Original Article

Biomass and energy connected with iron and steelmaking

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Abstract

This contribution elucidates the global evolution of iron and steelmaking, addressing critical concerns related to greenhouse gas emissions, energy utilization, and biomass integration. According to the findings presented in this paper, the future sustainability of iron and steelmaking, with minimal environmental impact, hinges on the widespread adoption of renewable energy sources. Specifically, the emphasis should be placed on harnessing the untapped potential of waste energy generated during the iron and steelmaking processes. This involves optimizing the utilization of energy derived from agricultural waste, organic waste sourced from urban areas, and livestock waste. By fully capitalizing on these energy sources, a substantial reduction in greenhouse gas (GHG) emissions from the iron and steel industry can be realized over the next 30 years. Consequently, this research endeavors to outline viable pathways for the steel industry to facilitate the decarbonization of their production processes.

Keywords: Environment; Energy; Iron and steelmaking; Decarbonization; Green house gas.

1 Introduction

Presently, there exists a global consensus emphasizing the imperative need to diminish the combustion of fossil fuels for the purpose of mitigating Greenhouse Gas (GHG) emissions. As depicted in Figure 1, the global energy matrix is predominantly reliant on fossil fuels. The paramount challenge for nations lies in substituting these fossil fuels, especially concerning the reduction of carbon dioxide (CO_2) emissions.

The substantial consumption of fossil fuels is predominantly propelled by the industrial sector. Since the onset of the industrial revolution, global industrial activity has witnessed a continuous escalation in production, consequently leading to heightened energy consumption, predominantly sourced from fossil fuels as showed in Figure 1 [2]. This trend has positioned the industrial sector at the forefront of discussions pertaining to GHG emissions.

The industrial sector, with a particular emphasis on steel production, stands as the primary focus for concerted decarbonization endeavors. In countries such as Brazil, endowed with abundant natural resources, biomass emerges as a strategic raw material applicable to both the steel industry and electricity generation. Brazil uniquely contributes to the global energy landscape with a distinctive matrix, comprising 54% from non-renewable sources and 46% from renewable sources, including hydro, wind, solar, and biomass [3].

The steel industry holds a pivotal role in a nation's economy, with its production intricately linked to the economic and social development of a country. However, it is crucial to recognize that the steel industry accounts for a substantial share of global carbon dioxide (CO_2) emissions, ranging from 6% to 10% of the total worldwide CO_2 emissions. Furthermore, within the industrial sector, the steel industry is responsible for approximately 25% of CO_2 emissions [4].

The blast furnace stands as the prevailing conversion process for contemporary steel production, and it is anticipated to maintain this dominance for an extended period, generating over 94% of primary iron globally [5].

The energy consumption and carbon dioxide (CO_2) emissions associated with the blast furnace constitute approximately 70% of the overall activities in steelmaking [6].

China takes the lead in worldwide crude steel production, contributing to slightly more than half of the total global output. According to He et al. [7], of the 1.9 billion tons produced, around 70% originated from the Blast Furnace – Basic Oxygen Furnace (BF-BOF) route.

Table 1 provides the steel production over 2021 and 2022, illustrating that several countries have a decrease of crude steel production from 2021 to 2022, except the emerging production countries as India, Brazil and Iran.

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An intriguing revelation is presented in the Net Zero by 2050 report by the International Energy Agency [6], 2021, indicating a roughly 5% reduction in CO_2 emissions within the industry in 2020, attributable to the deceleration induced by the pandemic. The report further underscores that the steel sector is poised to experience an approximate 12% increase in steel demand by 2050, necessitating an investment of around 10 trillion dollars to achieve Net Zero Emissions (NZE). Despite these efforts, the steel industry is projected to retain the use of coal in 2050, primarily for its role as a reducing agent, albeit in conjunction with Carbon Capture, Usage, and Storage (CCUS). Notably, the report concludes that a significant portion (85%) of CO_2 reductions in steel production by 2050 will be linked to the adoption of alternative materials and the enhanced efficiency of materials and processes, particularly in emerging countries.

Furthermore, estimates from [9] suggest that the global steel industry could face a 14% loss in potential value if it fails to mitigate its environmental impact. Consequently, prioritizing decarbonization becomes imperative to sustain economic competitiveness and maintain operational legitimacy. The challenges in meeting the decarbonization imperative include protracted investment cycles, spanning 10 to 15 years, substantial financing requirements in the multibillion-dollar range, and limitations in supplier capabilities.

This work aims to offer insights into low-cost alternatives, specifically those involving waste, for reducing emissions in the steel industry.

A compilation of selected works obtained through keyword searches, including biomass, waste, iron and steelmaking, and livestock, utilizing the Boolean operator AND will be presented. In addition, the main objective is to stimulate discussions on the subject among readers and researchers in the field.

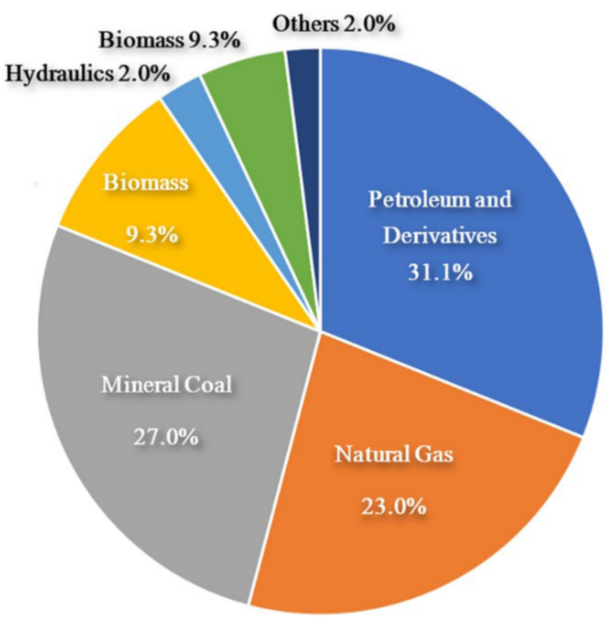

Figure 1. World energy matrix in 2021 [1].

2 Use of biomass in the iron and steelmaking

The utilization of biomass represents the oldest method of supplying energy to humankind and was historically employed, even within the steel industry until the early 20th century, serving as the primary reducing agent in blast furnaces. Contemporary perspectives view biomass favorably in the steel industry, particularly by the World Steel Association (WSA), as it is considered emissions-neutral, contingent upon its sourcing from reforestation areas and/or waste.

Biomass exhibits versatility across various steelmaking processes [10], offering benefits such as sustainable steel production and reduced process costs. However, for widespread adoption in the short term, additional investments in research and technology are imperative to adapt biomass seamlessly into steelmaking processes. Presently, steel mills face the challenge of producing cost-effective, high-quality steel with minimal greenhouse gas (GHG) emissions [11].

Despite its appeal for cost reduction and CO_2 emission mitigation, the global applicability of biomass is constrained by climatic and territorial factors. Regions in South America, Africa, and Australia are particularly favored for biomass production and resource availability [12].

Table 1. World crude steel production [8]

Rank	Country	Production (Mt)	
		2021	2022
1	China	1 035.2	1 018.0
2	India	118.2	125.3
3	Japan	96.3	89.2
4	United States	85.8	80.5
5	Russia	77.0	71.5
6	South Korea	70.4	65.8
7	Turkey	40.4	35.1
8	Germany	40.2	36.8
9	Brazil	34.1	36.1
10	Iran	28.3	30.6
World		**1 962.3**	**1 885.4**

It is crucial to highlight that biomass characteristics vary based on type, planting methods, climate, and soil conditions. These factors influence biomass composition and, consequently, its chemical analyses. In comparison to fossil fuels like coke and coal used in the steel industry, biomass generally exhibits lower levels of carbon, sulfur, ash, calorific value, and higher contents of volatiles, hydrogen, and oxygen. Considering these characteristics alone, biomass may not be fully feasible for metallurgical processes. However, treatments such as torrefaction and pyrolysis can enhance biomass properties [13].

The blast furnace and cokemaking processes stand out as having the greatest potential for replacing non-renewable coal with biomass, given that they are the primary consumers of fossil fuels in iron and steelmaking. In cokemaking, biomass can be incorporated into the coal blend to produce coke. Studies suggest that raw biomass may not be optimal for this purpose, primarily due to its high volatile content, which adversely affects coke strength. Figure 2 illustrates various studies evaluating the use of biomass, particularly agricultural waste, in coke production.

The Coke Reactivity Index (CRI) stands as a pivotal parameter for assessing coke quality in blast furnace operations. A higher CRI indicates increased reactivity, leading to faster consumption within the blast furnace. This accelerated consumption can diminish hot resistance (CSR), potentially causing permeability issues within the reactor.

The decline in CRI and CSR may be attributed to the pore structure of biomass, which persists in the coke structure post-coking. The porous nature of biomass, preserved in the coke matrix, acts as an inert material. This porous structure, with an abundance of pores, increases the contact surface with gases, rendering it more reactive. However, it also proves to be less resistant, significantly impacting CSR and CRI parameters [17]. Notably, CRI and CSR exhibit a high correlation index, suggesting that either index is theoretically sufficient to evaluate coke quality [18] highlights the significant advantages of using biomass, particularly the lower sulfur and ash content compared to coal. The lower sulfur content in biomass is advantageous for producing hot metal, and it opens opportunities for using coals with higher sulfur contents, often more economical in the market. Pre-treatments of biomass are recommended for cokemaking, and various studies [19,20], and [21] elaborate on these treatment methods.

Concerning the blast furnace, two primary means of utilizing biomass are through charcoal, loaded from the top of the furnace, and/or Pulverized Coal Injection (PCI). Charcoal offers a significant advantage in terms of CO_2 emissions, being considered emissions-neutral if produced from reforestation sources like Eucalyptus or other wood types [22]. presents a CO_2 emissions balance for hot metal production via a charcoal blast furnace, indicating a positive balance due to CO_2 absorption and O_2 release during photosynthesis. However, challenges include lower productivity compared to coke-fired blast furnaces and the requirement for land availability near plants for wood plantation and charcoal conversion.

Given that the majority of hot metal is produced through coke blast furnaces, a promising avenue for biomass use lies in Pulverized Coal Injection through tuyeres. This technique allows for the adjustment of injected amounts based on biomass availability.

For this purpose, biomass must exhibit specific characteristics, including low ash content, high carbon content, suitable grain size distribution, and high heat value [23].

To assess the feasibility of biomass in PCI, numerous tests have been conducted, particularly using agribusiness residues, at the Federal University of Ouro Preto (UFOP). The university's Pulverized Materials Injection Simulation Laboratory facilitates the simulation of blast furnace combustion zone conditions. Figure 3 illustrates results obtained from simulations conducted at UFOP for various agribusiness wastes.

These tests illustrate the combustion capacity of biomass in the combustion zone. It is evident that biomasses exhibit good combustion efficiency, which tends to decrease with higher injection rates. This decrease is a typical occurrence, as the injection of a larger quantity of material at lower temperatures into the combustion zone increases.

When evaluating the use of biomass in the blast furnace, consideration must be given to material availability. The blast furnace is sensitive to abrupt changes in materials with significantly different characteristics. Hence, a comprehensive analysis—covering technical, economic, and environmental aspects—is essential to ensure a secure replacement of coal.

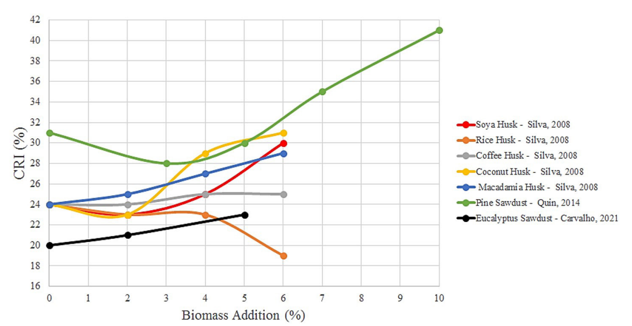

Figure 2. CRI for different biomasses [14-16].

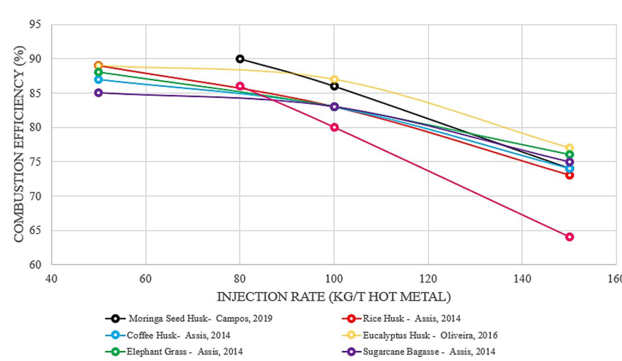

Figure 3. Combustion efficiency for some biomasses with different injection rates [12,24,25].

It's crucial to emphasize that even a partial reduction in the percentage of coal used in the process can yield benefits in terms of greenhouse gas emissions and cost reduction. Substituting a higher-value non-renewable fossil fuel with biomass, which typically has a lower value, can contribute positively to both emission balances and cost management. Therefore, a thoughtful and detailed assessment is necessary to safely implement the replacement of coal with biomass in the blast furnace process.

3 Environment and energy generation

Global emissions of greenhouse gases from combustion, energy, and industrial processes reached their highest annual level in 2021, as depicted in Figure 4. The data reveals a notable increase of 6% compared to 2020, elevating emissions to approximately 36.3 Gigatons (Gt), as reported by the International Energy Agency [26].

The iron and steel industry holds a distinctive position in global economic dynamics, largely owing to its utilization of equipment that necessitates high temperatures for processing. Consequently, it stands as the second-largest energy consumer in the industrial sector. Despite notable advancements in efficiency over recent decades, there remains significant potential for reducing energy consumption and CO_2 emissions by approximately 20%. This translates to potential savings of 4.7 exajoules (EJ) of energy and 350 megatons (Mt) of CO_2 [27].

The demand for steel plays a pivotal role in determining both energy consumption and CO_2 emissions within the sector. Despite a relatively stable demand from 2013 to 2016, global crude steel production witnessed an average annual increase of 3%. Even in 2020, a year marked by economic deceleration in other sectors, there was only a marginal reduction of 0.9% in steel production [26].

Specifically in Brazil, Figures 5 and 6 depict the total energy consumption and fuel usage distribution. Fueled by the integrated coke route, the Brazilian steel industry has the potential to double its greenhouse gas (GHG) emissions by 2050. This presents new and significant challenges for the sector, particularly as domestic steel consumption in Brazil is poised to increase, driven by the demands of infrastructure projects. In this context, it becomes imperative to explore strategies for augmenting steel production in Brazil while concurrently reducing GHG emissions [28].

Table 2 assesses 13 distinct technologies implemented across various steel routes, aiming to elucidate the impacts of energy intensity on the Brazilian steel industry. The provided values correspond to the reference costs within the international industry, and it is important to note that Brazil incurs additional costs related to the location factor when acquiring foreign equipment. This is attributed to tax charges that influence the overall cost, given that the technology in question is not domestically produced.

In the long term, the imperative for emission reductions necessitates a profound exploration of new process routes in the production of primary steel, incorporating modern technologies in smelting, direct reduction, and Carbon Capture, Utilization, and Storage (CCUS). The urgency and innovation required in the coming decade are crucial to laying the groundwork for technologies to be established post-2030. Consequently, substantial support and financial backing from governments and investors are essential to facilitate Research, Development, and Demonstration (RD&D) efforts, accelerating results and enabling the widespread implementation of promising technologies on a large scale [26].

4 Livestock and iron and steelmaking process

The connection between livestock and the iron and steelmaking process is intricately linked to energy and environmental considerations. Some authors have explored

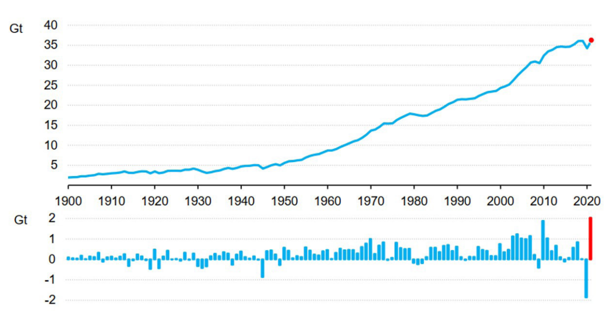

Figure 4. CO_2 emissions related to combustion and industrial processes in the period from 1900 to 2021 [26].

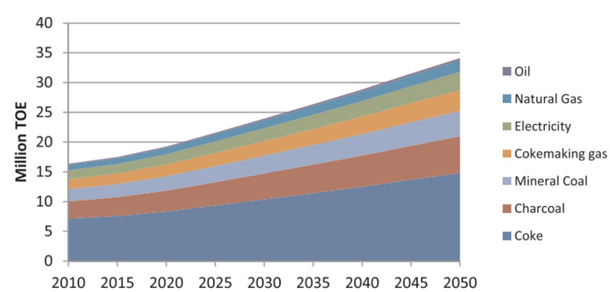

Figure 5. Energy consumption in the Brazilian steel sector [28].

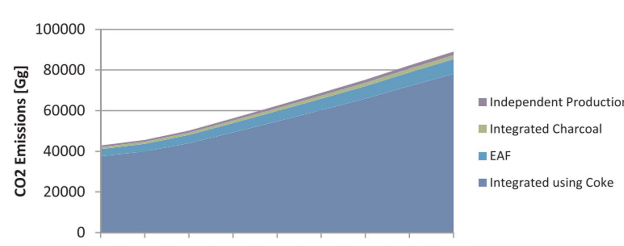

Figure 6. Projection of CO_2 emissions for the Brazilian steel sector [28].

Table 2. Low Carbon Technologies and main technical-economic parameters of Best Available Technologies [28]

Low Carbon Technologies	Route Applied	Installation Costs [USD/tonne]	O&M Costs [USD/tonne year]	Elec. Reduction [kWh/tonne steel]	Fuel Reduction [GJ/tonne steel
Waste Heat Recovery (WHR) on Sintering	Integrated Plants	3.6	0	0	0.40
Oxy Fuel Burners on EAFs	EAF	7.5	2.6	38.7	0
Scrap preheating on EAFs	EAF	12.22	3.0	60.94	0
Advanced Control Systems on EAFs	EAF	12.3	-	0	0.11
Advanced Thermal Power Plants	Integrated with Cokemaking	24	1.46	48.8	0
Variable Speed Drivers (VSD) on BOFs.	Integrated Plants	0.31	-	0.83	0
Coke Dry Quenching	Integrated with Cokemaking	36.7	0.13	0	0.37
Coal Moisture Control	Integrated with Cokemaking	20.2	–	0	0.18
Heat Recovery (HR) from Hot Air Furnaces	Plants with BF	2.2	–	0	0.08
Waste Heat Recovery (WHR) on EAFs	EAF	18.5	1.28	45	0
Top Pressure Recovery Turbine (TRT)	Integrated Plants	28.0	–	55.4	0
Pulverized Coal Injection − 225 g/ton de Steel	Integrated Plants	5.10	–	0	0.51
Sensible Heat Recovery (HR) from BOF	Integrated Plants	24.2	1.21	0	0.92

the possibility of substituting natural gas with biogas in iron production as a viable solution to mitigate the impact of using non-renewable sources on greenhouse gas (GHG) emissions. If the residues from cattle breeding are not utilized, they could be deposited into the soil, leading to the generation of a substantial amount of methane – a greenhouse gas over 20 times more potent than carbon dioxide. This could result in adverse effects on soil and water quality due to the distribution of these residues.

A potential solution to this problem involves the bio-digestion of cattle breeding waste in a controlled environment. In this process, waste is placed in a recipient where, after a certain period, it undergoes transformation into methane and carbon dioxide. Figure 7 illustrates a simple system where this conversion can take place, providing an environmentally sound approach to manage livestock waste and reduce its impact on soil and water quality.

Upon the generation of such gas, consideration arises regarding potential solutions for utilizing both gases. A viable and strategic solution has emerged. These gases can be employed either directly in the blast furnace or, after the reaction between the gases (as described by Equation 1), in a reformer. Through this approach, sponge iron can be produced using a Direct Reduction process:

$$CO_2 + CH_4 = 2\,CO + 2\,H_2 \tag{1}$$

This reaction occurs either in the raceway of the blast furnace if the gas replaces coal or in a reformer to facilitate the use of the reducing gas for sponge iron production in the Direct Reduction Process. There exists a patent where all these possibilities were extensively discussed and substantiated.

Table 3. Steel production based on Biogas from Livestock Waste [30]

Country	Steel Production (10^6 Tons)
India	600
Brazil	500
USA	450
China	400
Japan	300
Total	**2250**

Drawing on global livestock data, Table 3 provides a potential projection of Iron and Steel Production in five selected countries, leveraging livestock waste and organic waste collected in urban areas. The table considers steel production based on sponge iron utilization in the Electric Arc Furnace (EAF) or Basic Oxygen Furnace (BOF), with the caveat that sponge iron is limited to 40% of the burden in the latter case. Naturally, process modifications may be necessary to accommodate such a burden.

As evident in Table 3, the steel production in just five countries has the potential to exceed two billion tons, surpassing the global production in 2021 across all countries. Furthermore, the consequential impact on greenhouse gas (GHG) emissions would be significantly less compared to the scenario where coal or coke is not eliminated.

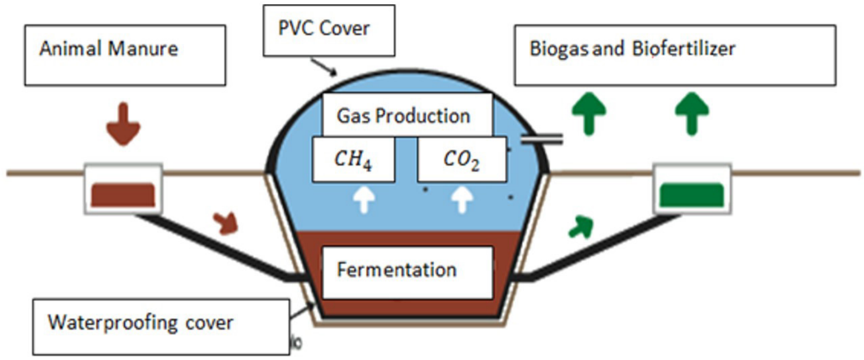

Figure 7. Bio Digestion of Waste generated by Cattle Breeding [29].

5 Discussion

Energy waste takes various forms, including leaving lights on in unoccupied spaces, unnecessary connections of electronics, running empty freezers, keeping refrigerators open while searching for items, using washing machines with small loads, and running high-power equipment unnecessarily (e.g., showers, heaters, air conditioning). Raising awareness about these types of "homemade" waste is crucial as, when multiplied across households, it can lead to significant advantages in reducing overall energy consumption. In addition to household waste, discussions at the last COP meeting in 2021 covered various aspects related to wind and solar energy, climate change, CO_2 emissions, global warming, and investments.

Developed countries worldwide have initiated programs to reduce energy consumption, minimize waste, and implement systems with greater energy efficiency. Factors such as per capita energy consumption, population growth, industrial mechanization, and automation contribute to the overall increase in energy demands. Base load energy sources, which are consistently maintained at 100% of the rated load, include thermoelectric, hydroelectric, and nuclear power. Photovoltaic and wind generation, while not basic, can replace basic generation when produced in excess, reducing reliance on water from hydroelectric lakes and conventional fuels.

Energy storage solutions involve techniques like pumping water to hydroelectric lakes during excess generation or storing energy at electric vehicle charging stations, with decreasing prices leading to increased sales and greater storage in vehicle fleet batteries. Plans for the future consumption of electric cars worldwide exceed 200 TWe.

China has announced plans to install over 100 nuclear reactors with capacities exceeding 1,000 MWe each in the next decade to support economic growth and reduce greenhouse gas emissions. Additionally, a fusion nuclear generator prototype, named ITER, is being developed in the south of France.

Some technical institutes globally are exploring the direct generation of heat without electricity for applications in heating and industrial processes.

Connected with the iron and steel industry, several challenges need to be addressed:

- Maximizing the use of biomass waste in coke making;
- Injecting biomass waste after pyrolysis in iron making;
- Incorporating biomass in the sintering and pelletizing processes;
- Substituting natural gas with biomass in Electric Arc Furnaces (EAF);
- Utilizing waste energy in iron and steelmaking processes;
- Exploring iron and steel production using biogas derived from cattle breeding waste.

6 Concluding remarks

In conclusion, based on the presented data:

- There is potential to reduce global energy consumption through human activities;
- Various forms of energy, such as solar energy, wind energy, and hydrogen, can be effectively utilized in iron and steel production;
- The incorporation of biomass in iron and steel production is crucial for mitigating greenhouse gas (GHG) emissions;
- Achieving the necessary global iron and steel production is feasible by exclusively relying on biogas without the use of coal or coke;
- Utilizing biogas from bio-digested cattle breeding waste can lead to the production of over two billion tons of steel in five selected countries.

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