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Supporting defossilization of the metallurgy sector with bio-coal and green hydrogen: A CO_2 emissions assessment

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Supporting defossilization of the metallurgy sector with bio-coal and green hydrogen: A CO_2 emissions assessment

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Abstract. Metallurgy is recognized worldwide as a strategic sector and steel can be used in many areas, from construction, packaging and transportation to the development of renewable energy plants. It is therefore expected that the demand for steel will continue to grow globally. However, the steel sector is the second largest consumer of industrial energy and heavily dependent on the use of fossil fuels. Therefore, much attention is placed on understanding what improvements are possible to reduce the GHG emissions, although the situation in the steel sector is very heterogeneous due to the complexity of the industrial process and the different configurations.

Recently, the production of green hydrogen has gained increasing attention as a clean energy vector which could replace fossil fuels in steel plants, and the process of biomethane pyrolysis is gaining momentum for the simultaneous production of green hydrogen and biogenic coal, without causing additional fossil CO_2 emissions. Based on European projections for biomethane availability until 2030 and 2050, the findings of this analysis confirm the potential contribution of biomethane to support the defossilization of the EU steel sector, ensuring annual climate emission savings from 77.4 to 285.2 $MtCO_2$, depending on the scenario considered, if the methane pyrolysis route is implemented. This paper assesses the environmental benefits of replacing fossil coal and natural gas with renewable alternatives, while also discussing the economic viability enabled by the EU Emissions Trading System (ETS) mechanism.

1. Introduction

The defossilization of the hard-to-abate metallurgy sector requires a radical change of current energy systems. The metallurgy sector currently accounts for approximately 8% of global final energy demand and around 7% of energy sector CO2 emissions (including process-related emissions) [1]. One of the main factors limiting the sustainability of steelmaking processes is the intensive use of fossil coal, which makes the steel sector the largest industrial coal consumer. Furthermore, the massive use of coal coke in metallurgy is not only necessary for energy purposes - it covers around 75% of the energy demand -, but also to produce coke, which is necessary to support chemical reactions for the iron ore refining process [1].

Despite its high energy consumption and significant environmental impact, the steel industry remains a strategic sector in the European framework. In 2020, European crude steel production accounted for 15 % of global production, with Germany leading, and followed by Italy, France and

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Spain. Steel is an essential material across a wide range of applications, from construction and transport to the installation of renewable energy plants, and supports approximately 2.6 million jobs [2]. With a turnover of around 125 billion euros [3], the steel sector an essential part of the EU economy.

At the same time, the European steel sector is responsible for around 4% of the greenhouse gas (GHG) emissions in Europe, with an average of 1.9 tonnes of CO_2 per tonne of steel produced [2]. Therefore, there is an urgent need for the sector to replace fossil coal and fossil fuels with alternative solutions to improve environmental performance, even if the transition to a low-carbon scenario is a major challenge.

In addition, for hard-to-abate sectors, including ironmaking and steelmaking, the EU has established a framework of financial incentives and penalties to steel companies toward cleaner technologies. A key policy instrument in this context is the EU Emissions Trading System (ETS), the world's first and largest carbon market. It ensures that greenhouse gas (GHG) emitters pay for their emissions, thereby creating a financial driver for decarbonization [4].

The ETS applies across all EU Member States, the European Free Trade Association countries, and Northern Ireland for electricity generation, and covers the most emission-intensive sectors. By assigning a monetary value to CO_2 emissions, the ETS effectively supports the defossilization of the metallurgical sector, making low-carbon alternatives more competitive against traditional fossil-based processes.

Recently, the production of green hydrogen has attracted increasing attention as a clean energy carrier. Low-carbon and renewable hydrogen is expected to be a key enabler of the energy transition, as Europe aims to achieve climate neutrality by 2050. In the shorter term, the EU's climate ambition is framed within the Fit-for-55 package, which sets a binding target to reduce net greenhouse gas (GHG) emissions by at least 55% compared to 1990 levels by 2030 [5]. Nevertheless, conventional hydrogen production today is still heavily dependent on fossil fuels and the green hydrogen is still not economic attractive. Almost half of global hydrogen production is carried out via Steam Methane Reforming (SMR), the reaction between methane and high-temperature steam, which emits large amounts of CO_2 as a byproduct [6]. In addition to SMR, two other widely used industrial pathways are partial oxidation (PO) and dry methane reforming (DMR) [7]. None of these three methods are low-carbon technologies: they only become carbon-neutral if coupled with carbon capture and storage (CCS) to sequester the CO_2 emissions. Moreover, to achieve a carbon-negative profile, the use of biomethane feedstock (instead of fossil natural gas) is required together with CCS.

The alternative process for hydrogen production, which does not produce CO_2 but a solid carbon product, is methane pyrolysis, also known as thermal decomposition of methane or direct methane cracking [8]. When biomethane is used as the feedstock instead of fossil-derived methane, the process becomes carbon-negative: the carbon originally captured by biomass during its growth is sequestered in solid form during pyrolysis. This solid carbon can be stored or potentially used in various industrial applications, such as the metallurgy sector.

Building on this approach, the H2STEEL project [9] introduces a breakthrough solution for the sustainable production of green hydrogen and biocoal from circular bio-waste streams via biomethane pyrolysis process, to boost the EU hydrogen economy and the defossilization of the European steel sector. The H2STEEL value chain enables the generation of green hydrogen starting from biomass, biological residues and wastes, which are often expensive and environmentally problematic to dispose of. Unlike conventional methods, the pyrolysis of methane/biomethane avoids the generating of CO_2 emissions, as the carbon is not released in gaseous form but instead captured as a solid byproduct that can be stored and/or utilized in downstream industries. In addition, a key innovation of the H2STEEL concept lies in the use of catalytic pyrolysis, employing carbon-based catalysts derived from bio-waste materials, in a truly carbon negative approach.

To gain a deeper understanding of the green production of hydrogen and biocoal for the steel industry, this study aims to quantify both the environmental impacts and the economic benefits arising from the replacement of natural gas and fossil coal with sustainable alternatives. Based on the results, the study seeks to formulate recommendations for EU policymakers and relevant authorities, in alignment with the European Union's climate objectives and industrial decarbonization strategies

2. Methodology

2.1 Inlet streams

Europe stands as the leading producer of biomethane, a target achieved thanks to a long tradition based on biogas production, which in recent years has progressively shifted toward biomethane upgrading technologies. More specifically, some studies estimate that 41 and 151 bcm of biomethane could be produced in the EU-27 by 2030 and 2050 respectively, compared to a current production of 3 bcm [10]. These projections exceed the RePowerEU target of 35 bcm per year by 2030, underlining the strategic importance of biomethane in achieving the EU's energy and climate goals.

On the other hand, significant biomass and biowaste resources are locally available across Europe, particularly from lignocellulosic biomass, organic fractions of municipal, sewage sludges and industrial waste [11]. These streams may serve as a valuable feedstock for the cost-effective production of waste-derived catalysts. This strategy not only facilitates the recovery of biogenic carbon, but also provides a sustainable pathway for the valorization of waste streams that might otherwise present significant economic and environmental burdens in terms of disposal.

Between 1992 and 2005, for example, an increase in annual sewage sludge production of around 50% was observed, due to improved wastewater treatment systems. Indeed, EU Member States were obliged to connect all municipalities with more than 2000 population equivalents to urban wastewater collection and treatment systems, so that more than 50,000 plants are currently in operation in the EU, producing 9.0–9.5 million tons of dry matter per year. If industrial sludge is included, it can be assumed that the production of sewage sludge in the European Union is around 13 million tons of dry matter per year [12-13].

In addition, 180 million tons of digestate are produced annually in the EU28, mainly from agricultural digestate and to a lesser extent from the organic fraction of mixed municipal waste. More specifically, about 23.7 million tons of dry biowaste are collected annually, from which about 2.5-3.5 million tons of digestate are produced per year [14-15].

Table 1 summarizes the current potential availability of digestates originated from different biowastes (urban separated biowaste, agricultural, mixed municipal solid waste) and sludge (civil and industrial).

Table 1. Current availability of bio-waste streams in EU-27 (on dry matter basis).

Material	Current availability (Mt/year)
Urban biowaste digestate	2.5 – 3.5
Agricultural digestate	18
Civil and industrial sludge	13
Digestate from mixed municipal solid waste	9.2

2.2 Conversion process

In the novel H2STEEL route, green hydrogen and biocoal are produced via Catalytic Methane Pyrolysis (CMP), using biomethane as feed gas and biowaste streams as a carbon-based precursor for the catalyst production. Although metal catalysts are traditionally used in the CMP process (i.e. Ni, Fe, Co, *et cetera*), their rapid deactivation, combined with environmental and economic costs associated with their regeneration, require alternative solutions [16], such as the use of carbon-based catalysts derived from the carbonization process of lignocellulosic material, sewage sludge and digestate. Given the low economic value of the catalyst obtained from biological waste matrices, the regeneration of the carbon-based catalyst, which would result in additional CO_2 emissions, is not necessary. The novelty of the process lies in the complete utilization of the biogenic carbon contained in the bio-waste streams for catalyst production through a combination of slow pyrolysis and chemical leaching, conducted under optimized conditions. In addition, during the CMP process, the carbon-based catalyst becomes progressively enriched with an additional carbon layer resulting from methane decomposition, and becomes a consumable product for the metallurgical company, promoting industrial synergies (Figure 1).

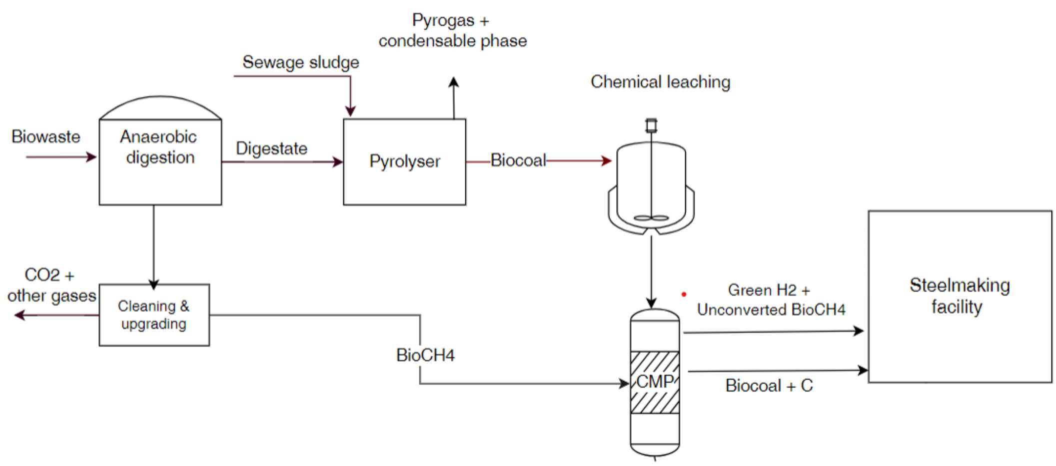

Figure 1. H2STEEL process scheme, including the steps of production of biomethane and upgraded biocoal as catalyst for the CMP process.

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The operating parameters for the CMP process were selected based on values reported in the literature, corresponding to a catalytic decomposition reaction conducted at 850–900 °C and 1 bar [17].
Operational complexities, such as the co-injection of inert gases (e.g., nitrogen) to lower the partial pressure of methane and the additional separation steps required to produce pure hydrogen, were excluded from the model, as these configurations are generally not considered viable at large industrial scales and have economic limitations.

Given the availability of biomethane in the EU-27 by 2030 and 2050, the amount of green hydrogen and biocarbon (only derived from biomethane cracking, without considering the carbon derived from the catalyst) was assessed according to the following reaction describing the complete decomposition of methane:

$$CH_4 \rightarrow C + 2H_2 \quad (1)$$

A methane conversion efficiency of 50 vol% was assumed for the analysis, leading to the simultaneous production of green hydrogen, biocoal, and a fraction of unconverted biomethane.

2.3 GHG balance
The avoided CO_2 emissions associated with the H2STEEL route were assessed by comparing it to a conventional fossil-based reference scenario, based on the following assumptions:

- the green hydrogen produced is assumed to replace the fossil methane on an energy-equivalent basis, and assuming a specific emission factor of 2.75 $kgCO_2/kgCH_4$.
- the biocoal produced is intended to replace fossil coal, assuming a specific emission factor of 2.6 $kgCO_2/kgC$. This value is lower than the stoichiometric factor of 3.67, as it accounts for the presence of residual impurities in the biocoal and the reduction in carbon content and yield due to process inefficiencies.
- The unconverted biomethane is intended to replace fossil natural gas, again applying a specific emission factor of 2.75 $kgCO_2/kgCH_4$.

In conventional steel production, all the carbon is released into the atmosphere in the form of CO_2, with the exception of a small fraction α that becomes incorporated into the steel matrix, and provisionally set at 10% (Figure 2).

The use of renewable inputs—namely green hydrogen, biocoal, and unconverted biomethane—as substitutes for fossil streams such as coal and methane in steel production leads to a net reduction in greenhouse gas (GHG) emissions. These emission savings are eligible under the EU Emissions Trading System (ETS), which enables companies to claim carbon credits for avoided CO_2 emissions. Therefore, the carbon credits from the ETS system were assessed taking into account an average price of 80 €/tCO_2. The avoided CO_2 emissions from the replacement of fossil coal and fossil methane with CMP products were considered under the assumption that all biomethane available in 2030 and 2050 will be used for this pathway. It is worth noting that the carbon sequestered in the steel -and not emitted into the atmosphere- is not covered by the ETS system.

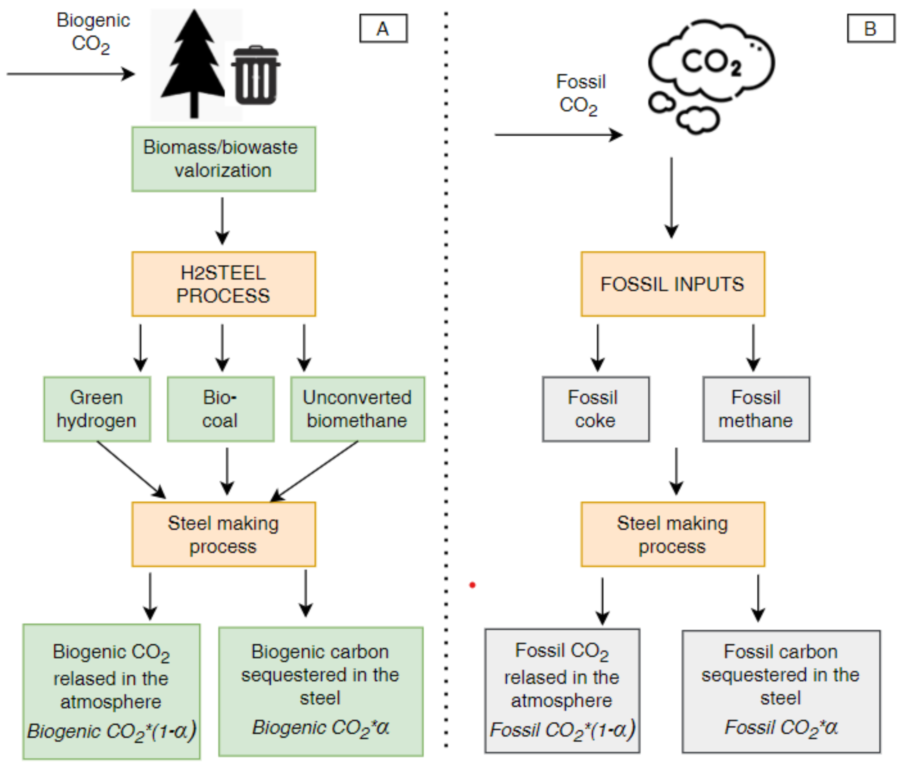

Figure 2. Methodology for the assessment of GHG savings when a biogenic route is performed (a), in comparison with a traditional and fossil route (b). Orange blocks: process blocks. Green blocks; biogenic items. Grey blocks: fossil streams.

3. Results

With respect to biomethane availability projected for 2030, the H2STEEL route presents significant environmental benefits. Specifically, it would enable the generation for industrial application of up to 3.4 million tons of green hydrogen and 10.1 million tons of solid carbon, with 13.5 million tons of unconverted biomethane recovered. This valorization of renewable resources contributes directly to displacing fossil-based feedstocks in steelmaking processes. In parallel, a significant reduction in net CO_2 emissions in the steel sector could be achieved. Based on the modelled scenario, the avoided emissions accounted for around 77 million tons of CO_2, resulting in economic savings of € 6.2 billion, calculated according to the current average price of €80 per tonne of CO_2 under the ETS. These savings are considerable, but they are based on the assumption that all available EU biomethane is used for CMP and that the resulting products are fully utilized within the steel industrial value chain.

Table 2 provides a comprehensive summary of the key figures related to the H2STEEL pathway for three reference years -today, 2030, and 2050-, corresponding to different levels of biomethane availability within the EU-27, and showing the amount of green hydrogen, biocoal and not converted biomethane, as well avoided CO_2 emissions emitted into the atmosphere, and economic savings. In addition, Figure 3 shows the estimated annual CO_2 emission reductions achievable through the H2STEEL pathway under different time scenarios (Today, 2030, 2050), broken down by contribution from green hydrogen, biocoal, and unconverted biomethane. The avoided emissions are calculated based on the replacement of fossil-based counterparts (coal and methane) in steelmaking processes.

As the steel production sector is subject to the EU ETS, the European carbon pricing system, the direct reduction of CO_2 emissions leads to carbon credits and significant economic benefits. Larger annual savings are expected for 2050 and are estimated at € 22.8 billion due to the higher availability of biomethane; however, it is important to underline that this figure only reflects the value of the carbon credits derived from reduced emissions, and a further assessment should also take into account the investment and operational costs associated with deploying the H2STEEL route at industrial scale, in terms of both CAPEX and OPEX.

Table 2. Main figures for the scenario at 2030 and 2050 in EU-27, considering that all the available biomethane is employed to catalytic methane cracking.

Reference year	**Biomethane available**	**Green hydrogen**	**Biocoal***	**Unconverted bio-methane**	**Total CO_2 savings****	**Carbon credits (EU-ETS allowances)**
Today	3 bcm	0.2 Mt	0.7 Mt	1 Mt	5.7 Mt	0.5 b€
2030	41 bcm	3.4 Mt	10.1 Mt	13.5 Mt	77.4 Mt	6.2 b€
2050	151 bcm	12.5 Mt	37.2 Mt	49.6 Mt	285.2 Mt	22.8 b€

* Derived solely from cracked biomethane, excluding the contribution of the carbon catalyst.

** Excluding the carbon sequestered in the steel and not released into the atmosphere (α value). Therefore, it is not considered in the EU ETS mechanism.

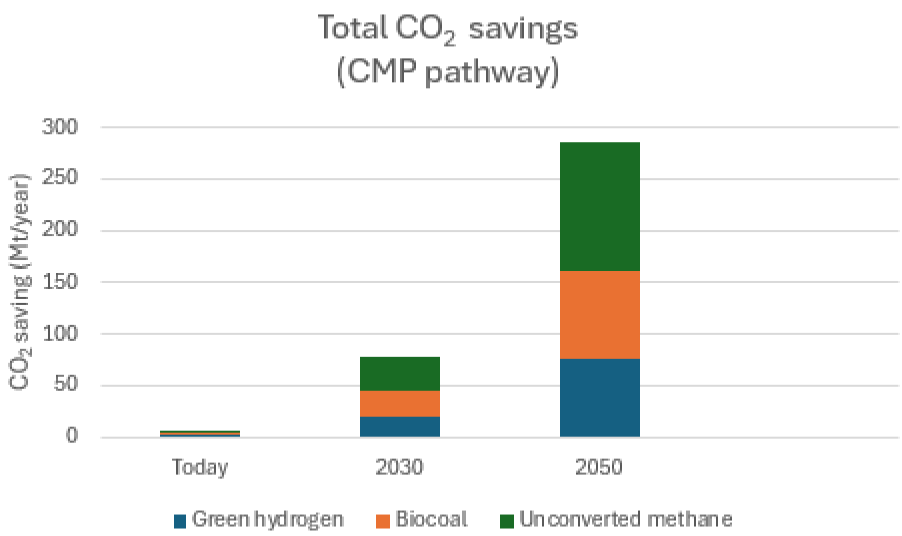

Figure 3. Estimated annual CO_2 emission reductions achievable through the H2STEEL pathway under different time scenarios (Today, 2030, 2050), broken down by contribution from green hydrogen, biocoal, and unconverted biomethane.

In parallel, an assessment of the demand for biowaste streams was carried out to evaluate whether the annual availability within the EU is sufficient to meet the requirements for the production of carbon-based catalysts fom CMP. Based on the mass balance outlined earlier, about 16.2 million tons of biochar-derived catalysts are needed in the current scenario ("Today"). In comparison, the total available biowaste streams in the EU amount to an estimated 43.7 million tonnes per year, measured on a dry matter basis (Table 1). While this indicates a theoretical surplus of feedstock, further analysis is necessary to define appropriate allocation strategies. Therefore, further considerations are required to evaluate how to prioritize the use of biomass (and biometahne) across EU strategic sectors in accordance to EU sustainability and decarbonization objectives.

4. Conclusions

The EU Emissions Trading Scheme is a cap-and-trade system designed to reduce greenhouse gas emissions by setting a cap of emissions for certain sectors of the economy. Steel production falls within the scope of the ETS but also other industries, such as the cement industry, are also subject to the same conditions. Therefore, the ETS framework can promote the proposed H2STEEL value chain and increase its market value, opening new opportunities thanks to the supply of large amounts of green hydrogen and biocoal produced by biomethane pyrolysis.
This approach delivers substantial environmental benefits for the steel sector, notably through avoided CO_2 emissions, while also offering significant economic returns through ETS carbon allowances, especially at current high carbon prices.
However, it is important to note that biomethane is a limited resource, as it relies on the availability of feedstocks suitable for anaerobic digestion. Other sectors, such as transport and industries that are difficult to electrify, could also benefit from its use. Therefore, strategic prioritization is essential, and biomethane should be allocated to those applications that maximize GHG savings, in alignment with broader EU climate targets and energy system integration strategies [18]. In addition, it is worth noting that the EU ambitious production targets—such as the 41 bcm/year by 2030— are very ambitious, and their achievements depend on several factors, including policy support, normative challenges and infrastructure investments.

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