cost-effective to delay the carbon neutrality of ISI to 2060 and further compensate the CO<sub>2</sub> emitted before, rather than investing massively and rapidly between 2040 and 2050 to become carbon negative.

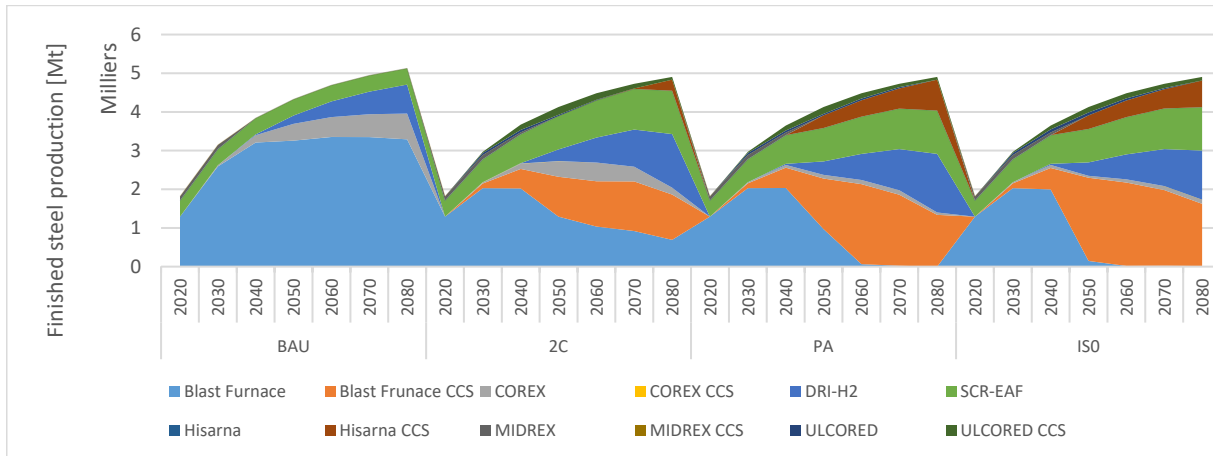


Figure 3: Finished steel production from different processes over time through the 4 scenarios

In terms of technology, these ambitions are achieved mainly thanks to CCS and hydrogen processes, as Figure 3 shows. Notably, even in a BAU scenario, the DRI process becomes cost-competitive and penetrates the world steel production mix significantly, with a cost of hydrogen of roughly 1.2\$/tH<sub>2</sub> starting from 2040. In the other scenarios, the industry heavily deploys carbon capture units, that avoid CO<sub>2</sub> 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<sub>2</sub> are captured from the ISI in a 2C scenario (resp. PA and ISO).

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

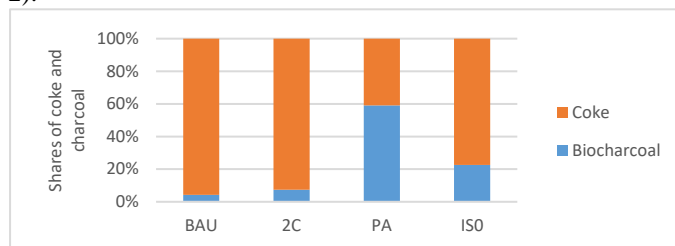


Figure 4: Average shares of charcoal and coke used globally

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.

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.

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<sub>4</sub> and N<sub>2</sub>O were not considered in achieving carbon neutrality but those would constrain even more the ISI as biomass harvesting emits these GHGs. Finally, in this study it has been set as hypothesis that charcoal is sustainably produced so other emissions are avoided, e.g. land use emissions. Then, the decarbonization of the ISI should carefully consider all the aspects included in the harvesting, transport, transformation, and final use of biomass to avoid negative collateral effects that would outweigh the biomass use benefits.

#### 4. CONCLUSIONS

The present study analyses, through a bottom-up prospective model (TIAM-Fr), how NETs can contribute to the decarbonization of the global steel sector. The analysis has been performed using four scenarios, a reference scenario (BAU), limiting the rise of the global temperature to 2°C (2C) and to 1.5°C (PA), and pushing the ISI to reach carbon neutrality by 2050. Then, the decarbonization of the ISI is complex and massive investments in CCS/CCU technologies in BF-BOF are needed as in all scenarios the deployment of this technology is vital to reach the established objectives. However, the use of CCS alone is not enough to reach the climate targets of limiting the rise of temperatures to 1.5°C by the end of the century, as it was needed to couple CCS with biomass in order to reach negative emissions. Charcoal would be deployed mostly in the Americas, the European Union and Africa. In addition, other low carbon technologies have also to be deployed, in particular the direct reduction of iron using H<sub>2</sub>. In this sense, NETs are essential to the decarbonation of the ISI and can massively contribute to climate objectives.

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