THE CIRCULAR ECONOMY: A CASE STUDY APPROACH CASE STUDY OF THE PRODUCTION OF METALLIZED BRIQUETS AND THEIR USE IN STEEL BLAST FURNACE

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ABSTRACT

Purpose: This article aims to bring information about the development and manufacture of metallic briquettes under the circular economy context.

Method/design/approach: The methodology used will be the case study descriptive category, in which we have: the description, through the expertise of a metallic briquettes Brazilian company, the local context, according to current legislation in Brazil, information on the cost-benefit ratio of briquettes in steel production and putting an end to the international scene with regard to the so-called circular economy and tripod of sustainability.

Results and conclusion: The metallic briquettes are particularly profitable to use in pig iron production. They are inside circular economy context allow to conclude that use of these briquettes as a part of charge in steel blast furnaces is according with tripod of sustainability.

Research implications: The research contributes to practical application of metallic briquettes derived from the agglomeration of co-products in the chain of production of pig iron. From the theoretical point of view, this work contributed to addressing the scarcity of research involving transformation of solid waste into briquettes as a part of charge in steel blast furnace.

Originality/value: The results obtained in this study are innovative and relevant to the scientific community, in the context of the use of metallic briquettes as a part of charge in steel blast furnace. The potential performance of metallic briquettes inside circular economy context allow to conclude that use of these briquettes is according with tripod of sustainability.

Keywords: Case Study, Circular Economy, Metallic Briquette, Pig Iron, Sustainability, Tripod of Sustainability.

A ECONOMIA CIRCULAR: UM ESTUDO DE CASO ABORDAGEM ESTUDO DE CASO DA PRODUÇÃO DE BRIQUETES METALIZADOS E SUA UTILIZAÇÃO NO ALTO-FORNO

RESUMO

Objetivo: Compreender a contribuição do briquete metalizado na cadeia de produção do ferro-gusa no contexto da economia circular.

Referencial teórico: O briquete metalizado é produto oriundo da aglomeração de finos e lamas de minério de ferro, também conhecidos como coprodutos no setor siderúrgico. Ele pode entrar como carga no Alto-forno para a produção de ferro-gusa. O uso do briquete agrega valor econômico e sustentabilidade à produção de ferro-gusa.

Método: A metodologia utilizada na pesquisa de informações será o de estudo de caso, de categoria descritiva. No estudo de caso, apresenta-se: a descrição, através da expertise de uma empresa nacional que produz briquetes

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metalizados; a contextualização local, segundo a legislação vigente no Brasil; e a sua adequação à proposta do tripé da sustentabilidade e da economia circular.

Resultados e conclusão: Os briquetes metalizados, como insumo inovador na produção de ferro-gusa a partir da lama de aciaria, é de produção viável e lucrativa para o setor produtivo siderúrgico. Dentro do contexto da economia circular permite concluir que a utilização desses briquetes metálicos como parte da carga em altos-fornos siderúrgicos está de acordo com o tripé da sustentabilidade.

Implicações da pesquisa: A pesquisa contribui para a aplicação prática de briquetes metalizados na cadeia produtiva do ferro-gusa. Do ponto de vista teórico, este trabalho contribuiu para suprir a escassez de pesquisas envolvendo briquetes metalizados como parte da carga de produção de ferro-gusa no Alto-forno.

Originalidade/valor: Os resultados obtidos neste estudo são inovadores e relevantes para a comunidade científica, no contexto da utilização de briquetes metalizados como parte da carga em Alto-forno siderúrgico.


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1 INTRODUCTION

The metal briquettes produced by the company under study involve the transformation of steelworks sludges, powders and fines (iron ore fines and other substances) into small agglomerated bodies that serve as a solid iron concentrate for the feeding of blast furnaces for the production of pig iron. In the process of producing the small agglomerates, fines of iron ore and other solid residues are used, generated in the steel processes, such as laminating russetting, as well as agglomerating chemicals and stabilizers. The metallized briquettes produced vary in size, resulting from the pressing system (which can be cold or hot), among other factors, and also, as described in its production, the insertion of special binders, with the aim of obtaining more robust products for delivery to customers in the steel sector.

The information from the metallized briquettes company in this case study allows an analysis of its relationship with the theoretical context of circular economy, by its alignment with the sustainability project of Arcelor Mittal. In this sense, the article conducts an analysis for a better understanding of what are the real contributions, technical, economic and sustainability, that the use of metallized briquettes can bring to the steel production chain of pig iron. This is how the destination of the solid waste from the companies that use metallic briquettes is addressed, and of their relationship with the circular economy.

2 THEORETICAL FRAME

The so-called Circular Economy came to stay and to set the agenda for everyone, companies, governments and societies. Social and environmental responsibility are today inseparable from the work of companies that want to perpetuate their actions in the world. Rather, an idea aimed only at reducing costs in the constructive processes of the industries, has transformed itself into the new economic model. The circularity capacity of the raw materials of the products, are increasingly present in the evaluation and demands of consumers, who are more attentive to the threats of sustainability of their own life on earth (Teixeira et al., 2021).

The industrial metallurgical companies are also moving, since they contribute in a significant way to this new world order. The quest to increase energy efficiency, to reduce
greenhouse gas (GHG) emissions, to recycle and reuse waste that they themselves generate, is on the agenda. Sustainability is generally the goal of companies (AVB, 2023).

2.1 Brief Presentation of the Company Producing Metallized Briquettes

The company that makes metallized briquettes under study is located in the Southeast region of Brazil, within the metropolitan region of Belo Horizonte, in the state of Minas Gerais (Brazil). It is located in a region where there is a large concentration of steel companies known as gouges, which specialize in the production of various products of pig iron. It was initially conceived to advise on the improvement of local steel production and to present an innovative and profitable solution for the inputs of pig iron production. The company currently produces metallized briquettes as its leading product. These feed the regional pig iron blast furnaces as part of their iron concentrate load. The aim of the briquetting company is to achieve decarbonization of the steel production process and align with the Arcelor Mittal Project (2023). To this end, new technologies are being used to reuse the solid waste (among others) from the production processes of the mines and the steel industry. This leads to an improvement in pig iron production, in addition to a decrease in the consumption of charcoal (and mineral) and energy as a whole. Briefly on the alignment of the briquettes company to the Arcellor Mittal project (2023), a scale is expected to be used to measure the progress of the briquettes company (in this case the industrial group) towards the zero carbon gas emission condition. The scale to be created is a user-friendly system, both for internal and external authorities. The score generated by the evaluation, according to the scale, grants the certification of the participating companies so that they can be better remunerated for the steel product they produce (pig iron, steel, etc.).

The metal briquettes produced by the company under study partly consist of the sludge, powders and fines of iron ore, known as co-products. In 2020, they accounted for 4% and 6% respectively of the generation of solid waste from the steelmaking production processes, according to the Brazil Steel Institute (IBS, 2020), in its Annual Sustainability Report in the Steel Sector. About 94% of the generation of solid waste is sold to third parties, who give different classifications and technical destinations according to: the area of operation; base and sub-base of road; leveling of land; agronomic use; concrete aggregates among others. The reuse of this waste by the steelworks themselves consists of only 2% of the total amount, and the passive stock reaches about 36% according to data from 2020 (IBS).

The company that produces briquettes is already participating in the industrial challenge to become more sustainable, therefore, it is aligned with the proposal of the ArcelorMittal project (ARCELOR MITTAL, 2023). In this case, the company seeks new technologies, as well as other companies involved in the project, and consequently certification as sustainable and its resulting zero carbon crediting (AVB, 2023). Understanding this challenge accepted by the company, and transforming it into a window of economic opportunity and of a sustainable character, the company presents the technology of the production of metallized briquettes (briquetting). It presents a technological response to the use of solid waste by the generating companies themselves, since they can consume the metallized briquettes in their current productive process.

2.2 Production of Pig Iron

The process of reducing iron ore into pig iron takes place in the reactors, called the blast furnace. Medeiros et al. (2007), the reactor, in addition to the favorable conditions for the reduction of iron ore, works as a countercurrent heat exchanger. The feed for the blast furnace is basically made up of concentrates of iron and carbon and founders, which are raw materials...
for the production of pig iron. Iron concentrate is generally iron ore benefited in the form of pellets (about 65% iron mass content) or sinter (about 63% iron mass content), coal benefited in the form of coke (about 70% to 90% total carbon) and flux (limestone and dolomite) that will serve to purify reduced iron in the ore, and that will generate a supernatant over pig iron, called slag. Pig iron is produced under thermodynamic conditions by the gases released by the coke, generated by the heat supplied by the burners and by the carbon from the coke itself. The heat supplied by the burners makes it possible to bring in thermal energy for the reactions that occur in the reactor. At the base of the reator, there is the main product, pig iron, whose primary constituent is iron (with about 95% of iron mass content, primary iron), having as its supernatant slag, which contains the impurities taken from the iron ore from the feed of the Blast Furnace (Barbosa, Silva, & Teixeira, 2022).

The raw materials, such as iron ore concentrate, coal coke or charcoal coke (or equivalent) and flux (limestone mainly) are alternately loaded through the conveyor belt to the top of the blast furnace, while the air, whether enriched with oxygen or not, is blown up by the blowers at the bottom of the blast furnace. In this process, there is the reduction of the concentrated iron ore by means of chemical reduction, or that is to say, the separation of a metal from its oxide, processed with the use of the reducing agent/fuel, which can be coal coke or charcoal coke, or a mixture of the two (or equivalent). This agent goes into combustion in the region of air inflation inside the furnace, generating reducing gases at high temperature (Rizzo, 2009). Carbon monoxide, carbon dioxide (CO$_2$), nitrogen make up the gas that comes out from the top of the blast furnace. After being mixed with coke oven gas, this gaseous compound is used to preheat the air blown up in the blast furnace (Barbosa, Silva, & Teixeira, 2022).

In the softening/melting/cohesive zone in the blast furnace, the final reduction occurs generating primary iron or pig iron (Mourão, 2007). Pig iron is normally used in liquid form, being driven by torpedo car to the steel plant. In the steel mill, pig iron is refined (it is purified from its impurities and alloy elements are added to it) and transformed into steel. Pig iron in its chemical composition has a carbon mass content ranging from 4% to 5%, in the form of cementite (Fe$_3$C), and impurities such as silicon (0.3% to 2% by mass), sulfur (0.01% to 1% by mass), phosphorus (0.05% to 2% by mass) and manganese (0.5% to 2% by mass). The pig iron (liquid) produced can be transformed into a product of pig iron (solid) or transported, for example by the torpedo car, to the steel plant, where it is again purified and suitable for the production of cast iron and steel of various types and purposes (Chiaverini, 1982).

### Table 1 - Types and Application in the Pig Iron Products Industry

<table>
<thead>
<tr>
<th>Type of product</th>
<th>Application in industry</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig iron (or steel plant)</td>
<td>Steel</td>
<td>&lt;1.5% silicon, 0.5-1% manganese, &lt;0.05% sulfur, &lt;0.12% phosphorus</td>
</tr>
<tr>
<td>Iron pig iron</td>
<td>Foundry</td>
<td>1.5-3.5% silicon, 0.5-1% manganese, &lt;0.05% sulfur, &lt;0.12% phosphorus</td>
</tr>
<tr>
<td>Nodular pig iron</td>
<td>Foundry</td>
<td>&lt;0.05% manganese, &lt;0.02% sulfur, &lt;0.05% phosphorus</td>
</tr>
</tbody>
</table>

**Source:** adapted from De Paula (2014)

The independent steelmakers of pig iron producers are called *gouges* and receive the National Classification of Economic Activities (CNAE, Brazil) under code 2411. The gouges have the purpose of producing and marketing products of pig iron to third parties (or market pig iron, *merchant pig iron*), instead of manufacturing it for consumption in their own production process, as is the case of integrated steel mills (CGEE, 2010).

The product of pig iron produced by the gouges is consumed by two industries: the steel industry (as basic pig iron) and the foundry (as pig iron or nodular pig iron, according to the type of cast iron production), with emphasis on the first (Table 1). The basic iron-guar product
is used in the steel industry by semi-integrated mills (based on electrical steel mills) for the improvement of productivity and for the manufacture of better quality steels. The foundry industry consumes for the production of cast iron the product of pig iron in the form of pig iron and nodular pig iron, the latter being obtained by means of a small addition of magnesium to the metallurgical liquid bath of iron and carbon, resulting in spheroidal graphites between the grains of iron. Millbank (2007) estimated that, in 2006, 60% of the world's non-captive production of pig iron products consumed by steel mills and about 40% by foundry industries (De Paula, 2014).

The Brazilian steel industry employs systems and processes updated with the best production techniques and has production results comparable to the world average. Those indicated in Brazilian steel production show favorable indicators of energy consumption, greenhouse gas (GHG) emissions and efficiency in the use of materials (Table 2).

The main alternatives that have been used by Brazilian companies to reduce GHG emissions in the steelworks are the following: the cogeneration of electrical energy through the reuse of heat and process gases; the substitution of inputs/fuels; the optimization of process control with automation; and the awareness/training programs of suppliers (Carvalho, Mesquita, & Melo, 2016). In global terms, GHG reduction is expected by the dissemination of innovative technologies to reduce energy consumption and generate lower emissions in the reduction phase, i.e. alternative processes applied to reactors, such as in the blast furnace: solid reduction; self-reduction; and reducing fusion (Carvalho, Mesquita, & Melo, 2016).

### 2.3 Sustainability in the Steel Sector

Muslemani et al. (2021), the global steel sector is the second largest industrial sector (after the cement sector) in greenhouse gas (GHG) emissions, due to its strong dependence on fossil fuel consumption. In view of the high demand for various iron products in the coming decades, the need for the decarbonization of steel industries has arisen. According to Fan and Friedmann (2021), the decarbonization challenge involves two main processes: the chemical reduction for iron ore refining (emission process), commonly with coke; and the high temperature heat source needed to operate the blast furnace.

The Brazilian Steel Plan of 2008 intends, in part, to face the challenge of decarbonization, in a national plan based on three main pillars, are: reduce emissions from the sector; avoid deforestation of native forests; and increase the competitiveness of the Brazilian steel sector (Pinto et al. 2018).

According to Ciftci (2021), the use of pig iron (or crude steel) products may increase the share in the use of scrap iron from demolished structures, vehicle carcasses and machinery at the end of their useful life, in the production of steel in electric furnaces. This can contribute to the reduction of carbon emissions in steel production. Figure 1 shows the availability of scrap by 2050. Scrap is thus emerging as one of the important raw materials in the steel sector that can contribute to reducing emissions from industry and the consumption of natural resources. Also according to Ciftci (2021), each ton of scrap used in steel production avoids the emission of 1.5 tons of CO₂, and the consumption of 1.4 tons of iron ore, 740 kg of coal and 120 kg of limestone.

The contribution of steel industries is significantly important to the world economy, but it is highly intensive in CO₂ emissions and energy consumption, as the coal route is the dominant in primary iron production, becoming a contributing industry for climate change (De Oliveira, Lemos, Canedo, & De Abreu, 2022). In addition to the efficient use of steel gases for energy and heat supply, the deployment of carbon capture and the use of renewable energy are an urgent necessity for the transition of the steel industry to carbon neutrality (Zhang et al., 2021).
The steel sector is deeply related to countries’ economies, and is expected to play a key role in the low-carbon transition by providing high-tech materials, many factors can determine how and in what direction the effects across the economy materialize (Bachner et al., 2020).

Zhao et al. (2019), a low-carbon, or carbon-neutral economy, is based on a low-pollution, low-emission, low-energy economic development model. Thus, this economy symbolizes a necessary shift in current production in fossil fuel consumption, as well as in the large amount of carbon emissions.

The products, waste and solid co-products of steel mills have been used to add sustainable and economic values, as is the case of Vietnam, where steel slag has been studied for application in various types of constructions, including buildings and floors. The results of the experiment indicate that steel slag, as a substitute for sand, can maintain the quality of traditional concrete, because the composition of slag contains many components of cement (Nguyen, Le, & Nguyen, 2018).

According to Zhang et al. (2021), the objective of carbon neutrality requires evolution in all areas and in the whole process of energy production and consumption, directly affecting production methods. The main ways to achieve a reduction in carbon dioxide is by reducing total energy consumption, especially fossil energy, using non-fossil energy to replace the mineral, and increasing carbon sinks by planting trees.

Additional production technologies can be implemented to reduce the effects of fossil fuel combustion, such as negative emission technologies. According to Mandova et al. (2019), the main role of negative emission technologies is basically to capture and store GHGs through reforestation, bioenergy generated from captured CO$_2$ and direct capture of atmospheric CO$_2$, among others. The maximum use of biomass products results in an advantageous reduction in carbon emissions by existing steel production technologies (Nwachukwu, Wang, & Wetterlund, 2021).

### 2.4 The Circular Economy, Sustainability

The concept of the circular economy starts from the principle that it is a new paradigm to be pursued and conquered, due to the urgency of the environmental agenda, the possibility of exhaustion of natural resources, the growing agglomeration of solid waste, and also the circularity of the use of raw materials with a view to combating the waste of its potential itself (Azevedo, 2015). *Reuse, Reduce and Recycle*, these three words illustrate well the concept, make use of materials and raw materials that have already been used in one or more production

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**Figure 1 - Availability of end-of-life scrap**

Source: adapted from Ciftci (2021)
cycles, this perspective gave rise to the term in English Brownfield, in Portuguese, brown - in free translation, that is, it is not a question of raw material extraction in natura, but rather of the reuse of other processes through which these materials have already passed (Teixeira et al., 2022).

With the alternative of the use of the circular economy, the dependence, or at least the exclusivity, of Extraction, Produce, Consume and Discard, which is the concept of the current Linear Economy (de Oliveira et al., 2021), is ended. In linear economics one has the extraction of raw materials from the so-called green fields or in English Greenfields, a concept given the extraction of resources in natura for production, and, after discarded consumption, produces a premature wear of the potential of materials and generating the so-called environmental liabilities, concepts in this respect will be addressed later, first is presented the origin of formal conceptualization, the roles of the State, society and enterprises in the circular economy (Teixeira et al., 2022).

Su et al. (2013), the concept of circular economy was raised by two British environmental economists, Pearce and Turner (1990). In the publication "Economy of Natural Resources and Environment", they pointed out that a traditional open economy was developed without any purpose with recycling and that it treated the environment as a reservoir of waste. However, under the first law of thermodynamics, in which total energy and matter remain constant in a closed system, the open system can and must be converted into a circular system by considering the relationship between the use of resources and residual waste. In other words, with the existing environmental problems and scarcity of resources, the authors suggested the need to look at the earth as a closed economic system: one in which the economy and the environment are not related by linear interconnections, but by a circular relationship. Through an analysis of the relationship between the economic and natural systems, they proposed a closed circuit of material flows in the economy, which was termed Circular Economy (Azevedo, 2015).

The Circular Economy is definitely in the spotlight in the world for the reasons already mentioned above, in addition to the important awareness that is forming among the new generations and by some companies. Formal implementation depends largely on government participation, compulsory participation, with a relevant role in public policies, legislation and investment, taking for itself the role of inducer of this new tool indispensable for the sustainability of production and life in society. It is up to the State to lead and implement the productive arrangement that provides the basis for this new phase of the economy that is the duty and right of all. By availing itself of its prerogatives of implementing the scenario, it opens the way for private enterprise to idealize and promote new businesses, companies already with the mentality of the circular economy in their reason of existence, generating employment and income and giving their contribution to the resources being used in a sustainable way economically and environmentally (Teixeira et al., 2022).

Europe is leading a movement of great importance about the Circular Economy, implementing specific and coordinated legislation, there are already fiscal and economic incentives aimed at this new phase of the economy, part from the recognition of the work of companies, with certifications that highlight the performance of business models based on the concepts of the CE, as well as the creation of partnerships around the world, that is, wherever there is an initiative anchored in the concepts of rethinking, reusing and recycling, can become a partner of European companies, or even take advantage of a market that takes into account sustainable business and are willing to pay more for their products due to their environmental value (Teixeira et al., 2022).

In Brazil, there is already specific legislation, it is the National Solid Waste Policy, Law No. 12,305/10 (Brazil, 2010), organizes the way the country deals with waste, demanding from the public and private sectors transparency in the management of its waste. It is an important
step, but, as yet not a productive arrangement, in this regard the country still needs to advance a lot, the abundance of natural resources has its limits, as already seen in other regions around the world, to enter once and for all into the concepts of the circular economy is more and more inadvisable. Initiatives in the country, which are still isolated by sector of activity, need to be promoted integration until the concept becomes intrinsic to consumption itself and to society as a whole.

The case of the Arcelor Mittal Company (Arcelor Mittal, 2023) is an example of sustainability accreditation projects initiatives in the steel sector. He appropriates the concept of evaluating, certifying and validating to the consumer an integrated action that aims at a production of steel with the goal of zero carbon emissions, whatever the forms of production. It is a concept of a global standard for the production of low carbon steel until it reaches zero carbon. There is not yet this standard in the world, but, this is the search of the company, it is the challenge to which they have set themselves, starting with the perception detected in a consumer that is increasingly demanding these efforts on the part of companies, creating a market where non-transparency, or even the non-adaptation to new standards acceptable from the environmental point of view, are penalized, and on the other hand, companies that implement such standards, will have access to a level of added value that encourages and values their efforts.

The Concept of Low Carbon Steel Standard (Figure 2) is based on three fundamental principles (World Steel Association, 2022):

- Double score, one that rewards the life cycle of the finished products, and another that rewards the producing companies as they decarbonize their processes;
- Incentives for decarbonization should cover all gains from new production technologies, not only the increased consumption of scrap with existing technologies;
• Include a clearly defined limit, from which carbon emissions are counted towards the decarbonization assessment system. The position of a steel producer in the graph shown in Figure 2 would be based on the incorporation of emissions per ton of hot-rolled steel produced, and the metal input they use.
• The steel producer that is at or below the limit would descend six steps on the scale, from A + to E - (Figure 2), on the contrary, the advance on the scale will take place as the producer decarbonizes, incorporating the percentages of the CO4 scale, and, therefore, with emissions below the limit.
• The limit for near-zero steel should be defined, taking into account all routes and technologies used for decarbonization.

The proposed Emissions Certification Seal (World Steel Association, 2022) is shown in Figure 3. According to Figure 3, it is proposed to:
• a transparent and easy-to-identify system measuring progress in decarbonization independent of the steel route;
• Be user-friendly by authorities, identifying low-emission production, creating markets that reward, and accelerating the process of business adoption;
• With a mass base of one (1) ton of hot-rolled product associated with physical steel production, regardless of technology.

With the scoring system obtained from Figure 3, it is expected to encourage sustainability by rewarding steel producers (World Steel Association, 2022), so that they can achieve higher ratings, structurally reducing emissions with investments in new technologies, is indispensable to reach the goal.

The Sustainability Tripod aligns with the Arcelor Mittal project (2023) by enabling addressing innovation, development and sustainability in all three dimensions, economic, social and environmental, which are the pillars that underpin the concepts of sustainability and sustainable development (Teixeira et al., 2023; Conceição et al., 2022; Khan; Ahmad, & Majava, 2021). However, the practical criteria proposed by Arcelor Mittal (2023) deal more with the productive aspect and the environmental issue. Through the practice of the project by the companies, the production is optimized, minimizing the harmful effects of various types of industrial waste, and the energy consumption, as observed by Conceição et al. (2022) for
projects addressing the sustainability tripod. However, the Arcellor Mittal (2023) project does not address in depth social issues and economic development aspects arising from the proposed crediting of zero carbon.

2.5 Environmental Asset and Liability

The terms environmental asset and environmental liability give rise to many discussions because they are often linked to fines, penalties or violations of environmental laws. According to Ribeiro et al. (2017, pp. 7), it has been noted:

"Environmental assets are assets acquired by companies to control, preserve and recover the environment. (...) the characteristics of environmental assets are different from company to company, since the productive processes and the goods used in the process, control, conservation and preservation of the environment vary according to the company. Therefore, more and more efforts are being made to protect the environment by reducing and preventing the effects of pollution." (Ribeiro et al., 2017, pp 7).

Also classified as environmental assets are investments in installations, machines, equipment, among others. Acquired with the intention of minimizing the impacts caused by environmental degradation, expenditure on research that has the same purpose should be given the same classification. Among the benefits that such expenses may bring to the entity, the most likely are: improving efficiency; increasing capacity; securing other assets; reducing or eliminating contamination resulting from operation in future financial years, among others. (Teixeira et al., 2022).

The term environmental liability is often linked to fines, penalties, or violations of environmental laws. The association between costs and compliance with regulations is very common (Ribeiro et al., 2017, pp. 8). Although it is a broad term, environmental liability can be defined as an obligation acquired as a result of past or present transactions that caused or caused damage to the environment or to third parties, voluntarily or involuntarily, which should be compensated through the delivery of economic benefits or service provision at a future time (Galdino et al., 2002).

3 METHOD

The choice of the most suitable method for carrying out research is directly linked to the objective and, consequently, to the questions that the researcher wants to answer. According to Gil (1994), one can classify research as to its objective into three basic categories: exploratory, explanatory and descriptive. Exploratory research aims to understand a phenomenon still little studied or specific aspects of a broad theory. Explanatory research identifies the factors that determine or contribute to the occurrence of phenomena, explaining their causes. And, finally, descriptive research describes a given population or phenomenon.

The methodology employed for the case study of the descriptive type of briquettes in order to evaluate their economic and environmental advantages was by the case study of a company that already produces iron-rich briquettes for Alto Forno and in-depth interviews. For the description of the expertise, the national solid waste processing company that produces metallized briquettes was chosen, since it already produces iron-rich briquettes for Alto Forno, serving the steel sector. The company that produces metallized briquettes is located in a region of great concentration of guseiras, which is the metropolitan region of Belo Horizonte, state of Minas Gerais (Brazil).

The case study is a research method that generally uses qualitative data, collected from real events, with the aim of explaining, exploring or describing current phenomena inserted in
their own context (Fraser, & Gondim, 2004). It is characterized by being a detailed study of few, or even a single object, providing in-depth knowledge (Yin, 2009).

The qualitative technique of in-depth interview is complementary to the methodology applied in this article. The interview was proposed in semi-open individual format and with semi-structured issues. It aims to explore a specific subject, according to Teixeira et al. (2021) on ‘circular economy and sustainability’. The in-depth interview was conducted with two people directly associated with senior management and direct shareholder of the metallized briquettes producing company. The interview sought information, perceptions and experiences of people by one of the shareholders and by the director of operations of the metallized briquettes company. They were selected for an interview because they were closely linked to the concept, development, manufacturing and distribution of metallized briquettes for the steel sector. The in-depth interview was followed by a script of eight (8) questions. They sought to obtain the intensity of each professional's answers on the subject, without performing the quantification or statistical representation to analyze them and present them in a structured way, according to Soares, Diehl and Vilvert (2016). The semi-structured interview allows for a better understanding of the meanings, values and opinions of the social actors about the production of metallized briquettes and their use in the blast furnace.

4 RESULTS AND DISCUSSIONS

The semi-structured interview, in the interviewer-interviewee interaction, allows a mediation, elaboration and registration about the perceptions and meanings that are attributed to the understanding of the particular reality related directly and indirectly to the production of metallized briquettes, such as the circular economy and sustainability. For this reason, it was chosen to start the results with the records obtained from the semi-structured interview.

4.1 Semi-Structured Interview

Through the interview, an attempt was made to understand how metallized briquettes were made, how they were used in blast furnaces and how they contributed; two representatives of the metallized briquettes producing company were selected, the first being the engineer and the operations director, and the second interviewee was the process engineer.

**Question 1: How is the processing of metallized briquettes?**

**Interviewee: Chief Operating Officer.**

**Response:**

"The production of metallized briquettes begins with the agglomeration of fine metals and ore sludges. These are mixed in appropriate proportions to achieve final uniformity in the ore content, according to the demand customers demand from the company. The mixture is then compacted to the appropriate size to be introduced and used in the blast furnace, respecting for this purpose the iron and phosphorus contents useful in the processing for the production of pig iron. The process of agglomeration of the fines begins with the receipt of the raw materials, and afterwards their useful classification and the management of the materials are carried out. The next stage to the agglomeration of the fines, is the mixture for the formation of the blends, drying. In the agglomeration, the binding agents are added to the fines and, immediately after, the conformation by roller pressing. The conformed material undergoes drying and ultimately maturing. After maturing, the briquetted product is ready to be transported and loaded into the steel blast furnace."

The answer to question 1 describes the briquetting process from the receipt of the briquettes that are ready for the consumer market.
Question 2: What are the raw materials of briquettes?
Interviewee: Chief Operating Officer.
Response: 
'Mines and ore sludges, among others'.
In the answer given to question 2, the interviewee highlights the differential of briquettes from their main raw materials, the sludge and ore fines.

Question 3: What are the binding agents in the production of briquettes?
Interviewee: Chief Operating Officer.
Response: 
"The main binding agents present on the market are: corn starch, lime, sodium derivatives, among others"
The answer given to question 3, we have the information of the composition additional to the briquettes, as well as the ore fines, so that this is consolidated dimensionally to be received in the Blast Furnaces.

Question 4: What is the impact on pig iron production?
Interviewee: Chief Operating Officer.
Response: 
"At the moment, metallic briquettes are limited to a participation in microfurnaces in the order of 20% of their total mass load. The large steel parks, the large steelworks with much larger blast furnaces and productive capacity do not yet use metallic briquettes, this demonstrates a huge potential for this product, which can and should still reach such industries because of the great contribution that can provide to this productive chain, right economy, more technical efficiency and undoubtedly the environmental contribution"
The answer to question 4 contains information on the main reactor receiving the briquettes, the so-called micro-furnaces, and the percentage of the feed mass of that reactor, 20% by mass.

Question 5: How are metallized briquettes characterized?
Interviewee: Process engineer.
Response: 
"Metallized briquette is the result of the agglomeration of fine metals and ore sludges in general, which are its main raw material. The reuse, the recycling of what used to be a logistical disturbance and an environmental liability in a finished product, is undoubtedly its most noble characteristic, the most important, the resulting is the generation of added value, transformed into a business that in turn generates employment and income. The final product will once again be used in the Blast Furnace."
The answer to question 5 highlights the circular role that the briquetting process promotes, as well as benefits such as value-added generation.

Question 6: What is the cost-benefit ratio of metallized briquettes as blast furnace charge?
Interviewee: Process engineer.
Response: 
"Since the raw material used for the production of metallic briquettes is sludge and ore fines, the first gain is that the process of reducing the oxide to the concentration of iron has already taken place, in this way the metallic iron is already present with approximate content varying between 58% and 64%, or that is to say, the energy consumption for its incorporation after loading into the Blast Furnace is significantly lower. Metallized briquette is a homogeneous product with an excellent concentration of metallic iron, and its acceptance by the Blast Furnace due to these characteristics already mentioned, corresponds to a scrap in terms of utilization, however, with lower acquisition cost. There was also an increase in the production of pig iron, with the briquette occupying the same physical space as the iron ore."
And, finally, an absolutely significant gain is the utilization of the sludge and fine minerals as raw material, something that was a logistical disturbance and mainly an environmental liability, becomes a finished and useful product again. Undoubtedly the production of metallic briquettes, clearly attends to the concept of the circular economy, which collects globally the best efforts, in order to be the response and contribution of heavy industry to the decrease of CO$_2$ in the atmosphere and considerable decrease of energy consumption."

The answer given to question 6 reinforces the answer given to question 5 by highlighting the role of circular economy that the briquetting process promotes, as well as benefits for the briquettting companies, such as the reduction of CO$_2$ emissions into the atmosphere and energy consumption in the production process of these companies.

**Question 7: Is there a decrease in coke consumption in blast furnace loads? How much?**

*Interviewee: Process engineer.*

*Response:*

"Yes, the use of metallic briquettes in the blast furnace makes it possible to reduce the use of charcoal, the exact number is not yet officially tabulated, however, we have the testimony of one of our customers, who here we will call Alpha, for ethical reasons, who carried out the account in empirical tests and reached the conclusion that the use of metallic briquettes, produced by the company, in the charge of its blast furnace, reduced by 10% the use of coke, with this saving obtained, the company ascertained that the briquettes purchased by them went free in the process, that is, more pig iron with lower cost.

The answer given to question 7 exemplifies the answer given to question 6, highlighting the benefits for companies consuming briquettes, such as pig iron with lower cost by reducing the consumption of coke (coal), as shown in Table 2.

**Question 8: Are there government incentives to engage in this economic activity?**

*Interviewee: Process engineer.*

*Response:*

"Yes, though, still restricted to the law on solid waste - Law No. 12,305, of August 2, 2010, which is a very recent legislation, it is necessary to implant and develop a specific productive arrangement.

The answer given to question 8 or final mentions Brazilian Law 12.305 of August 2, 2010 (BRAZIL, 2010) as restricting the actions of incentives for the production of briquettes.

### 4.2 Value Generated by Briquettes in the Production of Pig Iron

The benefits in the use of metallized briquettes in the pig iron production chain have as their highlights: the economic, because the briquettes combine a high content of iron and a low content of phosphorus (as an input of iron load for the blast furnace); and the environmental, because of the gain brought about by the agglomeration of solid residues, generated by the steel companies themselves, and which are accumulating passively, as seen previously.

By obtaining a more homogeneous material resulting from the briquetting process, the raw materials of the blast furnace, or loading materials, are improved, which will provide excellent productive performance with a more efficient space occupation in the Blast Furnace. These improvements bring about a reduction in the consumption of charcoal by metallic charge, which in turn represents financial savings, since metallic briquettes cost three times less.

The reduction of CO$_2$ emissions, using briquettes in the process of reducing the metal load, is related to lower coal consumption in the process, and lower energy consumption. Table 2 shows that the same amount of pig iron produced a lower carbon consumption using as a source of iron for the blast furnace using metallized briquettes. This saving allows a return of around R$450.00 per ton of pig iron produced in the blast furnace.
Table 2 - key figures regarding gains from the use of metallic briquettes.

<table>
<thead>
<tr>
<th>Item</th>
<th>Source Fe*</th>
<th>Consumption Source Fe (t)</th>
<th>Pig Pig Pig Produced (t)</th>
<th>Consumption Coal Plant (t)</th>
<th>Value spent on Charcoal</th>
<th>Volume Charcoal (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Concentrated ores (pellets and sinter)</td>
<td>1.82</td>
<td>1.00</td>
<td>0.53</td>
<td>R$1,008.00</td>
<td>2.24</td>
</tr>
<tr>
<td>2.</td>
<td>Metallized Briquettes</td>
<td>1.82</td>
<td>1.00</td>
<td>0.31</td>
<td>R$558.00</td>
<td>1.24</td>
</tr>
<tr>
<td>3.</td>
<td>Difference (2) - (1)</td>
<td>0</td>
<td>0</td>
<td>-0.25</td>
<td>-R$450.00</td>
<td>-1</td>
</tr>
</tbody>
</table>

* Equalized metallized ores and briquettes with a total Fe content of 56%;
*Charcoal = R $1,800 / ton. - Reference July 2022;
*Bulk Charcoal density = 250 kg/m³

**Source:** Data provided by the metallized briquetting company (2023)

Table 2 shows that the use of metallized briquettes in Blast Furnaces has the potential to:

1) Decrease in Specific Consumption of Vegetable Coal, savings of up to 45%, which is the main cost in the production of Pig Iron;
2) Improvement of the Productivity Index (daily production / useful volume of the Blast Furnace) due to lower utilization of charcoal, low density material in bulk, consequently greater useful utilization of the volume of the Blast Furnace (efficient space occupation of the Blast Furnace) reducing fixed costs of the Steel Mills.

Other specific benefits arising from the use of briquettes as a source of iron in the Blast Furnace are:

- Reforestation economy to compensate for charcoal consumed;
- Reduced Air and Electric Power Consumption;
- Making use of the CaO, MgO and low SiO₂ present in the briquette favors the load balance of the Blast Furnace and a reduction in the quantity of limestone hanged;
- Increase in the life of the oven coating.

Table 3 - Metal briquette mass content data sheet.

<table>
<thead>
<tr>
<th>Total Fe</th>
<th>Fe Met.</th>
<th>P</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 60%l</td>
<td>≥ 22 %</td>
<td>≤ 0,10 %</td>
<td>≤ 11 %</td>
<td>≤ 6 %</td>
<td>≤ 12 %</td>
</tr>
</tbody>
</table>

**Source:** Data provided by the metallized briquetting company (2023)

Table 3 presents the chemical composition of the briquettes, where its high iron content (greater than 60% by mass) is highlighted, which makes its use in blast furnaces for the production of pig iron possible.

4.3 Briquettes and their Context in the Circular Economy

It should be noted that metallized briquettes are the exact answer to the example given by ArcelorMittal, when it points to the use of new technologies for the introduction of raw materials in the blast furnace, with the capacity to reduce emissions, as well as only increasing scrap consumption with existing technologies.
The dynamics of the steel industry, as well as of several other industrial sectors, have been directly affected by economic and socio-environmental factors, which represent a major challenge for the sector. How, then, do metallized briquettes fit into this context? The raw material of the briquettes is the sludge and fine steel mill rich in iron ore, solid waste from steel processes. In this case, these raw materials have already been transformed, fulfilling a role in the linear economy, and would therefore become environmental liabilities that will possibly be deposited in tailings dams etc. By the briquetting process the waste is transformed into a new product that, in turn, returns to the steel mills in the feed of the Blast Furnace. In this case, the briquette fully complies with the concept of "Reuse, Reduce and Recycle". It at its origin is, therefore, a brownfield, material in a state of reuse, of reuse. This highlights the role of briquetting, which allows the waste (raw materials for briquettes) to be consumed to its full potential, making full use of all components.

5 FINAL CONSIDERATIONS

The Brazilian company that produces metallized briquettes presents itself as an innovative company. She is interested in the research, development and production of metallized briquettes as a concentrated input for blast furnaces of pig iron. The use of metallized briquettes in the Blast Furnace generates economic and also environmental value. The company demonstrates a real commitment to sustainability, with sustainable actions that represent a competitive differential.

The choice for the use of metallized briquettes in the pig iron production chain proposed by the company that produces metallized briquettes is innovative in the Brazilian market and offers room for growth in the metallurgical sector, since its use is still small in view of its beneficial potential in the steel industry. The use of briquettes in the steel industry faithfully responds to the proposal for the application of new technologies that reduce carbon emissions in the production of steel, a proposal that is being put forward by one of the largest steel producers in the world, ArcelorMittal. Thus the metallized briquettes company of this case study is in the position of evaluation and certification proposed by Arcelor Mittal and aligns itself with the sustainability tripod. As the company’s use of metallized briquettes from this case study feeding the blast furnace pig iron one has a sustainable production, which is the competitive and creditable differential. In this case, the dissemination of the information provided by the company that produces metallized briquettes for the economic and environmental gain obtained from the use of metallized briquettes in the blast furnace charge is of great importance, since it contributes towards an analysis and proof of the reduction in costs. Other relevant factors are the reduction of charcoal consumption, acting on the reduction of CO₂ emissions and lower cost with (environmental) reforestation.

The legislation on incentives for the production of metallized briquettes (briquetting) is restricted to the Brazilian law on solid waste, which limits greater investments in its production and, in a way, its disclosure as an input of iron concentrate for the blast furnace of pig iron. However, the responsible disposal of solid waste, such as steel sludge, ore fines and others, stands out in the briquetting process. This responsible destination generates economic value and is sustainable. It carries with it the prospect of raising metallized briquettes in a prominent place in the pig iron production chain.

To continue this work, quantitative research regarding the briquetting process is suggested, in a broader group of consumer companies in Brazil. In these new investigations, more technical data can be collected to consolidate the direct and indirect benefits that the use of briquettes as a burden for the blast furnace can achieve in the steel sector.
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The Circular Economy: a Case Study Approach Case Study of the Production of Metallized Briquets and Their use in Steel Blast Furnace


