UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

THE USE OF HYDROGEN TO REDUCE CO_2 EMISSIONS: A CASE STUDY IN ARCELORMITTAL TUBARÃO STEEL MILL

Trabalho de Formatura TF – 21/26

Letícia Schneid Lopes
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“Concentre-se nos pontos fortes, reconheça as fraquezas, agarre as oportunidades e proteja-se contra as ameaças.”

Sun Tzu (A Arte da Guerra).

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RESUMO

Atualmente, a indústria siderúrgica é uma das maiores emissoras de CO_2 do mundo, sendo a terceira maior indústria emissora dentro do setor energético brasileiro. Logo, a descarbonização do setor industrial pode contribuir no alcance das metas estabelecidas no Acordo de Paris (2015) de redução das emissões de gases do efeito estufa, e principalmente do CO_2. Portanto, o presente trabalho avalia o potencial do hidrogênio em possibilitar a descarbonização da siderurgia brasileira, tendo como estudo de caso a principal usina produtora de aço e geradora de CO_2 do país, a ArcelorMittal Tubarão, no estado de Espírito Santo. Como metodologia, o estudo buscou determinar o valor de CO_2 emitido caso houvesse a diminuição do uso de coque nos altos-fornos, substituindo-o pelo aumento da injeção de hidrogênio nas ventaneiras para atuar como agente redutor do minério de ferro. Inicialmente, aplicou-se um modelo de insumo-produto multirregional, o qual concluiu que os maiores níveis de emissão de CO_2 em kg/EUR pertencem ao processo de geração dos produtos primários de ferro e aço, e ligas de ferro. Posteriormente, ambos hidrogênios verde e azul, em conjunto com o coque, foram analisados por meio de quatro hipotéticos cenários. Os resultados demonstraram que houve redução de CO_2 emitido utilizando hidrogênio verde, enquanto que, o hidrogênio azul obteve reduções pouco significativas. Assim, concluiu-se que o hidrogênio verde é uma alternativa promissora no futuro próximo à ArcelorMittal Tubarão. Para tanto, é necessário que ocorra incentivo à adoção de tecnologias e combustíveis alternativos como o hidrogênio, que possibilitem a descarbonização da siderurgia e em maior escala do setor energético brasileiro. Em contrapartida, ressalta-se a necessidade da diminuição do custo do hidrogênio para torná-lo economicamente viável e da elaboração de políticas públicas e regulamentação no país.

Palavras-Chave: Hidrogênio verde; Hidrogênio azul; Emissões de Dióxido de Carbono; Indústria siderúrgica; ArcelorMittal Tubarão; Brasil.

ABSTRACT

Currently, the steel industry is one of the major sources of CO_2 emissions globally, and it is the third biggest emitter inside the Brazilian energy sector. Hence, the decarbonization of the industrial sector could contribute to reaching the goals established in the Paris Agreement (2015) that aim to reduce greenhouse gases emissions, mainly CO_2. Therefore, the present work evaluates the potential of hydrogen to decarbonize the Brazilian steel sector by applying a case study in the ArcelorMittal Tubarão steel mill, located in Espirito Santo state, and that is the main steel producer and CO_2 emitter. As a methodology, the study sought to determine the value of CO_2 emitted if the coke usage in blast furnaces was reduced, and partially replaced for hydrogen injection in the tuyeres, to act as a reducing agent of the iron ore. Initially, a multiregional input-output model was applied, which concluded that the highest levels of CO_2 emission in Kg/EUR belongs to generating primary products of iron and steel and iron alloys. Posteriorly, blue and green hydrogen, partially combined with coke, were separately analyzed throughout four hypothetical scenarios. The results achieved demonstrate a reduction of CO_2 emitted when green hydrogen was used, but with blue hydrogen, no significant reduction was obtained. Thereby, it was concluded that green hydrogen is a promising alternative for the new future of the ArcelorMittal Tubarão. Thus, it is necessary to encourage the adoption of technologies and non-fossil fuels, making possible the decarbonization of the steel sector and the Brazilian energy sector on a larger scale. Nevertheless, it is necessary to decrease the hydrogen costs to make it economically feasible and elaborate public policies and regulations in the country.

Keywords: Green Hydrogen; Blue Hydrogen; Carbon Dioxide emissions; Steel Industry; ArcelorMittal Tubarão; Brazil.

SUMÁRIO

INTRODUÇÃO

A pesquisa desenvolvida no presente trabalho teve sua construção por meio de dois projetos no nível de Iniciação Científica, durante o período de março de 2020 à setembro de 2021, desenvolvidos no *Research Centre for Greenhouse Gas Innovation* (RCGGI). O primeiro projeto de iniciação científica teve como objetivo a análise do conceito Power-to-Gas e do uso de hidrogênio (H_2) como meios à redução de gases do efeito estufa (GEE), o qual pertencia ao Projeto 26 intitulado "*Evaluation of small LNG and CNG supply options for transportation to off-grid locations; and planning expansion and operation of multimodal integrated networks*". O segundo projeto objetivou avaliar a implementação de tecnologias de captura e armazenamento de carbono (CCS) e de H_2 dentro da indústria siderúrgica brasileira, e respondia ao Projeto 42, intitulado "Avaliação de impacto ambiental de atividades de CCS no Brasil e aspectos legais". Além disso, o suporte financeiro deste trabalho foi oferecido por meio das bolsas de estudos já mencionadas nos agradecimentos, em parceria com a empresa SHELL BRASIL e a Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP.

Durante o período de realização da Iniciação Científica foi possível participar do desenvolvimento de trabalhos em parceria com outros pesquisadores do RCGGI relacionados ao tema de redução de GEE, como o artigo submetido à Revista de Desenvolvimento e Meio Ambiente intitulado "O Papel das políticas públicas na redução das emissões veiculares de gases do efeito estufa no estado de São Paulo", e ao tema do H_2, como o trabalho apresentado no Energy Virtual Experience (EVEx) 2020, intitulado "O estado da arte do hidrogênio no setor rodoviário brasileiro". Ademais, o tema do H_2 aplicado à siderurgia surgiu inicialmente em 2020 com o título de "Hidrogênio Verde como combustível alternativo na Indústria Siderúrgica Brasileira junto ao uso de Tecnologias de Captura e Armazenamento de Carbono", apresentado em uma primeira versão no 28° Simpósio Internacional de Iniciação Científica da Universidade de São Paulo (SIICUSP) em outubro de 2020.

Após dois anos de Iniciação Científica com tema voltado à mitigação das mudanças climáticas e medidas para a redução de GEE, buscou-se conhecimento para o aprofundamento da pesquisa na questão do H_2. Neste sentido, com a finalização da bolsa, optou-se por estender o tema com o objetivo de se escrever um artigo e também apresentá-lo como Trabalho de Formatura. Logo, os parágrafos a seguir buscam justificar o tema proposto nesse presente trabalho.

Atualmente, a preocupação mundial com o aquecimento global gerado pelo aumento das emissões de GEE está exigindo que os países acionem novas medidas de baixo, médio e longo prazos para controlar, reduzir e/ou zerar essas emissões (EPE, 2020). O setor energético mundial é o maior gerador de GEE, principalmente dióxido de carbono (CO_2), através dos setores de transporte e industrial (IEA, 2020a). O setor industrial global, por sua vez, ainda é muito dependente de combustíveis fósseis e suas emissões são, majoritariamente, advindas dos setores químico, de cimento e siderúrgico, que respondem por cerca de 70% do CO_2 emitido nos dias atuais e, responderão por 80% em 2070, segundo as projeções nos Cenários de Desenvolvimento Sustentáveis (IEA, 2020a). Em 2018, a siderurgia foi responsável por emitir 8% das emissões globais de CO_2, tornando-a uma peça chave na mitigação das mudanças climáticas e na descarbonização do setor industrial (Hoffmann et al., 2020).

Para o aprofundamento do tema proposto, o aço é um dos pilares centrais da sociedade atual, porém, a dependência de carvão mineral para a geração de coque e produção de aço causa uma grande quantidade de emissão de CO_2. O coque ainda é muito utilizado devido a rota de produção de ferro e aço nos altos fornos, que representa 70% da produção de aço global (IEA, 2020a) e, ocorre em usinas integradas. A indústria siderúrgica brasileira segue o mesmo padrão global, emitindo de 8 a 12% das emissões de CO_2 do setor industrial no país (Potenza et al., 2021), provindas também de usinas integradas responsáveis por 75% da produção de aço (IAB, 2021a) que usam coque como combustível. A região sudeste brasileira detém 86% da produção de ferro e aço, principalmente os estados de Minas Gerais, Rio de Janeiro e Espírito Santo (IAB, 2021a), logo, as emissões de CO_2 concentram-se nestes estados.

Neste contexto de emissões de CO_2, tanto no Brasil quanto no mundo, os maiores desafio encontrados para esse setor da indústria pesada são as poucas opções de tecnologias de baixo carbono disponíveis e a preços acessíveis (IEA, 2020a). Estas tecnologias tornam-se importantes para o alcance do objetivo estabelecido no Acordo de Paris em 2015, de restringir o aquecimento da temperatura global em até 2°C acima dos níveis pré-industriais (IEA, 2017; Åhman et al., 2018). Nesse sentido, o Brasil foi o primeiro país emergente a determinar metas de mitigação de GEE associadas ao objetivo do Acordo de Paris, que recentemente estabeleceram uma redução de 37% em 2025 e 43% em 2030 em relação aos níveis de GEE emitidos em 2005, de acordo com a sua Contribuição Determinada Nacional, reformulada em 2020 (BRASIL, 2016; Souza and Corazza, 2017). Porém, no Brasil as tecnologias e os esforços para o cumprimento dessas metas ainda não são suficientes para alcançar as metas propostas (Potenza et al., 2021).

Diante desse problema, este presente trabalho busca entender melhor as perspectivas para se alcançar a descarbonização do setor, com foco no setor siderúrgico por meio do estudo de caso da principal usina siderúrgica integrada emissora de CO_2 e produtora de aço do Brasil, a ArcelorMittal Tubarão, localizada no estado do Espírito Santo. Os combustíveis escolhidos para aplicar neste estudo foram o H_2 verde e azul, pois são uma alternativa de baixo carbono ou zero que vem sendo amplamente estudada e debatida para o setor siderúrgico em diversos países, junto com outras maneiras de descarbonizar o setor (Tacke and Steffen, 2003; Wang et al., 2009; Fick et al., 2014; Hasanbeigi et al., 2014; Nogami et al., 2014; Suopajärvi et al., 2014; Quader et al., 2015; Yilmaz et al., 2017; Åhman et al., 2018; Karakaya et al., 2018; H-Vision, 2019; Bhaskar et al., 2020; Draxler et al., 2020). No entanto, o debate sobre o H_2 na indústria siderúrgica brasileira ainda é incipiente, tendo poucos estudos sobre a mitigação das emissões de CO_2, e que costumam ser mais voltados ao uso de bioredutores como, por exemplo, o carvão vegetal (Junca et al.; Passos, 2009; Carvalho et al., 2016; Martinez and Pinto, 2017; de Souza and Pacca, 2021).

Sendo assim, o artigo trata de um tema de relevância para o cenário brasileiro, o qual pode ser importante no futuro para contribuir com metas de descarbonização mais desafiadoras (Potenza et al., 2021). O uso do H_2 no processo de redução de ferro representa uma estratégia de *CDA – Carbon Direct Avoidance* na siderurgia, que baseia-se na melhoria da eficiência energética e substituição de combustíveis fósseis (Hoffmann et al., 2020). No caso da usina integrada, o H_2 atua como agente redutor, substituindo parcialmente o coque utilizado para a redução de minério de ferro nos altos-fornos, etapa em que ocorre a maior emissão de CO_2 (Åhman et al., 2018). A substituição não pode ser total devido à propriedades físico-químicas e termodinâmicas exigidas para o processo dentro dos altos-fornos (Nogami et al., 2014; Yilmaz et al., 2017).

Portanto, optou-se pela realização de um estudo de caso em uma usina siderúrgica de grande porte, que venha demonstrando interesse pela redução de CO_2 emitido, com infraestrutura suficiente para implementar o uso de H_2 possivelmente. A ArcelorMittal Tubarão, além de cumprir todos os critérios acima, também foi possível coletar dados públicos sobre o balanço energético da usina, viabilizando a construção do estudo de caso desejado. Como contribuição, este trabalho pretende complementar a pesquisa do H_2 como combustível de baixo ou zero carbono direcionada à busca pela descarbonização da indústria siderúrgica, para auxiliar no alcance das metas determinadas no Acordo de Paris e, fomentar mais a pesquisa e desenvolvimento dessa tecnologia no Brasil, voltada também a outros setores da matriz energética.

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INTRODUCTION

It is known that anthropogenic emissions of greenhouse gases (GHG) have contributed significantly to the increase in global average surface temperature observed since the mid-20th century (IEA, 2020a). The GHG are defined by United Nations standards and are mostly composed of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), which represents the largest volume of emissions among GHG (IEMA, 2014; GSSB, 2016). In this sense, global economic and population growth, combined with the development of countries, have increased the CO_2 emission levels. Thus, to reduce CO_2 emissions, it is necessary to understand the main sources of these emissions.

The energy sector has been the largest contributor to world CO_2 emissions, which come mostly from the industry, building and transport sectors (IEA, 2020a). In 2020, the industry sector emitted 8.7 gigatons of CO_2 ($GtCO_2$), equivalent to 26% of all energy CO_2 emissions (IEA, 2021a). These emissions are mostly derived from heavy industries such as cement, chemicals, and steel[1], including iron and steel productions (IEA, 2017). In Brazil, the energy sector is one of the major CO_2 emitters, despite the country representing only 1.34% of CO_2 global emissions (Ritchie and Roser, 2020). Similar to the world's heavy industry, the steel industry is the third main contributor of the CO_2 emissions in the Brazilian industrial sector, which is the second-largest emitter in the country's energy sector (EPE, 2021; Potenza et al., 2021). In 2020, 85% of the Brazilian steel industry produced 1.6 tons of CO_2 (tCO_2) per ton of crude steel (tcs), which is equal to an absolute emission of 44.7 megatons of CO_2 ($MtCO_2$) (IAB, 2021b).

The high levels of CO_2 emissions have led countries to adopt global and national measures to mitigate these emissions. One of these measures was the 21st Conference of the Parties (COP – 21) of the United Nations Framework on Climate Change (UNFCCC) as known as the Paris Agreement, in which 195 countries ratified the Agreement (UNFCCC, 2015). The Agreement determined that nations should seek to stabilize their GHG emission in order to limit the global average temperature increase to well below 2°C, ideally at 1.5°C compared to pre-industrial levels (UNFCCC, 2015). Each country's commitment is represented by its National Determined Contributions (NDC) that set up goals to reduce GHG emissions, and consequently, CO_2. (Souza and Corazza, 2017; EPE, 2018).

[1] The terms "iron and steel sector" and "steel industry" are used in this publication interchangeably.

Brazil was one of the first countries to ratify the NDC, which has been conducted in terms of the National Policy of Climate Change (Law 12.187/2009); the Forest Code (Law 12.651/2012); and the National System of Conservation Units (Law 9.985/2000) (BRASIL, 2016). At first, Brazil aimed to reduce its GHG emissions of 2005 by 37% and 43% until 2025 and 2030 (BRASIL, 2016). Hence, to achieve these determined goals, new measures should be implemented in the country, focused on the main CO_2 emitting sectors, such as the Brazilian steel industry.

Based on the context above mentioned, measures for the steel industry can be proposed based on international examples under development, such as carbon pricing schemes, low-carbon technologies and circular economy adoption, recirculated water, scrap use, renewable energy sources, and low-to-zero emission fuels (IAB, 2018; IEA, 2020b). Among the alternatives to decarbonize the steel industry, the most discussed are the use of charcoal or hydrogen (H_2) instead of coke and Carbon Capture Usage (CCU) and Storage (CCS) technologies (Quader et al., 2015; Bhaskar et al., 2020; Draxler et al., 2020; Hoffmann et al., 2020; IEA, 2020a, 2020b).

In Brazil, the use of charcoal is already under operation, for example, in Aço Verde Brasil, which became the first steel mill to reach carbon neutrality in the world (IAB, 2021b). However, its use is only possible at medium-to-small size blast furnaces due to its low mechanical resistance. A high-production blast furnace (BF) would require a large charcoal volume, making the process too expensive and unfeasible (EPE, 2018; IAB, 2021b).

Although the use of H_2 in the steel industry has not yet been applied in Brazil, the fuel has been the most feasible and globally applicable disruptive alternative for the future (IEA, 2020a, 2020b). This H_2 utilization in the BF is a Carbon Direct Avoidance (CDA) strategy responsible for increasing the furnace efficiency. H_2 is applied as a reducing agent, replacing part of the consumed coke to generate hot metal (or pig iron) in BF, decreasing CO_2 emissions (Tacke and Steffen, 2003; Nogami et al., 2014; Yilmaz et al., 2017). This technology is based on the injection of H_2 through tuyeres, reacting with the oxygen molecule from FeO, reducing it into water steam ($H_2O_{(g)}$) and iron (Fe) (Tacke and Steffen, 2003; Yilmaz et al., 2017). Besides, this H_2-FeO reaction is endothermic, so it tends to cool down the BF, reducing its inside pressure and allowing more H_2 to be injected (Nogami et al., 2014). However, due to the BF cooling, there is a limit in the efficiency of the FeO reduction process and on the volume of the injected H_2. According to Yilmaz et al. (2017), this low injection limit in the BF is 27.5 kg of H_2 per ton of hot metal (thm). Furthermore, it is estimated that using H_2 can reduce about 20% of direct CO_2 emissions in the iron reduction process (Nogami et al., 2014).

Hence, given the panorama of the Brazilian steel industry about CO_2 emissions and H_2 potential, the objective of the current work is to analyze the implementation feasibility of H_2 to decarbonize this sector, using a case study of a specific integrated steel mill, chosen from guiding criteria. The choice to carry out a case study was because H_2 is slightly studied in Brazil, mainly if focused on the steel industry. Thus, the integrated steel mill defined as the case study was ArcelorMittal Tubarão (AMT), located in Espírito Santo state. This steel mill complied with the criteria adopted because it is the largest steel producer and CO_2 generator in Brazil and has demonstrated proposals aimed to decarbonize its iron and steel production chain (Linke; ArcelorMittal, 2018, 2020; IAB, 2021b).

The case study addresses the use of H_2 in the iron ore reduction process, the main source of CO_2 emissions in an integrated steel mill (IEA, 2020a). Moreover, blue and green H_2 were treated in this work, which differs through their production processes. These H_2 were separately combined with coke to then apply in four hypothetical scenarios, making it possible to observe the potential of green and blue H_2 in reducing CO_2 emissions. In this way, the main question to be answered is: From the current Brazilian steel panorama and its CO_2 emissions, how H_2 could contribute to the decarbonization of the steel industry? Finally, as a contribution, this work intends to complement the research of H_2 as a fuel for the steel industry's decarbonization and further encourage the research and development of this and other alternative technologies in Brazil.

LITERATURE REVIEW

Steel industry production chain

Firstly, the steelmaking chain comprehends two types of routes. The primary route is referent to the integrated facilities, where iron production occurs onsite (BF-BOF route). In addition, a secondary route is represented by steel production through the use of recycled steel scrap in electric arc furnaces (EAFs) (IEA, 2020b). Globally, about 75% of the steel is produced using the BF-BOF route (WSA, 2021a), which is the present work's focus. This route produces steel using iron ore, coal, limestone and steel scrap. In this route, two main processes represent raw material processing: metallurgical coke and iron ore (sinter or pellet) beneficiations, in which limestone is used as an auxiliary raw material (Birat, 2010; Quader et al., 2015; Yilmaz et al., 2017).

The raw-materials processing encompasses sintering and coking processes, producing sinter at the agglomeration plants and coke in the coke ovens, respectively. These two products are fuels that feed BF in the ironmaking process. The exothermic reaction between iron ore and coke in BF can be shortly described as $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$. Besides that, the tuyeres inject hot air with a high concentration of oxygen (O_2) and a temperature of roughly 1200ºC (Viera, D. H., 2012 apud. EPE, 2018a). The O_2 reacts with the carbon from coke producing carbon monoxide (CO). CO ascends in the BF and reacts with the oxygen molecule from iron ore (FeO), reducing itself and producing CO_2 and Fe (Passos, 2009). The main reactions described are presented in Figure 1.

$$3\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2$$
$$Fe_3O_4 + CO = 3\,FeO + CO_2$$
$$FeO + CO = \mathbf{Fe} + \mathbf{CO_2}$$
$$CO_2 + C = 2\,CO \text{ (Boudoard Reaction)}$$

Figure 1: Main reactions involved in reducing of iron ore in the BF.

Then, the generated pure iron descends into a countercurrent through the BF (IPCC, 2006b). In the process, pulverized coal (PCI) is also injected through the tuyeres. This PCI helps decrease coke consumption and increase the BF efficiency (Passos, 2009; Carvalho et al., 2016; EPE, 2018a). The outcomes products from the iron ore reduction step are hot metal, scrap, and blast furnace gases (BFG) (Passos, 2009). Moreover, the energy required for the process is around 13 – 14 GJ per ton of hot metal (thm). Consequently, ironmaking is the most energy-intensive phase in iron and steel production chains (Hasanbeigi et al., 2014). So, to provide the necessary heat to BF, coke carbon is also used as an energy source (IPCC, 2006b).

The following step refers to the steel refining, which begins at the Basic Oxygen Furnace (BOF) and goes to the LD-converter phase (Paula, 2012; EPE, 2018). Initially, the hot metal is desulfurized. Then, high purity O_2 is injected, which reacts with the existing carbon in hot metal, generating an exothermic reaction, which exhales the energy required to melt the material and reduce the steel carbon rate. The hot metal contains roughly 3-4% of carbon, which must be reduced to less than 1% to generate the steel correctly (IPCC, 2006b).

This initial refining phase is proceeded by mechanical conformation processes. After casting, the crude steel will be rolled to generate the final outcome products such as plates, bars, and others (EPE, 2018; IEA, 2020b; IAB, 2021b). Figure 2 is a simplified diagram of steel production using BF-BOF route.

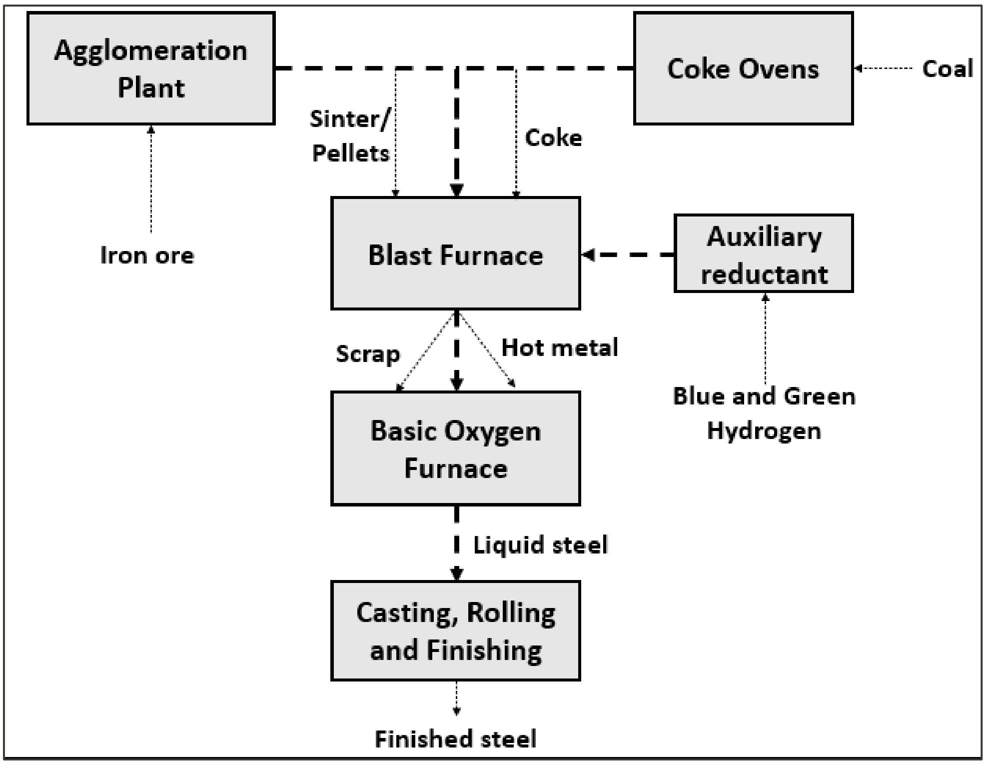

Figure 2: Flow Diagram of steel production through BF-BOF route.

The ironmaking phase is the major responsible for CO_2 emissions, and there are many initiatives around the world to decarbonize the steel industry (Quader et al., 2015). Hence, the change on the ironmaking fuels by introducing cleaner alternatives such as hydrogen could play an important role. Among some countries that already have invested in this change are Austria, Germany, Swede, Japan, the United States, Korea and China (Zhang et al., 2021).

Hydrogen application on the steel industry

The improvement of new disruptive technologies made the transition of the industrial sector to a low-carbon industry more viable, reducing its CO_2 emissions, mainly related to the use of fossil fuels (IEA, 2017). Hydrogen is one of the options addressed in the fossil fuels decarbonization context, and it might play an important role in the industry, particularly the steel sector (Åhman et al., 2018).

Due to fossil fuels prices, grey H_2 production is the most cost-effective process. However, as a disadvantage, a large amount of CO_2 has been emitted, almost 900 Mt per year (IEA, 2021b). Grey H_2 is the hydrogen produced from fossil fuels through hydrocarbon reforming, including partial oxidation and autothermal steam reforming (Nikolaidis and Poullikkas, 2017). Steam reforming (SR) method is based on hydrocarbon and steam reactions that produce carbon oxides and H_2 (Nikolaidis and Poullikkas, 2017). Moreover, another H_2 has been determined, which is tourquise H_2 produced from natural gas (NG) pyrolysis (EPRS, 2021), but it is not discussed in the present work.

Therefore, the grey H_2 production process uses NG, methane and other methane containing gases as raw materials. In order to produce a near 100% purity H_2, SR parameters include high temperatures, pressure up to 3 MPa, steam-to-carbon ratios of 3.5, and nickel as a catalyst agent (Ersöz, 2008). A desulphurization step frequently accompanies SR to avoid poisoning of the reforming due to some sulfur compounds. According to Muradov (2001), the energy required for steam methane reforming (SMR) is 63,3 KJ/mol H_2 (using 30-35% of the natural gas demand), reaching a total emission of 0,3-0,4 m^3 of CO_2 per m^3 of H_2. Moreover, SMR is the most common process used to produce large-scale grey H_2 (Muradov, 2001; Nikolaidis and Poullikkas, 2017; Shell, 2017).

In another perspective, H_2 production using renewable energy is more expensive. Still, as an emission-free future is expected in the coming decades, the cost of the process is decreasing (IRENA, 2019). Hydrogen produced from renewable sources is also known as green H_2 (Bhaskar et al., 2020; Hoffmann et al., 2020), and there are many methods for its production. One of the main methods for H_2 generation is the electrolysis process, which consists of water splitting using renewable electricity (Armijo and Philibert, 2020). It includes an electrolyzer containing an anode and a cathode immersed in an electrolyte. An electrical current is applied in the electrolyzer, promoting water splitting into H_2 and O_2, which are evolved on the cathode and anode, respectively (Armijo and Philibert, 2020).

There are three main technologies used for this process: alkaline electrolysis, proton exchange membrane (PEM) and solid oxide electrolysis (SOE) (Shell, 2017). In PEM technology, water is introduced into the anode where it is dissociated, producing O_2, which remains with the water in the anode, and protons (H^+) that cross a membrane to the cathode to form H_2 (Rivkin et al., 2017). In contrast, in alkaline electrolysis and SOE, water is added to the cathode. Then, the water is dissociated into H_2 and hydroxide ions (OH^-), which is transported through the aqueous electrolyte to the anode. The reaction that represents each system is described in Table 1.

Table 1: Electrolysis main reactions divided between PEM and, SOE and Alkaline types.

• PEM		• Alkaline and SOE	
Anode	Cathode	Cathode	Anode
$2H_2O = O_2 + 4H^+ + 4e^-$	$4H^+ + 4e^- = 2H_2$	$2H_2O + 2e^- = 2OH^- + H_2$	$4OH^- = O_2 + 2H_2O + 4e^-$

Alkaline electrolysis is currently the most cost-effective of these three technologies, with a system consumption of 53,4 kWh/kg of H_2 and an annual production of 380 tH_2 (Nazir et al., 2020). Although electrolysis technologies use energy from solar, hydro, wind renewable sources, the high electricity consumption restricts their participation in the global hydrogen market due to the high energy cost (Nikolaidis and Poullikkas, 2017; Shell, 2017). In contrast to this scenario, blue hydrogen is also produced from fossil fuels, but coupled with carbon capture methods, which are used to reduce CO_2 emissions.

Afterwards, the captured CO_2 is stored in geological formations or salt caverns (CCS) or destined for industrial uses (CCU) (Rochedo et al., 2016; Jiang and Ashworth, 2020). As blue hydrogen involves the addition of CO_2 capture methods, there are some initiatives outside Brazil, in which it is already possible to observe the blue hydrogen potential (H-Vision, 2019). This is the case of the "H-Vision Initiative" in the Netherlands, the "Hydrogen to Magnum" in Norway and the "H21 NoE (North of England)" in the United Kingdom (IRENA, 2019).

Once any type of hydrogen is produced, the compound can be directed to many different applications. In Europe, for example, hydrogen has been applied in the steel industry as more initiatives are created. Ultra-low CO_2 steelmaking (ULCOS) was an important European initiative based on developing CO_2 breakthrough technologies to reduce CO_2 emissions by 50% in the steel sector (Quader et al., 2015). ULCOS proposed technologies such as the tog gas recycling in BF (TRG-BF), which captures the emitted BF top gas and reuses it as an auxiliary energy and heat provider, with also a coal partial substitution for biomass or natural gas as reducing agents (Draxler et al., 2020).

Moreover, another initiative related to hydrogen use in the steel industry is the HISARNA smelting technology, which has a high reduction potential of CO_2 emissions near 70%. However, it will only reach commercial maturity in the next decades (Quader et al., 2015; Karakaya et al., 2018). Furthermore, these options could be accompanied by CCS and CCU technologies. Although ULCORED and ULCOWIN are also other possible technologies, as they use NG/biomass and electrolysis for direct iron reduction, respectively, HISARNA process is the most cost-benefit technology (Quader et al., 2015).

In the case of CCU and CCS usage, the technologies are considered essential to obtain high carbon emissions reduction rates. These technologies are based on capturing CO_2 released in the atmosphere through several processes that can be used to generate other products or storage in the subsurface (Hoffmann et al., 2020). Quader et al. (2015) approach five technologies of CO_2 capture: chemical; physical; or mixed absorption (physical and chemical); adsorption using solid adsorbents; physical separation via membrane; phases division by cryogenics and gas hydrates; and chemical bond via mineral carbonation. However, there are almost no CCS or CCU plants applied on an industrial scale, yet technologies such as HIsarna, FINEX, and COREX are being analyzed on commercial scales (IEA, 2020b). Currently, the biggest obstacles for both CCS and CCU is the high cost of implementation, and the environmental and social uncertainties, even though it has a significant technological maturity (Tacke and Steffen, 2003; Arasto et al., 2013; Rochedo et al., 2016; Hoffmann et al., 2020; de Souza and Pacca, 2021).

Regarding CCS technologies, the option of storage of CO_2, is more economically viable and advantageous on coastal areas and locations with caves or saline aquifers (Wich-Konrad et al., 2020). Although, in compared to CCU, CCS technology is less attractive due to the transportation phase to the storage location (Bhaskar et al., 2020). On the case of CCU, options have been analyzed, such as the capture of CO_2 and feedback in the blast furnace (Roussanaly et al., 2021) or the use for the production of ammonia and methanol from post-combustion processes (Wich-Konrad et al., 2020). Along with CCS and CCU, CDA technologies are the main discussed options to reach the steel industry decarbonization. On this way, H_2 represents a strategy among the CDA technologies, and a disruptive opportunity for the steel industry (Hoffmann et al., 2020).

Moreover, the most effective way to reduce CO_2 emission in the sector is through the use of H_2 on the direct reduction of iron ore in electric arc furnaces, which should replace the BF-BOF route in the next years. If using green H_2, this technology can be even more effective in emissions reduction, as both electricity and H_2 come from renewable sources (Bhaskar et al., 2020). A 2.3 gigatons of CO_2 is expected to be reduced through green H_2 and ammonia within the iron and steelmaking process (IEA, 2017). Another study of the DR-method using pure H_2 and biomass has been developed by Swedish iron and steelmaking companies (LKAB, SSAB and Vattenfall), that is supported by the Swedish Energy Agency, and its pilot plant might move towards a large-scale operation (~1 Mt of DRI) facility by 2025 (IEA, 2018, 2021b).

Although, the present work aims to study the H_2 usage as a reducing agent injected into BF, which has also been shown to be a possible alternative (Wang et al., 2009; Hasanbeigi et al., 2014; Hoffmann et al., 2020; EPRS, 2021). This technology alternative could play an important role in the transition to a low-carbon DR-EAF route, given that many countries, e.g. Brazil, still have BF-BOF as their major steelmaking process (IAB, 2021a). BF-BOF represents the main current route, and its replacement by more emission-free methods will demand time and high investments. Therefore, it is necessary to search for alternatives that facilitate the transition low-carbon steel industry, which is mainly achieved through the use of green H_2 on the production of direct reduced iron in EAF (EPRS, 2021).

METHODOLOGY

The methodologic approach of this research is based on five steps, as it is shown in Figure 1. In Brazil, iron and steel are mostly generated in integrated steel mills, more than 80% (IAB, 2021b). Thus, the study is directed toward the Brazilian context, focusing on its steel industry, specifically integrated steel mills, and possible technologies to reduce CO_2 emissions in this sector. The alternative technology chosen to build up four hypothetical scenarios uses green and blue H_2 in the ironmaking process. The blue and green H_2 and coke emission factors were applied to the scenarios. The data used on the development of the scenario was from the selected Brazilian integrated steel mill, determined through an extensive data collection.

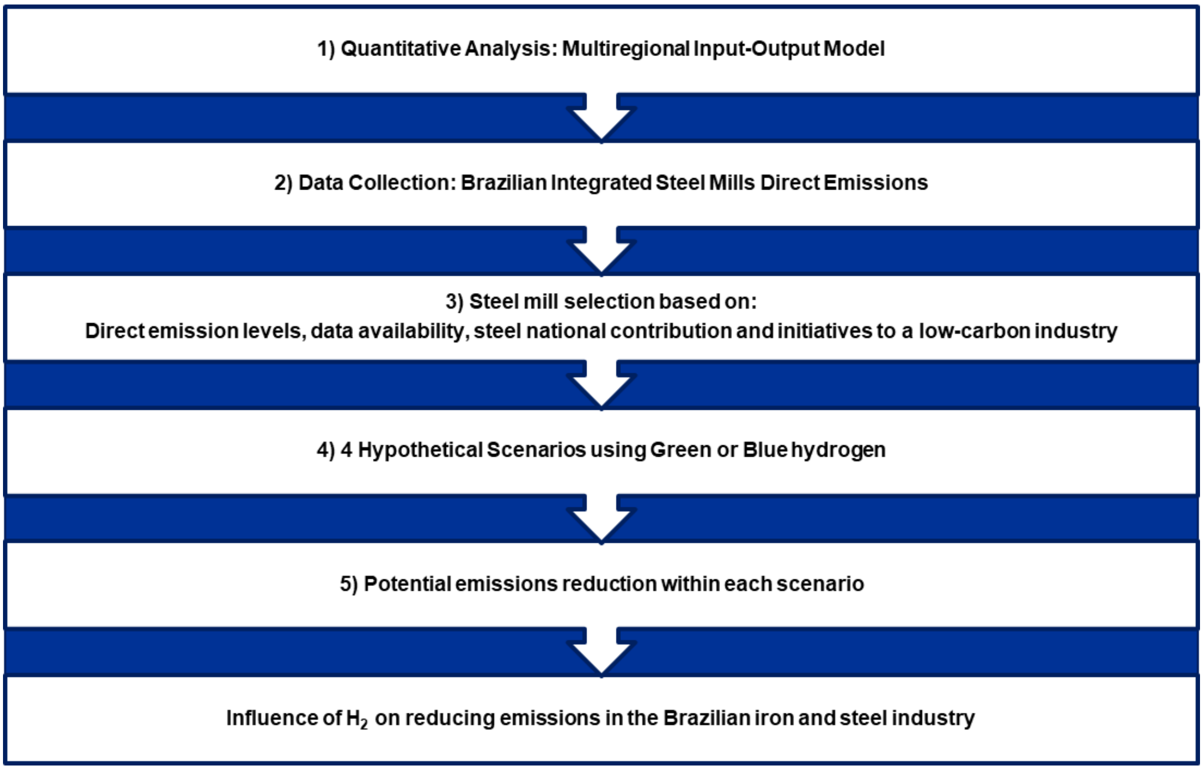

Figure 3: Methodology procedures are divided into five steps, establishing a discussion about the influence of H_2, on reducing CO_2 emissions in the Brazilian steel industry.

Multiregional input-output model (MIOM)

Firstly, a multiregional input-output model (MIOM) was elaborated to offer a quantitative analysis of the iron and steel production chain. From this model construction, direct and indirect emissions referent to the process are determined for further comparison. The model portrays CO_2e emission flows between iron and steel production and other products in a multiregional perspective.

The Exiobase database was used to calculate iron and steel CO_2e emissions in the chain, and Python 3.8 was used for data treatment. Exiobase contains supply-use data from several countries, which is used to estimate emissions and resource extractions by industry (EXIOBASE, 2021). Finally, this data collection produces an input-output table (IOT) that can be used to analyze "environmental impacts associated with the final consumption of product groups" (EXIOBASE, 2021, p.1), in this particular case of the Brazilian iron and steel industry.

Exiobase 3.4 – IOT – 2011 offers the data used for matrix **A** construction. The matrix is fed by the most recent technical coefficient data from different sectors, resulting in a matrix composed of 9800 rows and 9800 columns. Then, an identify matrix (**I**) is subtracted by matrix **A**, and $(\mathbf{I}-\mathbf{A})^{-1}$ is the Leontief inverse matrix relative to this subtraction. Finally, multiply the inverse matrix by the column vector (**d**) representing the final consumption of each product (Mubako et al., 2013), according to Equation 1.

$$T = (I - A)^{-1} * d \quad \text{(Equation 1)}$$

The method offers an output through the total demand induced (**T**) multiplied by carbon emissions coefficient values (**Ce**), so finding iron and steel chain *Carbon Footprint* through a multiregional analysis, according to Equation 2.

$$\text{Carbon Footprint} = T * Ce \quad \text{(Equation 2)}$$

Emissions data collection from Brazilian integrated steel mills

In order to find emissions data of the leading Brazilian companies with integrated steel mills and their characteristics, documents from the Environmental Impact Study (EIA) and Environmental Impact Report (RIMA) and GHG Protocol Brazilian Program were used (IMA; EAESP, 2021). However, even though this study focuses on CO_2, the emissions inventoried in the reports of Brazilian steel companies usually appear in the form of CO_2e.

Firstly, EIA/RIMA are technical reports emitted to analyze the positive and negative consequences that a determined enterprise may cause for the environment, providing or not an environmental licensing (IMA, 2021). The data collected from EIA/RIMA will provide the information about emissions potential of the steel mills considered. Secondly, GHG Protocol Brazilian Program is an online database in which some companies can submit their environmental and emission data for public consultation. It was created to afford standards and instruments for emissions calculation with international quality and to adapt GHG Protocol guidelines for the Brazilian context (EAESP, 2021).

The data collected from the GHG Protocol Brazilian Program source provided the actual values of Scope 1 and Scope 2 emissions related to the integrated steel mills. Direct emissions (Scope 1) are a classification term relative to CO_2 emitted directly directly from sources owned or controlled by the companies, and from the manufacturing processes and fuels combustion (CETESB, 2011). Scope 1, along with Scope 2 (indirect emission from energy acquisition) and 3 (the rest of indirect emissions) exist to be presented on corporate inventories of CO_2 emissions, that follow the ISO 14064-1 norm and are determined according to the methodologies from GHG Protocol (FGV, 2009).

Then, to study the Brazilian steel industry current context referent to CO_2 emissions, 12 integrated steel mills were selected through *Aço Brazil Institute* reports (IAB, 2020, 2021a). Moreover, it is worth mentioning that the available information about Gerdau integrated mills refers to all the units summarized.

Scenario's development

The analysis of the MIOM added to the data collection step led to the choice of the best integrated steel mill in Brazil, which would be able to provide a broader discussion about the H_2 application through a study case, using hypothetical scenarios to estimate CO_2 potential reductions. Therefore, the scenarios production required a data acquisition referent to the AMT steel mill and fuels emission factors used in the ironmaking process (Table 2). The choice of AMT steel mill is further discussed on the *Results* topic of this article. The data related to the plant were taken from an energy balance report from 2018 (Ludgero, 2018).

Regarding the AMT plant, the first emission factor (EF) required was referent to pig iron production (EF_{HM}). This factor was calculated from the total CO_2 emissions of AMT in 2018, found on the emissions inventory presented in the ArcelorMittal Report for the Brazilian GHG Protocol Program in 2019 (ArcelorMittal, 2019). Then, CO_2 total value was divided by the total volume of pig iron produced by the company (AMT) in that year (Ludgero, 2018). EF_{HM} obtained was equal to 1,83 tCO_2 per ton of hot metal (tCO_2/t hm), which is an acceptable value given that, in 2019, the global CO_2 intensity was 1,83 t CO_2/ tcs cast (WSA, 2020). Parallelly, an emission factor (EF) referring to the 2006 IPCC guidelines was collected (IPCC, 2006a). This EF was related to the coking coal used to produce the coke added into BF's iron ore reduction step.

Table 2: Parameters used for the scenario's development.

Parameters	Value	Unity	Reference
Scope 1 Emissions	13.854.896	tCO_2	ArcelorMittal GHG Protocol Report of 2018 (ArcelorMittal, 2019)
Crude steel (cs) production	7.149.305	tcs	ArcelorMittal Tubarão - Energetic Balance (Ludgero, 2018)
Productivity ton of hot metal (thm) per ton of crude steel	1,06	thm/tcs	
Hot metal production, according to its yield in 2018	7.578.263	thm	
Energy consumed in BF **(E_{BF})**	0,022075	TJ/thm	
EF_{HM}	1,83	tCO_2/thm	
Energy required to produce hydrogen through SMR **(E_{SMR})**	63,30	KJ/mol H_2	(Muradov, 2001)
Molar mass H_2 (***M_{H2}***)	2,00	g/mol H_2	-

$\mathbf{EF^{II}_{blue\ H2}}$	**2,54**	Kg CO_2/Kg H_2	(Cantuarias-Villessuzanne et al., 2016)

The second necessary factor refers to the fuels used in coke, blue and green hydrogen in the ironmaking process. Green hydrogen, as already demonstrated, is free from CO_2 emissions (WSA, 2021b). Blue hydrogen also has an emission factor to be considered, as it is not completely a carbon-free fuel (H-Vision, 2019). In this way, the EF ($\mathbf{EF^{II}_{blue\ H2}}$) related to blue hydrogen is presented on Cantuarias Villessuzanne et al. (2016) along with William et al. (2009), Ibrahim (2007), and Robert et al. (2013). However, the blue hydrogen emission factor in tons of CO_2 per terajoules ($\mathbf{EF^{I}_{blue\ H2}}$) is needed to be determined, so allowing its use for the scenario's development.

Therefore, Equation 3 exposes the method used to find this emission factor, and consists of multiplying the molar mass of H_2 with $\mathbf{EF^{II}_{blue\ H2}}$, then dividing by the energy required for H_2 production via SMR. All parameters mentioned above are summarised in Table 2 and 3.

Equation 3: $EF^{I}_{blue\ H2} = \{[(E_{SMR})^{-1} * M_{H2} * EF^{II}_{blue\ H2}]/1000\}$

$$EF^{I}_{blue\ H2} = 80,25\ t\ CO_2/TJ$$

Afterwards, coke emission factor was withdrawn from Volume 2 - Energies, contained in the IPCC report of 2006 (IPCC, 2006a). This report offers coke emission factors divided into three categories: "Default Emission Factor", "Upper" and "Lower". Furthermore, the EF used are associated with "Coking Coal" fuel and are referent only to CO_2 emissions (Table 3).

Table 3: Coking Coal emission factor available on the IPCC Report of 2006. Source: (IPCC, 2006a, p.16).

Coking Coal (tCO_2/TJ)	Lower	Default Emission Factor	Upper	Reference
$\mathbf{EF_{coke}}$	87,3	94,6	101	(IPCC, 2006a)

$$\mathbf{1)}\ E_{H2} = P_n * E_{BF} * EF^{I}_{blue\ H2}$$

$$\mathbf{2)}\ E_{coke} = P_n * E_{BF} * EF_{coke}$$

$$\mathbf{3)}\ E_{total\ (t\ CO2/\ t\ hm)} = E_{coke} + EF_{hm} + E_{H2}$$

Figure 4: Equations used to calculate the CO_2 emission values per ton of hot metal generated by hydrogen (1) and coke (2), that were added to the pig iron (EF_{hm}) emissions to find the final CO_2/thm values (3).

RESULTS AND DISCUSSION

Throughout the MIOM development and results, it was possible to determine that primary products related to the Brazilian basic iron and steelmaking processes (iron, steel and iron alloys) are the main GHG and CO_2 emissions sources. Figures 5 and 6 demonstrate the MIOM results, in kg of GHG per Euro and kg of CO_2 per EUR, respectively. Furthermore, Brazil's first position as seen on the left side of these figures is followed by the sum of all other countries' emissions data, except Canada and Japan, which are described separately in both figures due to their slightly higher emissions. This CO_2 distribution observed in Figures 5 and 6 is better represented in Figure 7 graphics, showing the predominance of direct emissions in the steel industry.

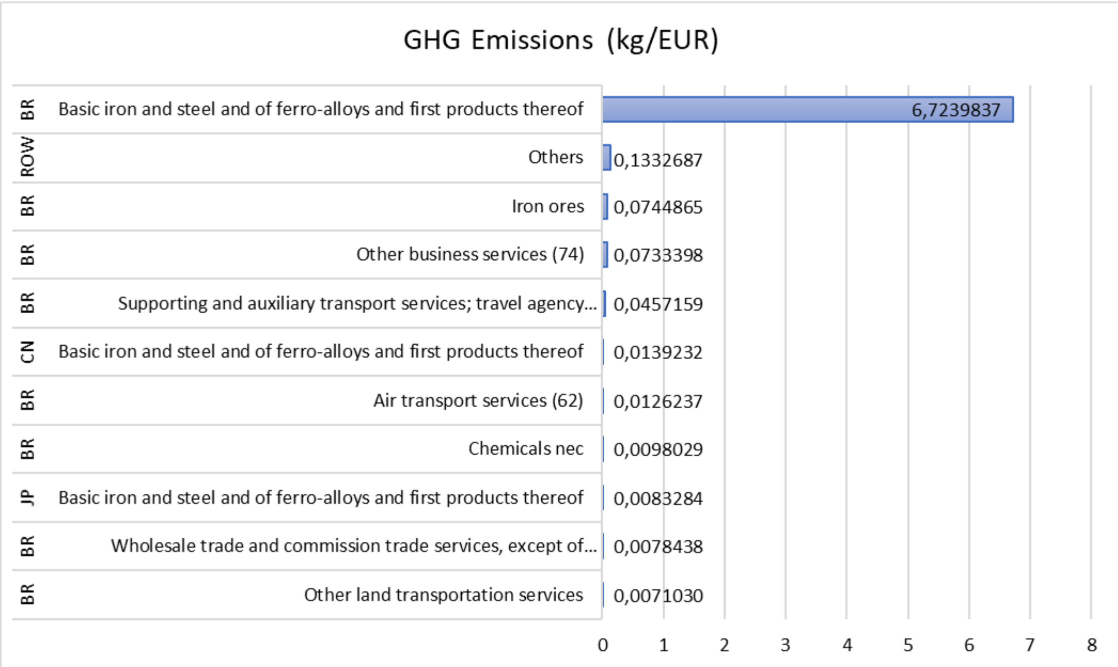

Figure 5: MIOM results represented by kg of GHG emission per EUR.

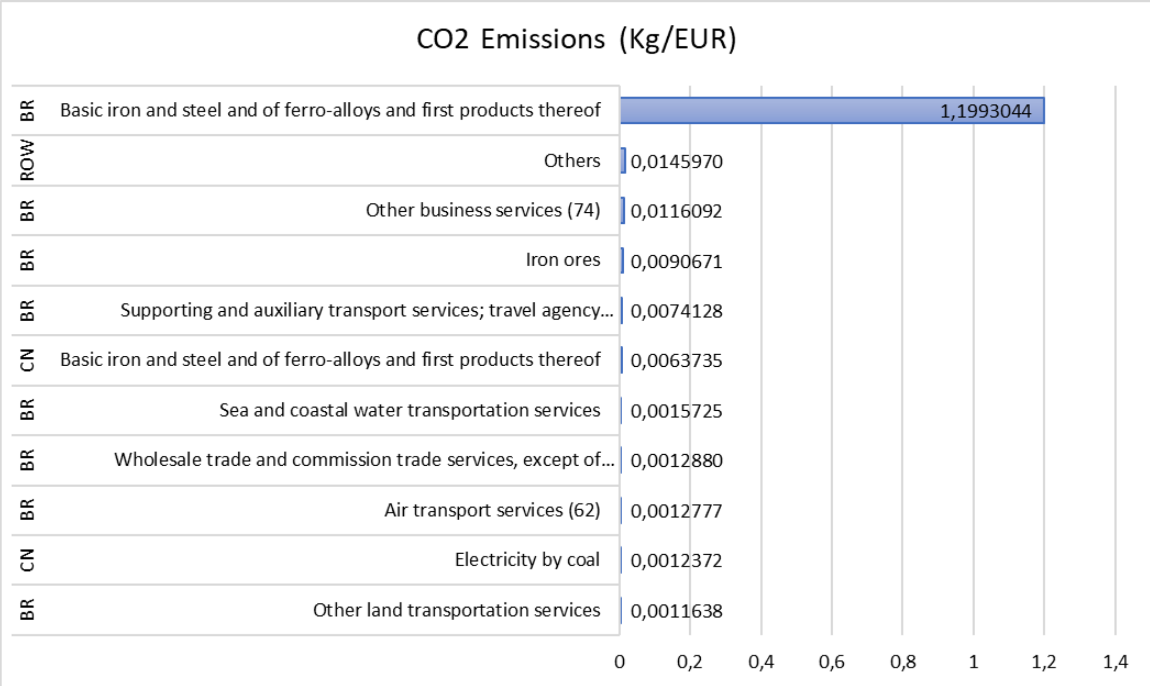

Figure 6: MIOM results represented by kg of CO_2 emissions per EUR.

Thus, through Fig. 7 it was also possible to observe that direct emissions, represented by Scope 1, are the main source of GHG and, consequently, CO_2 in the iron and steel manufacturing chain. Other reports already have demonstrated a predominance of CO_2 emissions in the same basic primary processes (IEA, 2017). Furthermore, as most of CO_2 emitted are from direct emission sources, many companies only offer Scope 1 database in their GHG inventories. Despite almost all of these GHG emissions coming from CO_2, these inventories are usually expressed only in CO_2e units. This is why Table 4 emissions are only expressed defined on CO_2e, not CO_2 metric unit.

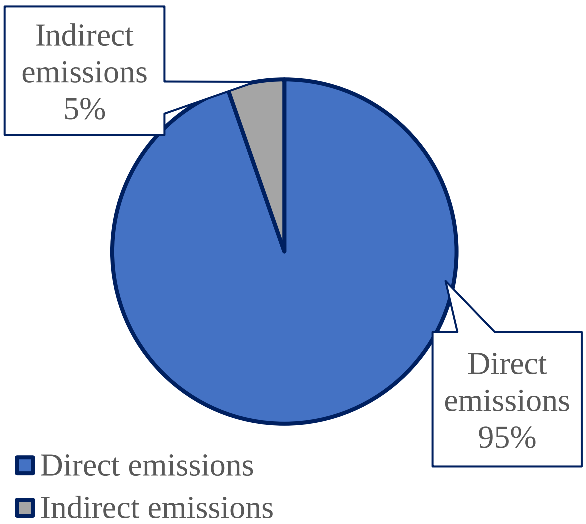

Figure 7: Steel production chain emissions separated into direct and indirect emissions, obtained through MIOM.

Table 4: Main Brazilian integrated steel mills, their Scopes 1 and 2 emissions expressed in tons of CO_2e and their main strategies for reducing emissions.

Integrated steel mills	Scope 1 (tCO_2e)	Scope 2 (tCO_2e)	Total	Strategies and Plans for combating and managing emissions
ArcelorMittal Mineração - Andrade	30.523,62	NA	30.523,62	**Carbon Guiding Plans -** Significant emission reductions by 2030; **Climate Action Report** (ArcelorMittal Worldwide) - Carbon neutral in Europe by 2050.
ArcelorMittal Vega	83.407,28	NA	83.407,28	**Emission reduction projects**: **1) AMT:** (i) Partial replacement of coal and coke with natural gas in blast furnace; (ii) Long Segment VPS Projects - Reduction of Natural Gas consumption (Efficiency); (iii) Transport of Coils by Cabotage; (iv) Cogeneration of Electric Energy through the reuse of LDG; (v) Cogeneration of Electricity from Heat Recovered in Heat Recovery; 2**) Juiz de Fora steel mill:** (i) Pig iron production with renewable reducing agent and methane reduction in carbonization; (ii) Reuse of BFG in the lamination reheating furnaces.
ArcelorMittal Barra Mansa	27.446,65	NA	27.446,65	
ArcelorMittal Mineração - Serra Azul	11.910,11	NA	11.910,11	
ArcelorMittal Piracicaba	111.412	NA	111.412	
ArcelorMittal Monlevade	2.167.463	NA	2.167.463	
ArcelorMittal Resende	61.559,33	NA	61.559,33	
ArcelorMittal Tubarão (AMT)	11.881.072	NA	11.881.072	
ArcelorMittal Juiz de Fora	67.725,4	NA	67.725,4	
Ternium Brasil	9.667.696	NA	9.667.696	**Energy Efficiency Plan** within the scope of the energy management system (EMS): Combustible Gas Balance Automation in progress as a basic improvement project for the management of the GHG inventory.
Usiminas: Ipatinga steel mill	7.515.019	110.337,0	7.625.356	Monitoring program consisting of continuous measurement equipment, installed in the main chimneys, and isokinetic monitoring, both for controlling emissions from dedusting systems and from the combustion
Usiminas: Cubatão steel mill	137.814	25.050	162.864	

				processes of the steel plants. Regions air quality where it operates is checked by continuous monitoring stations located around its industrial plants.
Gerdau	9.056.519	2.890.986	11.947.505	Circular economy strategies such as the use of ferrous scrap, reuse of waste as co-products. Participation in the Emissions Trading System Simulation of Fundação Getulio Vargas (FGV) on the carbon market. Use of charcoal as a bioreductive agent in BF.
NA: not available information.				

The second methodologic step was researching emission inventories of Brazilian integrated steel mills (Table 4). The research has shown that ArcelorMittal company comprehends the majority of the data collected, and has ArcelorMittal Tubarão (AMT) and as the main CO_2e emitting plants (Linke; ArcelorMittal, 2019). Gerdau appears to be similar to AMT's total emission value, but Gerdau's emission is related to all its Brazilian steel mills (Figure 8). Compared to ArcelorMittal Brasil, Gerdau's mills hold almost 6 Mt less (Gerdau, 2019; ArcelorMittal, 2020).

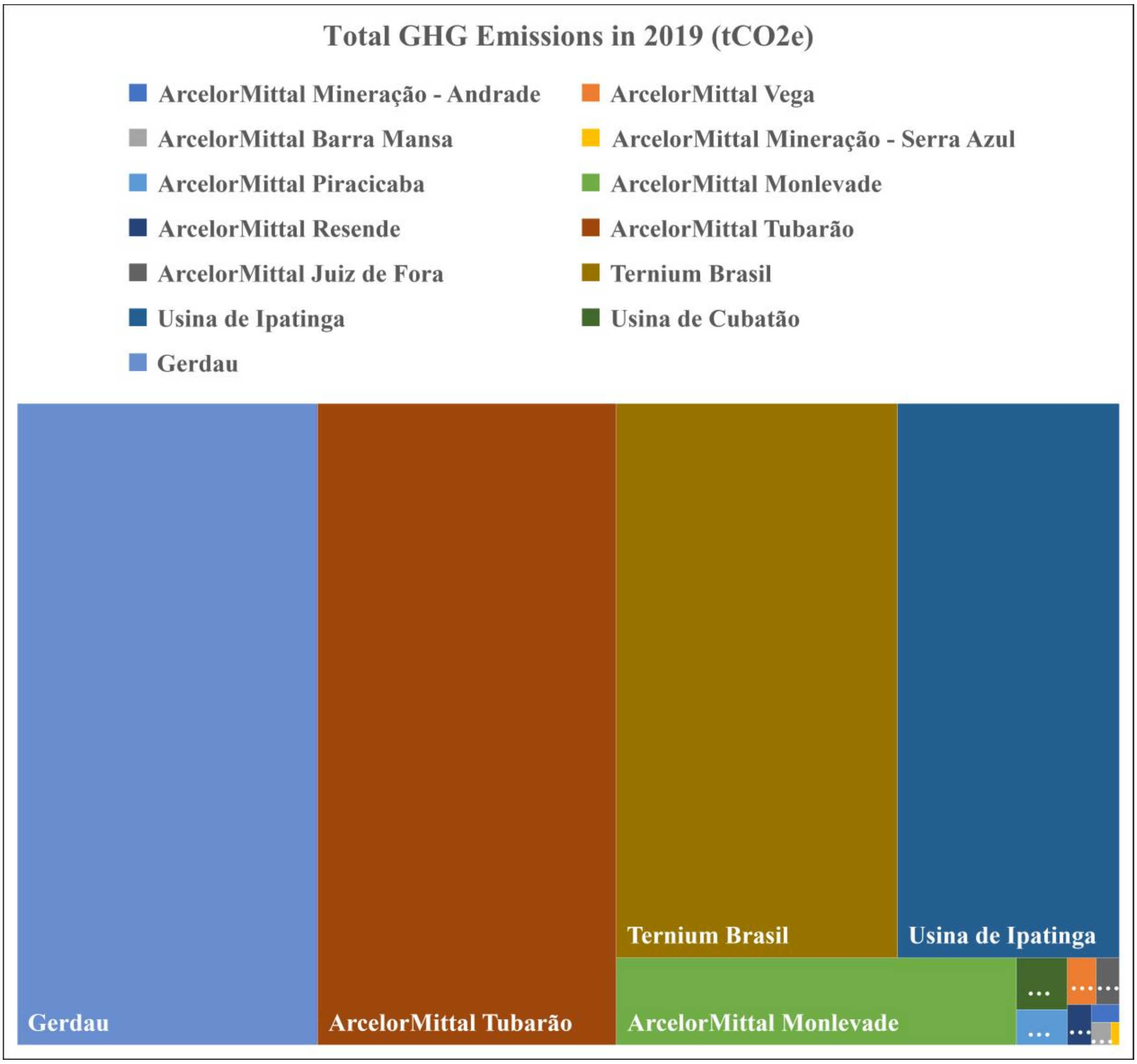

Figure 8: Graphic representing the Brazilian Integrated steel mills emissions in tCO_2e in 2019.

Throughout the research, strategies and plans for combating and managing emissions were found, and AMT is the one that has more initiatives until the present moment. Among these strategies in AMT (Table 4) are the partial replacement of coal and coke with natural gas in BF; the use of cabotage transport; and cogeneration of electric energy through the reuse of basic oxygen furnace gas and the heat recovered at the Heat Recovery unit, that are part of the ArcelorMittal Clean Development Mechanism (ArcelorMittal, 2019). Due to this steel process gases reuse, AMT stands out among other plants for its clean energy cogeneration system (ArcelorMittal, 2018).

Moreover, AMT has a history of working on climate change, introducing clean technologies since 1990 and being the first integrated steel mill to approve a Clean Development Mechanism project in the world (ArcelorMittal, 2020). More recently, with a received investment of R$ 50 million, AMT concluded the construction of the biggest desalinization plant in Brazil. The treatment plant will allow the production of up to 500 m^3/h of industrial water for use in the AMT unit (ArcelorMittal, 2020). Thus, implementing proposals for technological innovation in AMT is a good option as it is not only the biggest crude steel producer mill in Brazil, almost 5 Mt in 2020 (IAB, 2021a), but also it has shown intentions to search for a more sustainable industry (ArcelorMittal, 2020).

Another advantage of AMT steel plant is its geographic position (Figure 9), which allows the development of new innovative projects for technologies such as hydrogen and possibly CCU or CCS. The infrastructure and the energy self-sufficiency potential available, combined with the high investments, favorable location and climate change reduction targets, make AMT one of the main options for introducing new low-carbon technologies. As presented in Figure 9, the Brazilian gas pipeline was included in order to verify if it would be possible to transport gases such as H_2 to other locations. AMT is also located near the Praia Mole port terminal, which gives it a strategic position.

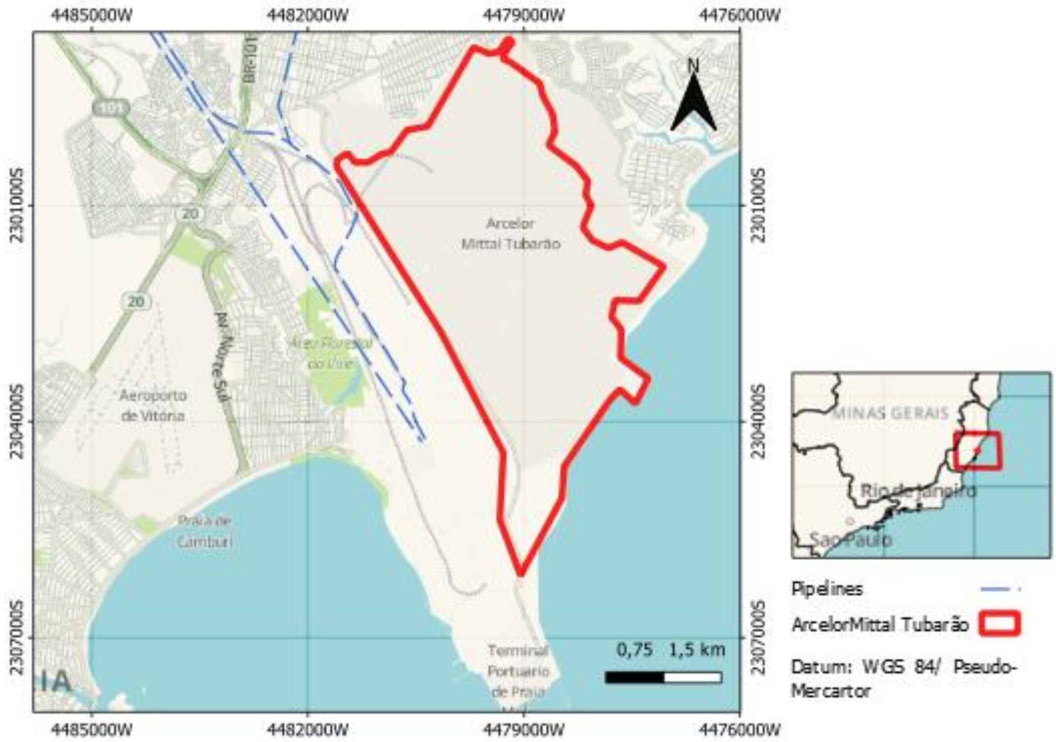

Figure 9: ArcelorMittal Tubarão geographic location map, with the presence of the Brazilian gas pipeline that crosses the site. Source: author.

The introduction of new low-carbon technologies, in this case, blue and green hydrogen, in AMT steel mill, is the final process that this work sought to analyze. After collecting data from AMT (Ludgero, 2018), four scenarios were developed using Tables 2 and 3. They can be divided into 1) using 100% of coke as reducing agent in BF; 2) with 70% coke and 30% blue H_2; 3) using 60% of coke and 40% of blue H_2, and 4) using 60 % of coke and 40% of green hydrogen. In the first scenario, all fuel used in BF was coke, and PCI was not considered separate from coke.

The same was assumed for scenarios 2, 3 and 4, that added hydrogen as auxiliary fuel. The scenarios considered a tuyeres hot injected H_2 into BF as fuel and showed that green H_2 is the best alternative technology (Figure 10). The biggest reduction of CO_2 emissions occurred on scenario 4 (Table 5) values. These reductions accounted for an almost 22% lower emission values on the "Upper" and "Default" columns in scenario 1. The "Lower" column showed an emission reduction about 21% between the scenarios 1 and 4. Although, the use of blue H_2 (scenario 2 and 3) compared to scenario 1 values demonstraded subtle changes. These variations of the three categories in Table 5 can be found in Figure 10, highlighting the "Upper" CO_2 emission values behavior.

Table 5: Four scenarios characterization and their results related to the used coke emission factor (Table 3), which has three values (lower, default and upper).

			Emissions (tCO_2/thm)		
Scenario	**Fuel**	**P_n (%)**	**Lower**	**Default**	**Upper**
1	Coke	100	3,76	3,92	4,06
2	Coke	70	3,71	3,82	3,92
	Blue H_2	30			
3	Coke	60	3,69	3,79	3,87
	Blue H_2	40			
4	Coke	60	2,98	3,08	3,17
	Green H_2	40			

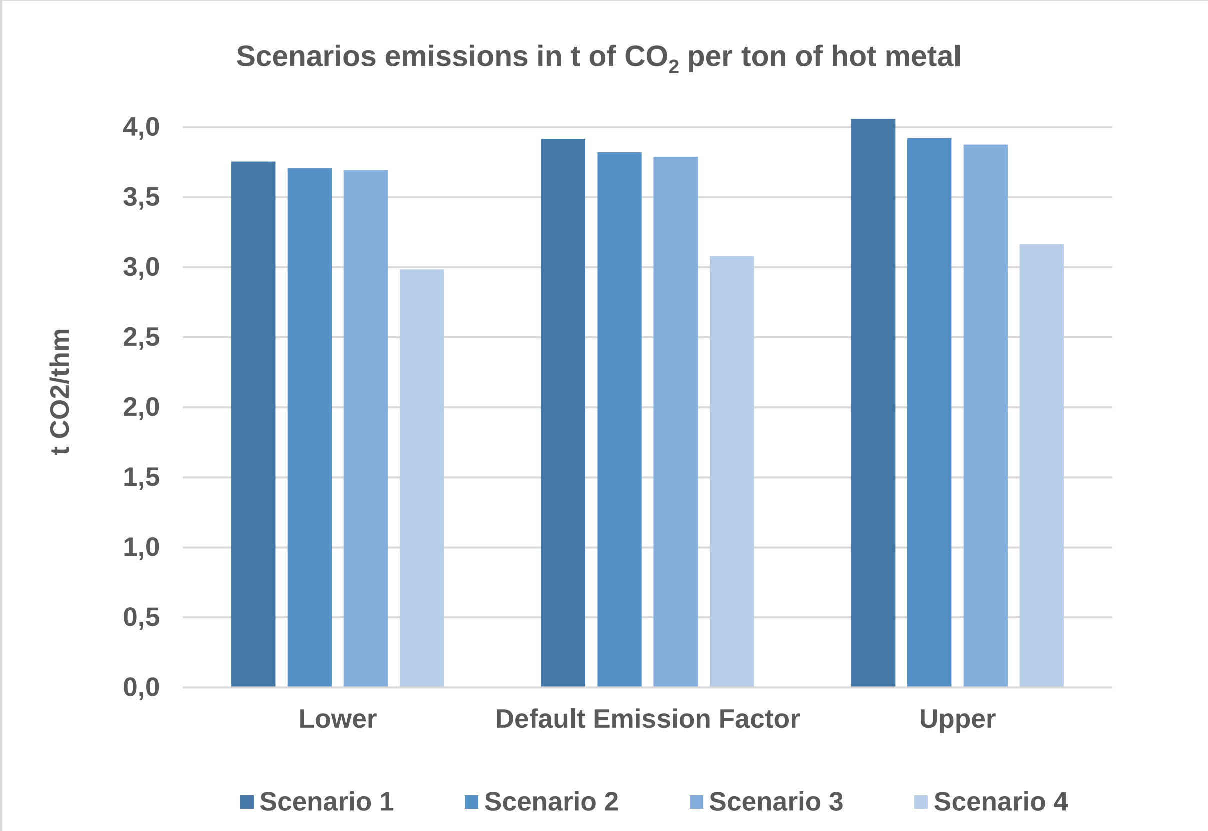

Figure 10: Scenarios results described in Table 5, comparing the use of blue H_2 in "2" and "3", and green H_2 in "4".

Heavy industries such as steel may have specific factors such as high-temperature heat requirements, long plants lifetimes (30-40 years), global market trade considerations that make emissions hard to abate and endear costs for low-carbon technologies development and applications (IEA, 2020a). Although, the results obtained in this work corroborated for demonstration of H_2 usage in the ironmaking process as a possible CDA technology to reduce CO_2 emissions in AMT. Green H_2 proved to be the best option according to the established scenarios. So, the main question starts to be how green H_2 could be implemented in AMT.

AMT is a steel mill whose infrastructure could allow the adoption of clean technologies. Charcoal has been already used in the form of PCI to decrease BF CO_2 emissions. BFG is also reused as a heat source through Heat Recovery (see Table 4).

Despite biomass charcoal good opportunity in Brazil, the technology can not totally supply ironmaking demand in BF at an integrated steel mill as AMT. Charcoal has low mechanical resistance properties, which requires a bigger volume to equalize with the productivity provided (EPE, 2018). So, using charcoal as the only carbon source would be economically unfeasible. Thus, charcoal as PCI can simultaneously be injected with H_2, promoting more emission reduction to the ironmaking phase, as none of them can supply entirely BF requirements (Nogami et al., 2014; Hoffmann et al., 2020).

In the case of BFG, the surplus gas could be captured by CCS technology. BFG is composed of CO, CO_2, and H_2, and it is mainly recovered, cleaned, and reused for hot steam (injected through the tuyeres) and electric energy cogeneration (EPE, 2018). The co-products usage has been a good alternative to improve energy efficiency or even export off-site. However, these alternatives might not be enough in the medium to long-term, so breakthrough technologies can become the best option as soon as they reach commercial size and readiness levels (WSA, 2021a). Thus, the CCU, CCS, and H_2 are found in this context of disruptive technologies.

CCU technology may be a good strategy, but it is not available on an industrial scale. CCS technology is less favorable due to transportation cost to the storage location (Bhaskar et al., 2020; Hoffmann et al., 2020). Hydrogen usage to increase BF efficiency is a high-maturity technology available at competitive costs, but if it is produced by fossil fuels (Hoffmann et al., 2020). So, blue H_2 could participate as a transition fuel, implemented in the form of a high-efficiency technology. However, as the results of this article showed, blue H_2 would not reduce emissions compared to the cost generated for producing this H_2. Therefore, it would be more justifiable to focus investments on green H_2.

Green H_2 would require the investment in plants for water electrolysis, preferably onsite or near the steel mill, due to H_2 transportation costs. H_2 can be transported by pipelines or road transport (Vargas et al., 2006). H_2 storage and distribution is also a challenge because it needs cryogenics (for liquid H_2) or high-pressure (for gaseous H_2) tanks (Cabral et al., 2014). Other requirements would be the water source and renewable electricity for the electrolysis demand.

On this context, AMT has the advantage of being located near the pipelines grid (Figure 9), and having a new desalination plant. These characteristics could help the water and transport demand with the right investment. Moreover, renewable electricity could be taken from the Brazilian energy grid, mostly renewable (CGEE, 2010). Furthermore, AMT belongs to one of the biggest steel companies in the world, so with the proper incentives, the investment can certainly be viable. However, the cost analysis for introducing these breakthrough technologies is not part of the scope of this work and, therefore, could be discussed in other future articles.

CONCLUSION

Through this work, it was possible to analyze the influence of H_2 on the reduction of the CO_2 emissions in the AMT steel mill. Initially, green H_2 proved to be the best technological alternative to mitigate these emissions involved in the ironmaking process. Although green H_2 has limitations when used in the BF, which could be resolved by adding charcoal as PCI and a substitute fuel for coke, that is added to the BF, increasing the CO_2 emission avoidance.

Furthermore, the BFG recovery and carbon capture technologies such as CCS and CCU could help reduce this emission even more. However, specifications from AMT's blast furnaces and implementation costs need to be addressed in order to conclude the best cost-beneficial way to reduce CO_2 emissions.

Moreover, it is expected that in the long-term Brazilian steel industry will start to implement secondary mills, so producing steel by the EAF route. Thus, the present work proposes using H_2 as a transition element in the sector, until the production of direct reduced iron through the EAF using green H_2 is implemented in Brazil. For a broader discussion, researches should be produced, relatives to other technologies applications and costs in AMT, using more recent data.

Finally, due to the COVID-19 pandemic, the steel industry was affected by investments and production decreases, requiring a high recovery in the next years. In this sense, increasing public interest in low-carbon technologies and climate change discussion might motivate industries to recover by adopting more sustainable projects focusing on CO_2 mitigation. Therefore, government support is essential to provide long-term visions backed up by detailed clean energy strategies involving measures that are tailored to local infrastructure and technology needs.

CONCLUSÃO

O presente trabalho apresentou uma forma alternativa por meio do potencial do H_2 em descarbonizar o setor siderúrgico brasileiro, bem como suas principais limitações. O H_2 verde apresenta-se como uma boa alternativa de descarbonização futura para usinas siderúrgicas. Ademais, o Brasil tem potencial para ser um importante produtor de H_2 verde devido à alta participação das fontes renováveis na matriz energética, podendo utilizá-lo em diferentes setores, por exemplo a siderurgia, ou exportar para outros países.

Em relação aos estudos de H_2, por este ser um alternativa de baixa emissão ou zero prevista para o longo prazo, este trabalho acrescenta à pesquisa científica desse como elemento de transição para reduzir as emissões de CO_2 e no auxílio ao cumprimento das metas climáticas. Além disso, o estudo fornece possíveis ações para reduzir a pegada de carbono de um dos principais setores industrias do país e apresenta-se como parte dos estudos pioneiros sobre o tema, pois ainda é pouco discutido no Brasil em ambos os ambientes: acadêmico e setores público-privado. Assim, o presente trabalho pode auxiliar na tomada de decisão pelas partes pública e privada para introduzir novas tecnologias e alternativas no setor, estabelecendo as medidas e regulamentações necessárias para a sua incorporação ao meio.

Por fim, o estudo demonstra a necessidade e possibilidade de um mercado de expansão para a área da geociências, voltado ao estudo das mudanças climáticas, energias renováveis, e combustíveis e tecnologias de baixo carbono. O trabalho também associa-se a questão do armazenamento de carbono, o qual envolve o estudo de localidades como formações geológicas e carvernas salinas. Portanto, esse é um tema com aplicabilidade em diversas áreas, que podem envolver assuntos diversos da geociências, como a geologia econômica, ambiental e mesmo mineração.

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