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**TOWARDS A SUSTAINABLE STEEL INDUSTRY: Assessing Nuclear and
Renewable Energy Solutions for Decarbonization in Brazil**

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"Education is the most powerful weapon
which you can use to change the world."
(MANDELA)

ABSTRACT

The entire world is currently looking for solutions to reduce uncontrolled greenhouse gas emissions to prevent even more severe consequences on the planet due to climate change. The steelmaking industry is currently among the biggest CO₂ producers in the world; therefore, it is facing the challenge of quick and affordable decarbonization. This research offers an overview of the challenges and developments on the decarbonization of the steel industry in Brazil, through hydrogen utilization for iron reduction by supply electricity from a Nuclear-Renewable Hybrid Energy Systems (N-RHES). The analysis compares the economic viability of a study case in the steelmaking industry in the Ceara State by comparing two different ways of production; the first one is the traditional blast furnace-basic oxygen furnace (BF-BOF) route using as power supply coal power and the second one uses the process of hydrogen-direct reduced iron (H-DRI) route with a complete sustainable and low carbon emissions. All the electricity needed for H-DRI process to be completed is provided by the N-RHES, where the main demands of electricity are for the electric arc furnace (EAF) and the electricity to produce hydrogen through electrolyzes. The outputs show promising results for the viability of the H-DRI considering the coal cost, CO₂ emission fee, SMR cost, and the electrolyzer efficiency. The feasibility of steel production through H-DRI route with clean hydrogen will be able to shift the future path of this industry, decreasing significantly its GHG emissions.

Keywords: Nuclear-renewable hybrid energy systems; Decarbonization of steel industry; Hydrogen; HDRI.

RESUMO

Atualmente, o mundo está em busca de soluções para reduzir as emissões descontroladas de gases de efeito estufa, a fim de evitar consequências ainda mais graves decorrentes das mudanças climáticas. A indústria siderúrgica, que está entre os maiores emissores de CO₂, enfrenta o desafio de realizar uma descarbonização rápida e acessível. Este trabalho apresenta uma visão abrangente dos desafios e avanços na descarbonização do setor de aço no Brasil, focando na utilização de hidrogênio para a redução do ferro, alimentada por Sistemas de Energia Híbrida Nuclear-Renovável (N-RHES). O estudo compara a viabilidade econômica de dois métodos de produção na indústria siderúrgica do estado do Ceará. O primeiro método é a rota tradicional “*blast furnace-basic oxygen furnace*” (BF-BOF), que utiliza energia proveniente do carvão. O segundo método adota o processo de substituição do coque de carvão utilizado para a redução do ferro por hidrogênio (H-DRI), que se destaca por ser sustentável e apresentar baixas emissões de carbono. A totalidade da eletricidade necessária para o processo H-DRI é fornecida pelo N-RHES, com as principais demandas energéticas voltadas para o forno de arco elétrico (EAF) e para a produção de hidrogênio via eletrólise. Os resultados indicam uma viabilidade promissora para a implementação do H-DRI, considerando fatores como o custo do carvão, a taxa de emissão de CO₂, o custo do Small Modular Reactor (SMR) e a eficiência do eletrolizador. A adoção do processo H-DRI com hidrogênio limpo tem o potencial de transformar significativamente o futuro da indústria siderúrgica, reduzindo suas emissões de gases de efeito estufa.

Palavras-chave: Sistemas de energia híbrida nuclear-renovável; Descarbonização da indústria do aço; Hidrogênio; H-DRI.

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1. INTRODUCTION

Since the beginning of the industrial revolution population has grown immeasurable and in the last century it has quadrupled to 8 billion [1]. This increase in population was due to the improvements in technology which allow better life conditions, improving health, education, sanitation and communication. In order to maintain modern society's well-being, energy sources such as electricity, heating, and transportation are necessary. The issue is that the majority of these sources employ non-renewable fuels.

The 1973 oil crisis resulted in an increase in global oil market prices, which marked the beginning of an era that brought to the forefront significant concerns regarding the consumption of fossil fuels. Issues such as resource depletion, pollution, and sustainability became increasingly prominent [2]. Since then, governments have been searching for alternative energy sources such as solar, wind, biofuels, hydropower and nuclear to supply the human activities and comfort of modern society. This results in an energy revolution that motivates society to pursue sustainability, transition to low-carbon technologies, reduces greenhouse gas emissions, and improves energy security.

The climate has been affected by the exacerbated use of fossil fuel resources, which has caused a change in seasonality by boosting drought, hotter temperatures, and severe storms. These impacts are more commonly observed around the world, including the rising ocean, loss of species, and displacement of people. According to 'Our World in Data', in 2022, the majority of primary energy consumption is made up of fossil fuels, with oil, coal, and natural gas being the most popular [3]. Many experts suggest using low-carbon technologies, such as nuclear, to support renewable energy in this change, in order to reduce the energy mix's reliance on fossil fuels [4].

Industry is the sixth most energy-intensive economic sector worldwide [3]. The industry uses iron and steel production, which is carbon intensive and requires a lot of coal derivatives, charcoal, and natural gas [5] [6] [7] [8]. The Federation of Industries of the State of Paraíba (FIEPB), in Brazil, estimates that the metallurgic sector, which involves mining, manufacturing, foundry, and metal treatment, accounts for around 3.1% of the Brazilian GDP [9] [10]. The primary resources needed for iron production

in Brazil are coal coke (42.31%), charcoal (17.63%), steam coal (13.78%), electricity (9.49%), natural gas (8.36%), gas coke (7.21%), and others [8].

Due to its large use of coal and electricity, the steelmaking industry is responsible for 7% of global CO₂ emissions, mostly due to its use of coal [11]. The traditional way of producing steel is through the blast furnace/basic oxygen furnace route (BF-BOF), which produces roughly 1.9 tCO₂/t_{steel} [12].

Given the substantial CO₂ emissions generated by the steel industry, this research seeks to evaluate and propose effective strategies for its decarbonization. The central focus is on comparing an innovative system that utilizes hydrogen as a replacement for coal in the iron reduction process. This hydrogen will be produced using electricity derived from Nuclear-Renewable Hybrid Energy Systems (N-RHES). Subsequent chapters will explore the potential of this approach to significantly reduce greenhouse gas emissions while ensuring the continued viability of steel production.

In Chapter 2, this work will provide a literature review covering greenhouse gas emissions, Brazil's energy matrix, the steel-making process, and various energy generation methods. Chapter 3 will outline the methodology employed in this study. In Chapter 4, the results will be presented, including findings from the sensitivity analysis. Finally, Chapter 5 will offer the conclusions drawn from this research.

2. LITERATURE REVIEW

This chapter provides a comprehensive overview of key topics relevant to the context of energy and greenhouse gas emissions, with a focus on Brazil's energy landscape and the steelmaking industry.

The literature review sets the stage for understanding the key energy and emissions challenges and introduces promising technologies decarbonization, particularly in the context of steelmaking industry.

2.1. Global Greenhouse Gas Emissions

A large amount of solar energy reaches the Earth every day, a parcel of this energy is reflected to the space when it reaches the top of the atmosphere, another part is absorbed by the oceans and land surface, leading to Earth's warming. The heat is partially emitted back into space in larger wavelengths, which are blocked by greenhouse gases present in the atmosphere, resulting in blocking terrestrial radiation. The Earth's habitability is made possible by the presence of these gases in the atmosphere, as without them, the average temperature of the planet would be very low [13].

The climate stays naturally stable when there is a balance between incident solar energy and the heat reflected from the Earth's surface. The energy balance can be altered in multiple ways, such as changes in the amount of energy reflected into space from longer wavelengths, which is caused by the increase of greenhouse gases in the atmosphere. The elevated levels of greenhouse gas emissions led to changes in CO₂ overall concentration [14]. The uncontrollable increase of greenhouse gas emissions is being addressed as the primary cause of Earth's average surface temperature increasing rapidly, resulting in major catastrophes related to climate change. Figure 1 displays a comparison of Earth's temperature change, where the first map depicts the temperature difference in 1884, and the second map displays the same difference in 2022 [15].

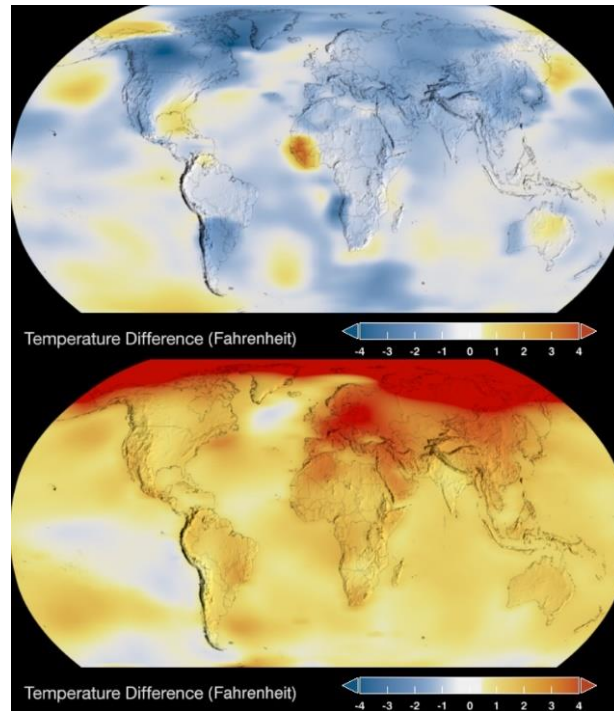


Figure 1 – Earth's temperature difference 1884 – 2022 [15]

CO₂ emissions were minimal before the Industrial Revolution, but they began to increase gradually until the mid-20th century. The total global CO₂ emissions in 1950 was 6 billion tons, but by 1990 it had nearly quadrupled to over 20 billion tons. Emissions have been steadily increasing, and today they are surpassing 35 billion tons annually. While growth has slowed down in recent years, the greenhouse emissions haven't reached their peak yet. Figure 2 demonstrates the rise in global CO₂ emissions, from the mid-19th century to 2022.

Despite the fact that GHG emissions are still rising in many regions, several countries have successfully decreased their emissions in recent decades, as demonstrated in Figure 3. The distribution of emissions has experienced a significant shift over time. The United Kingdom (UK) was the largest emitter in the world until 1888, when the United States of America (USA) surpassed it. Early industrialization in the UK resulted in significant improvements in living standards for most of its population. Following the UK's industrial development, North America and Oceania also saw rising emissions and improved living standards [14].

Annual CO₂ emissions

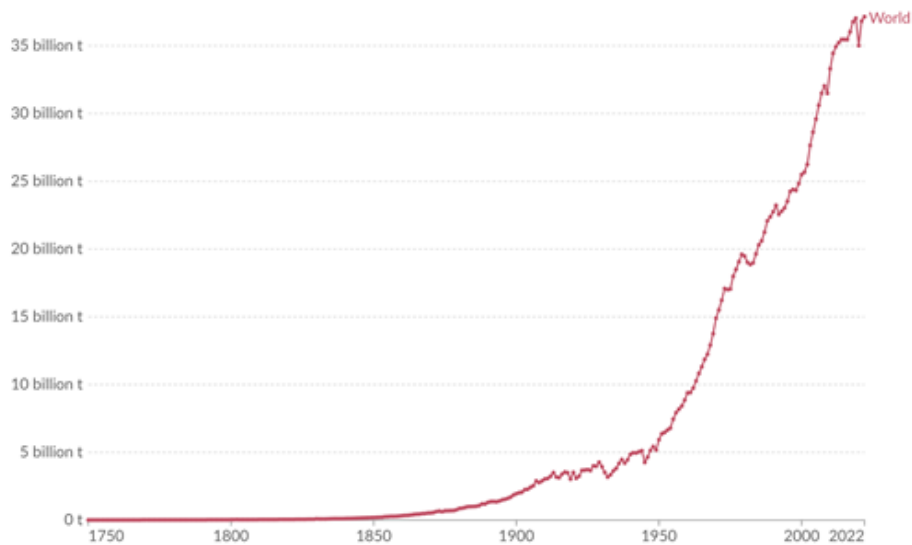


Figure 2 – Global CO₂ emissions [13]

Today, Asia is home to many of the largest emitters. The region has only experienced a rapid increase in GHG emissions in the last few decades, which was caused by its late industrialization. The quality of life has been significantly improved, with a 30-year increase in life expectancy since 1950, a sharp decline in extreme poverty, and widespread access to formal education.

To achieve global objectives, it is crucial to take collective action, particularly from the top emitters. China, the USA, and the 28 countries of the European Union (EU) together make up over half of global emissions. A commitment from these major emitters is essential to make significant progress toward global climate goals [14].

CO₂ and other greenhouse gases are released in almost all human activities and economic sectors: transportation, which is caused by the use of fossil fuels, and industrial, which is caused by the production process of cement, steel, aluminum, and others [16]. To prevent severe climate change, it is necessary to reduce global greenhouse gas emissions rapidly. About three-fourths of emissions are caused by energy use, about one-fifth by agricultural and land use, and the remaining are caused by industry and waste [17].

Share of global CO₂ emissions

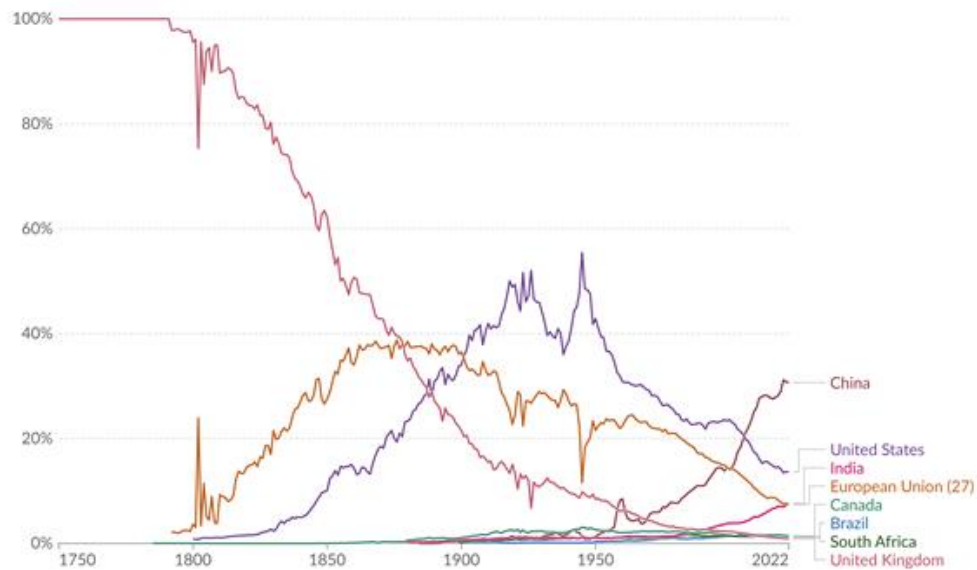


Figure 3 – Share of global CO₂ emissions

2.2. Brazilian Electricity Matrix

From 2019 to 2020, Brazil's installed capacity for electricity production grew by approximately 2.7%, with hydroelectric generation contributing the most. Solar generation had the biggest proportional increase, closing 2020 with an increase in installed capacity of 32.9% compared to the previous year. It should be noted that there was a 37.6% increase in 2019 as compared to 2018 [18].

In 2022, Brazil had a total electricity generation of 677.1 TWh, a 3% increase over the previous year. The public service plants and autoproducers had a combined responsibility of 81.4% and 18.6% [19]. Industrial facilities that produce energy for their own consumption are considered self-production, which can be found in the Paper and Pulp sector, Steel, Sugar and Alcohol, and Chemical industries, among others.

The amount of electricity generated from non-renewable sources decreased significantly in 2022 compared to 2021, as depicted in Figure 4. Non-renewable sources made up 22.6% of the total in the previous year.

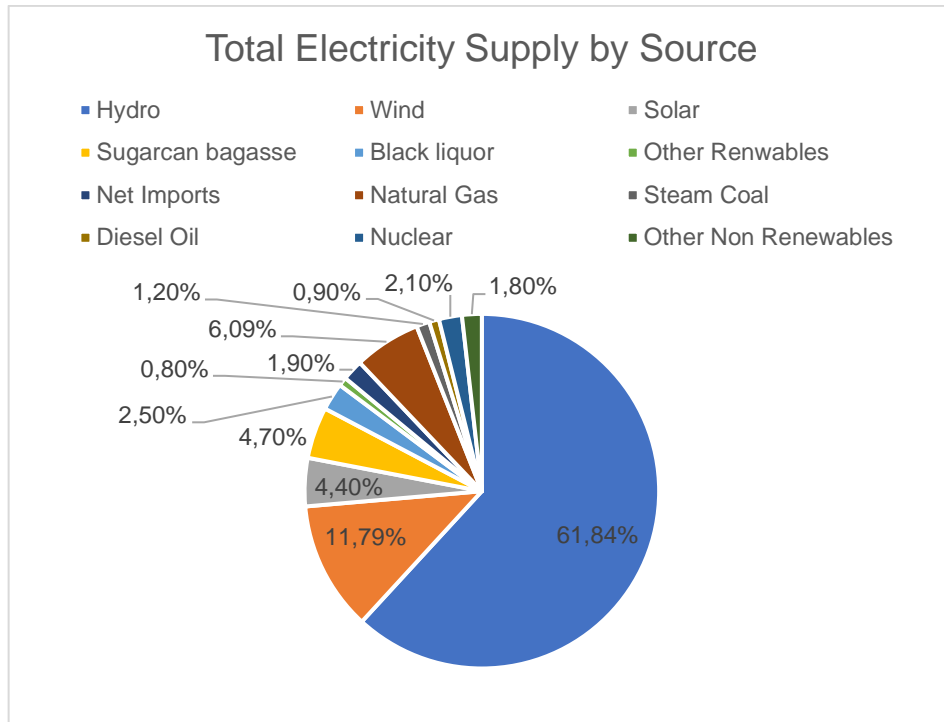


Figure 4 – Brazilian total electricity supply by source [19]

The industrial, residential, and commercial sectors in Brazil account for more than 81% of total electricity consumption, as shown in Figure 5. In 2021, the percentage of these three sectors increased by 2.44%, 7.50%, and 2.96%, respectively. [18]

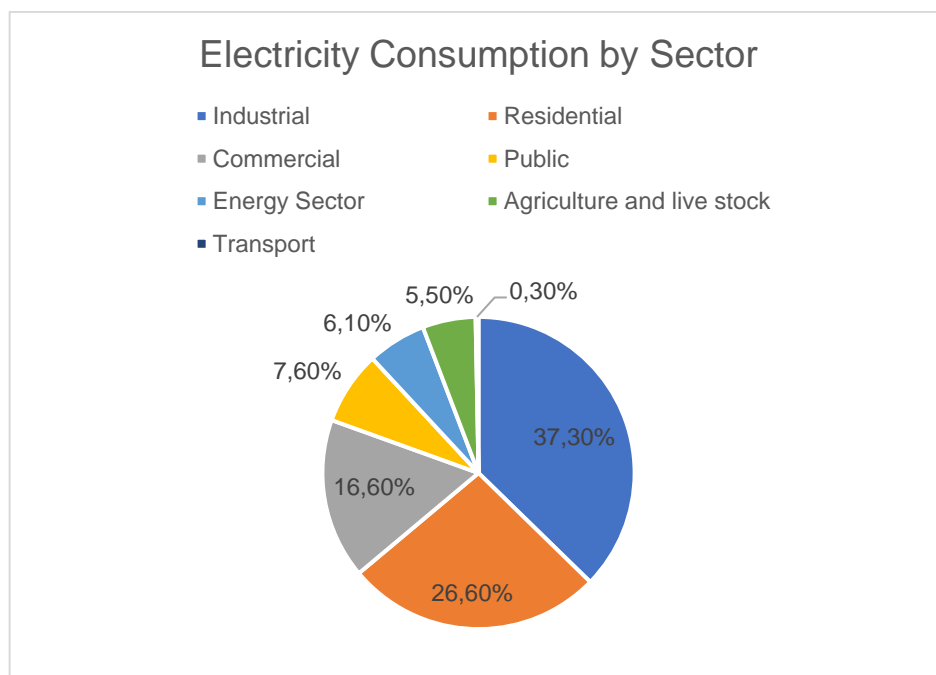


Figure 5 – Electricity consumption by sector [19]

2.3. Brazilian Energy Production

Although the Brazilian electricity matrix is mainly renewable, as shown on Figure 4, the overall energy supply strongly relies on fossil fuels. The total provision from non-renewables sources totalizes 52.7%. The country's energy supply is dominated by petroleum and oil products, accounting for 35.7%, followed by natural gas with 10.5%, as depicted on Figure 6. The primary source of renewable energy is still hydraulics, accounting for 12.5% of this total [19].

Even though Brazil still has a big contribution from non-renewable energy on its total supply, the country is still outstanding when compared to the rest of the world, which has an average of only 12% on renewable energy matrix participation [20].

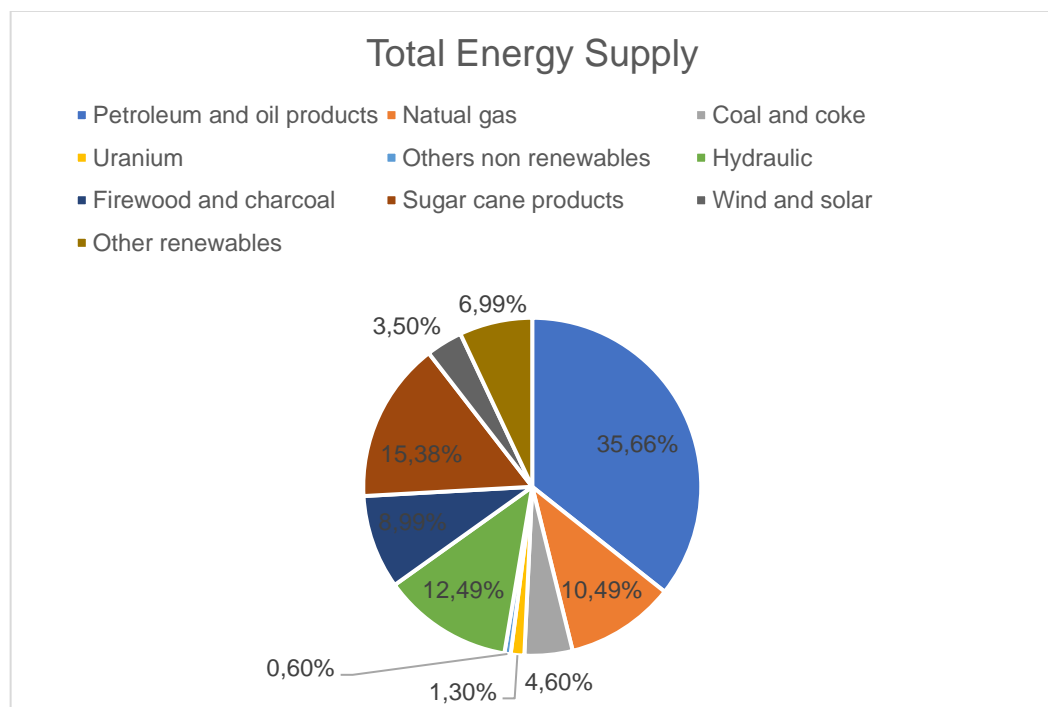


Figure 6 – Total electricity supply by source [19]

The dependence of fossil fuels can lead to energy security problems due to instable fuel prices and availability. At the same time, it increases greenhouse gas emissions.

2.4. Steel Making

There are three leading processes that produce steel [21]:

- I. Blast Furnace - Basic Oxygen Furnace (BF-BOF),
- II. Direct Reduction – Electric Arc Furnace (DR-EAF)
- III. Electric Arc Furnace (EAF)

The world currently produces around 1.9 billion tons of steel each year. In 2023, China alone was responsible for 53.9% of this amount, and Brazil produced 31.8 million tons of steel. Considering the worldwide production, around 71.1% was made through BF-BOF process and 28.6% through EAF route [22].

Steel originates from iron ore, a natural compound of iron, oxygen, and other minerals. The raw materials undergo mining and subsequent transformation into steel through two distinct processes: the blast furnace/basic oxygen furnace route and the electric arc furnace route. Ongoing advancements are consistently enhancing both processes to address the imperative of achieving low-emission steelmaking [23].

The blast furnace (BOF) process of steelmaking begins by feeding a huge shaft from the blast furnace with ore, coke and limestone. Then, hot air is blown at the bottom of the furnace, where there are alternate layers of those materials. When the coke burns, heat and carbon monoxide are generated. Afterwards, the heat melts the charge, and the CO removes the oxygen from iron ore, producing hot metal (approximately 1,480 °C). The metal flows to the bottom of the furnace and is transported to the Basic Oxygen Furnace (BOF), where oxygen is added to remove the carbon from the hot metal, converting it in steel [23].

The steel production in electric arc furnaces (EAF) relies heavily on scrap steel, making it a key method for recycling steel into new products. Currently, EAF accounts for about 20% of steel production in Australia and around 23% globally. In this process, electrical energy supplied through graphite electrodes melts the scrap. Recycling steel through EAF saves substantial amounts of energy and raw materials, including over 1400 kg of iron ore, 740 kg of coal, and 120 kg of limestone for every 1000 kg of steel scrap processed. However, EAF steel production is constrained by the availability of scrap

steel and potential impacts on steel quality [21].

On the other hand, the DRI is the process that converts the solid iron ore to metallic iron without the liquid phase as in the blast furnace process [24]. The primary feature of the DRI processes is the use of hydrocarbon-based gases produced from reforming natural gas or coal gasification to react with iron. Afterwards the DRI is fed to an electric arc furnace (EAF) for steel production [25].

The H-DRI route consists of using hydrogen as the reduced agent. The combination of DRI and EAF using hydrogen is currently considered the most viable long-term solution to achieve carbon-neutral steel production. Although, the hydrogen must be produced through a low-carbon route.

The production of steelmaker could be turned low carbon emitter using electricity for the conventional processes (electric arc furnaces, ladle refining furnaces, casting and rolling pumps, fans, compressors, and lighting) and to produce hydrogen, through electrolysis [26]. Therefore, to supply enough low-carbon electricity for both, it is needed a reliable, uninterrupted and secure electricity production; to overcome this problem, this work proposes the utilization of off-grid energy system, consisting of a hybrid system with small modular reactors (SMR) and renewable energy, well known as, Nuclear Renewable Hybrid Energy System (N-RHES). This system relies on the high-capacity factor of the nuclear energy, used in the system as baseload to support the transition in the integration process of renewables to the any energy mix [12].

Figure 7 depicts the various pathways to produce steel and presents a simplified diagram illustrating the three routes of production the BF-BOF route, the DRI-EAF route, and scrap-EAF route. Therefore, this study compares the BF/BOF route with the H-DRI-EAF route for steelmaking production.

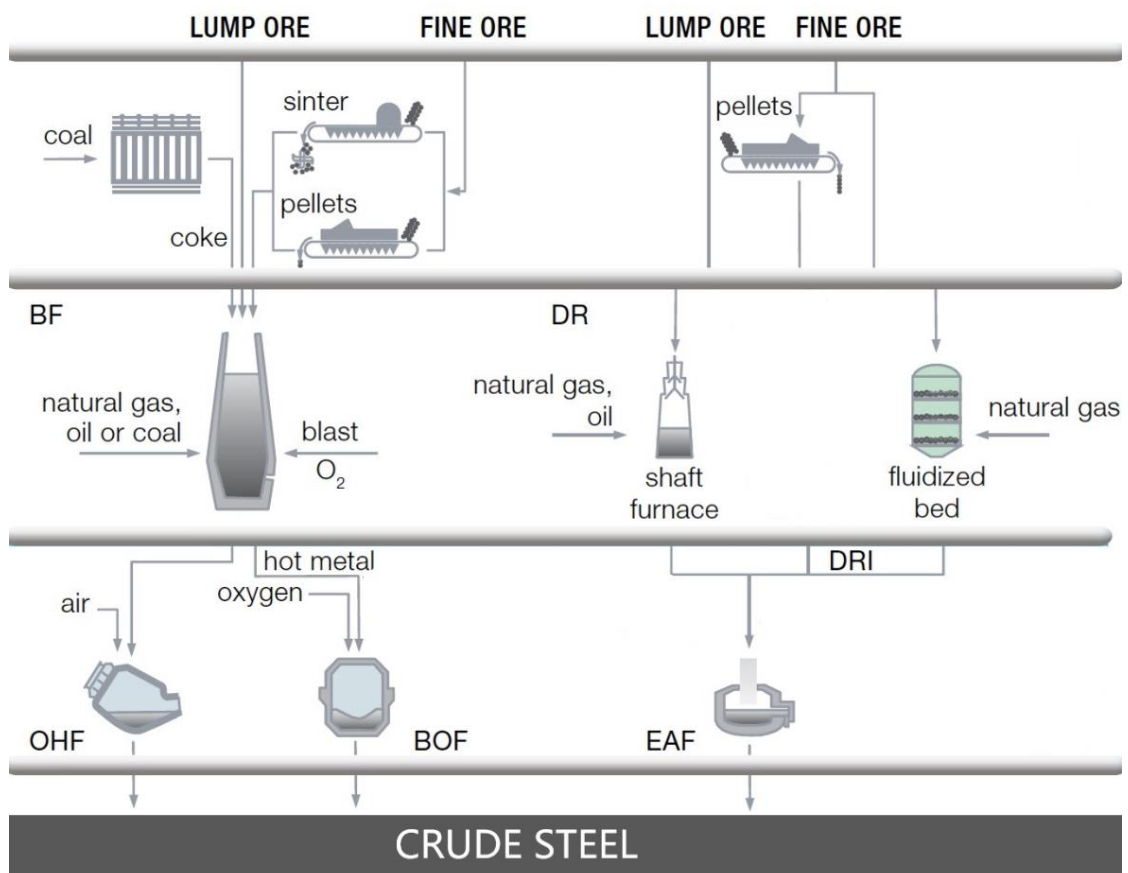


Figure 7 – Steelmaking production routes [23]

2.5. Energy Generation

Electricity plays a crucial role in modern life. While energy generation is currently the largest global source of CO_2 emissions, it is also at the forefront of the transition to net zero emissions through the swift adoption of renewable sources like solar and wind. Efforts to combat climate change are driving rapidly electrification across various sectors including transportation, residential and industrial. The electrification of those economics sectors is consequently leading to a substantial rise in electricity demand [27].

Renewable sources have low GHG emissions rates when compared to conventional fossil fuels, although their main common disadvantaged it's the intermittency on generation which leads to a need for energy storage. This fact can make the usage of renewable energies unsuitable for certain regions, due to the increase of overall price and instability on supply [28].

2.5.1. Small Modular Reactors

Traditional thermal power plants burn fossil fuels such as coal, natural gas, diesel to be able to produce heat, boiling water to produce steam. Electricity production process from nuclear power plants, the heat generation is controlled by fission reaction chain in the nuclear fuel, increasing the water temperature that either boils the water producing steam or exchange the water heat from the primary system to a secondary system. The heat exchange produces steam in the secondary system, which then the steam production as traditional thermal power plants do to spins the turbine for electricity generation [29]. Outstandingly, nuclear power plants do not produce greenhouse gases during electricity generation as the traditional power plants.

Nuclear reactors are a viable and strategic option for ensuring energy supply and CO₂ emissions mitigation in many countries, like France, USA, Japan, UK, and Russia. However, the substantial investment costs and intricate technology pose challenges, especially for developing nations. A potential solution to this dilemma involves downsizing nuclear reactors, creating compact, modular designs that can be easily adapted. This approach promotes the accessibility for developing countries to acquire modules for a cheaper price. As defined by the International Atomic Energy Agency (IAEA), these streamlined reactors are referred to as Small Modular Reactors (SMRs), ranging in power outputs from 10 MWe up to 300 MWe [30].

The countries in favor of nuclear energy are looking for the development of SMR to be competitive with renewable energies and natural gas power plants which most of the time are cheaper than the traditional NPPs. Nonetheless, over the years nuclear energy has been proven that is a reliable energy source with low carbon footprint. Moreover, SMR could be a solution for some of the problems for nuclear energy, such as, scalability, lower initial capital investment, flexibility in siting, non-electric applications, reduced nuclear waste and more compatibility with renewables energies (due to SMR can help balance the grid and ensure continuous supply), modularization, and design simplification as highlighted in Figure 8 [31, 29].

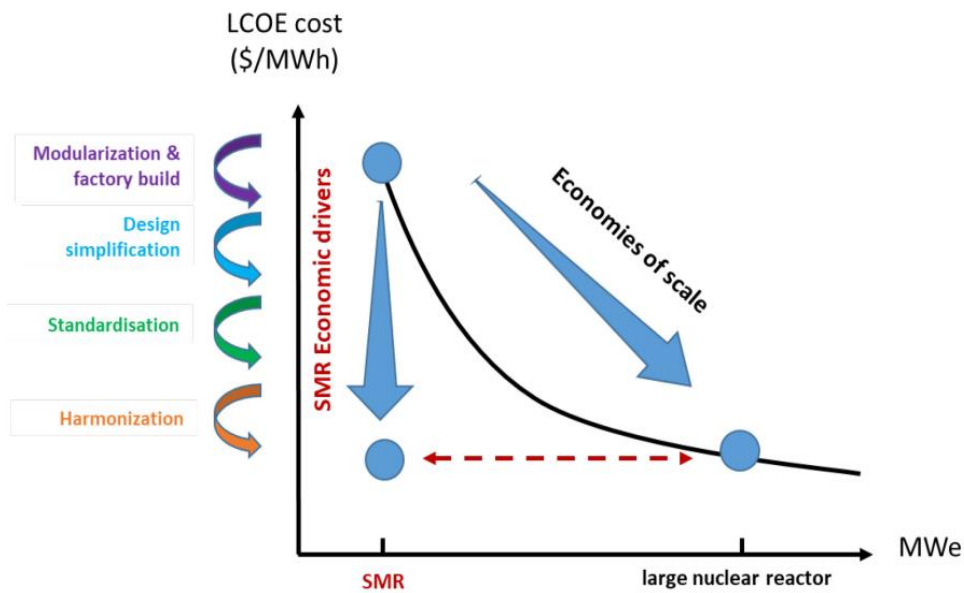


Figure 8 – SMR key economic drivers to compensate for diseconomies of scale [29]

2.5.2. Hybrid Energy Systems

The N-RHES mix the features of Nuclear Energy system such as continuous base-load electricity and low carbon emission with the flexibility, cost-effectiveness, low carbon footprint, low operation costs and abundance from renewable energy sources [32] [33]. This combination can help to balance the electricity supply to the energy systems reducing the risk of blackout or energy shortages, and the utilization of SMRs could even improve the system. There are many advantages to use SMR in a N-RHES such as they are cheaper, faster to build, could be installed by modules, and even have more flexibility than conventional nuclear power plants [29]. The N-RHES could help to enhance reliability and provide enough electricity to supply the needs of electricity for the steel making production and the hydrogen production needed to change the route from BF-BOF to a H-DRI route. In addition, the N-RHES can provide not only electricity in a reliable way, but it can also work with cogeneration purposes, such as heat production for industrial processes [4].

The best way to guarantee energy supply and security is through diversification. Presently, several works are studying the integration of SMR with renewable energy for electricity production on isolated systems, creating also an environmentally friendly

system [34]. The seasonal flexibility and load following ability of nuclear generation make a very important combination to support the integration with renewables. In addition, the N-RHEs can provide not only electricity in a reliable way, as well as work for cogeneration purposes [4].

As highlighted in the references [33] [4] these N-RHEs offer several key benefits as:

1. Support the grid with dispatchable, flexible, and low carbon electricity generation.
2. Provide heat to industrial sector, reducing industry cost with fossil fuels.
3. Offer synchronous generation to support the grid, frequency, and voltage regulation. N-RHEs can swiftly respond to the ramping up and down of electricity production.
4. With controlled energy dispatch, N-RHEs can maximize or minimize electricity and cogenerate products based on demand without introducing significant complexity and cost, thereby becoming a more effective system.

3. METHODOLOGY

This study compares two different scenarios for one steelmaking plant, with production capacity of 2 Mton per year, and located in Ceará State, Brazil. The first scenario, featuring a conventional steel plant using the blast furnace route (BF-BOF route) with electricity supplied by a coal power plant, as depicted in Figure 9. The second one considers the steel production using H-DRI route, where the hydrogen used for the steel reduction is produced by electrolysis process which demands electricity, in addition to the electricity demand for the EAF. Hence, the electricity produced should supply the electrolysis process to produce hydrogen and the electricity demand from EAF, as illustrated in Figure 10.

The steel production through the BF-BOF route demands a total energy input of 17.4 GJ/ton_{steel} [35] and the primary fuel is coal, fuel which is also used for the electricity generation of the power plant. Then, this route results in a total emission of 1.9 tonCO₂/ton_{steel}, totalizing 3.8 MtonCO₂ per year, if considered a project lifetime of 60 years, the cumulative emission reaches 228 MtonCO₂. On the flip side, the H-DRI route proposal aims to decarbonize the industry, utilizing a Nuclear-Renewable Hybrid Energy System (N-RHES), as depicted in Figure 10. This system is carbon-free for electricity production.

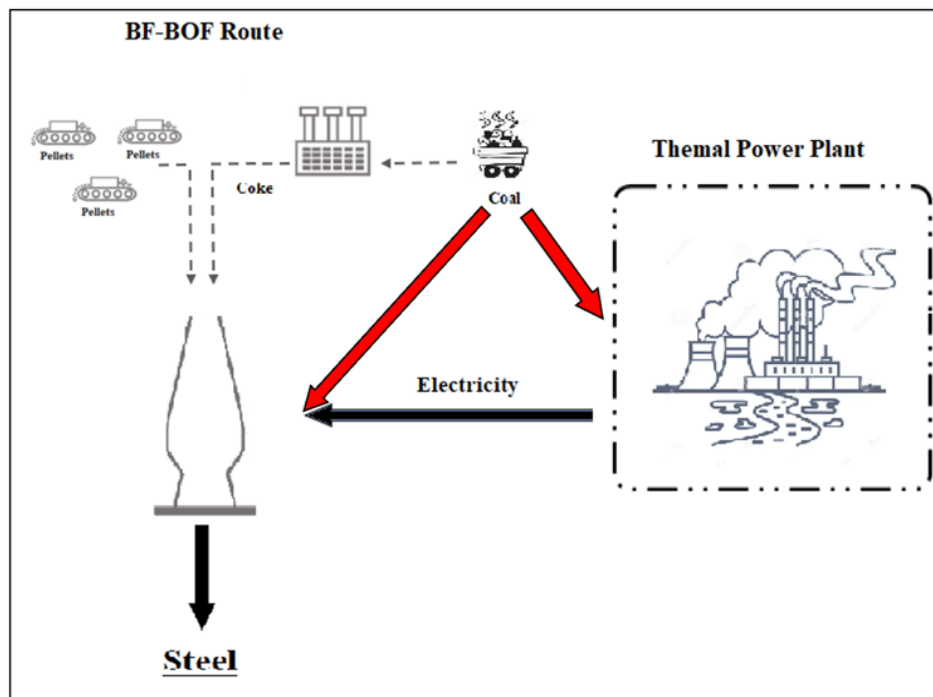


Figure 9 – Steel production through BF-BOF route

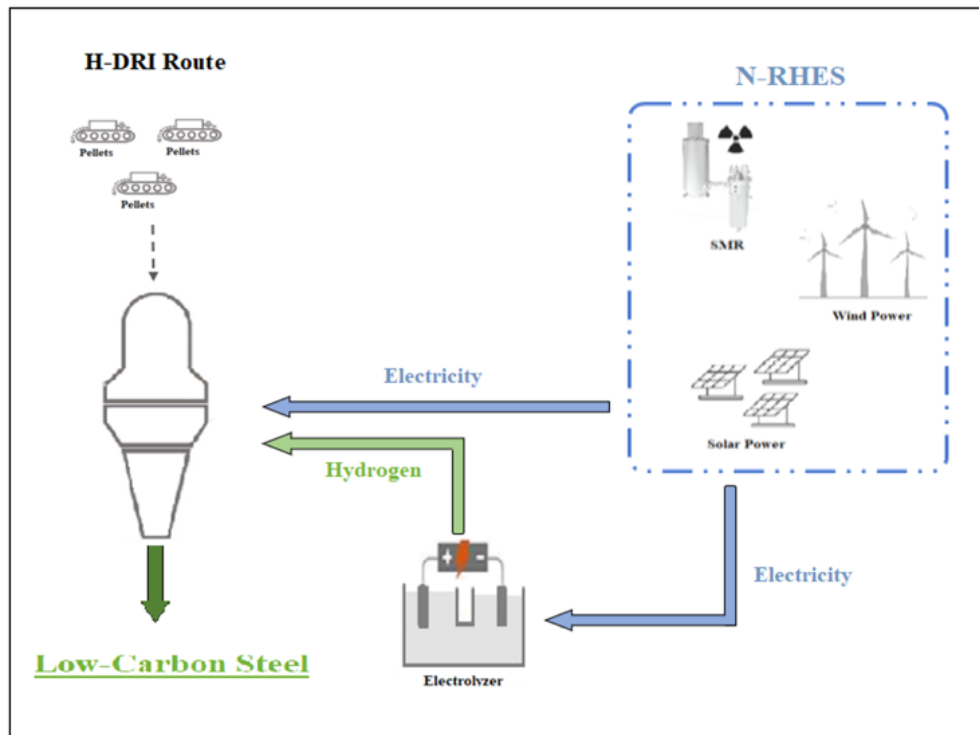


Figure 10 – Low-carbon steel production through H-DRI route

3.1. N-HRES model

The considerations for this work opted to simplify the calculations, focusing mainly on the expenditures related to energy supplies:

- Both steel plants, following the BF-BOF and the H-DRI routes, are assumed to be constructed from scratch, with comparable investment values;
- The primary energy inputs considered for the first scenario is coal, which should supply an energy input of $17.4 \text{ GJ/t}_{\text{steel}}$ (90% of energy input) for the BF-BOF route and 10% for the electricity supply;
- The primary energy inputs considered for the second scenario are hydrogen and electricity.

For clarity, the initial considerations guiding the estimations are summarized in Table 1.

Table 1 – Demand consideration for steel production (2 Mton per year).

Type of Demand	Value(US\$)	Unit
Coal	770 [36]	kg per ton of steel produced
Electricity for BF-BOF Route	483.33	kWh per ton of steel produced
H ₂	70	kgH ₂ per ton of steel produced
Electricity for H-DRI Route	383.33	kWh per ton of steel produced

Extensive analyses were conducted to identify the optimal location for the system. The objective was to determine a competitive levelized cost of energy (LCOE). However, due to variations in daily radiation at different locations, the photovoltaic power plant proved unsuitable, as it was increasing the system overall LCOE. Consequently, the final system model incorporates a Small Modular Reactor (SMR) and a wind power plant. Addressing the demand for both electricity and hydrogen, an initial proposal outlined a system with three key components that could be composed of small modular reactor, wind power plant, and photovoltaic power plant.

3.1.1. SMR for N-RHES

Currently, there are more than 80 Small Modular Reactors (SMRs) under development, one already operating and another under construction. The SMRs can be classified in many ways; one of them is according to its cooling system. There are three main groups in this classification: PWR (Pressurized Water Reactors), Gas-Cooled Reactors, and Molten Salt Reactors [37].

In this work, the focus is on exploring the exciting possibilities of seamlessly combining SMRs with renewable energy sources for the exclusive generation of electricity. The reactor's potential takes an intriguing turn as the exploration delves into a hybrid system capable of not only producing electricity but also generating steam for industrial applications and supporting high temperature electrolyzes. This choice will allow the reactor to have both utilization ways. While this particular aspect extends beyond the

current scope of our discussion, it sparks the promise of future research endeavors. Considering the high temperatures required by the steelmaking industry and certain electrolyzers, the proposed case study suggests the use of a High Temperature Gas Reactor (HTGR).

The selected SMR for this study is the XE-100, currently under development by X-Energy, a USA-based company, as illustrated in Figure 11. This project comprises modular reactors, each capable of delivering 80 MWe, with the flexibility of grouping four modules to achieve a total capacity of 320 MWe. Notably, the nuclear power plant has the capacity to produce steam at high temperatures, reaching 565°C, a valuable feature for applications such as hydrogen generation, for example through solid oxide electrolyzer [38], and other industrial processes applications [39] (those were not accounted on this study, but they can be considered for future models). In the present era, when considering low carbon energy sources, nuclear energy stands out as one of the few capable of simultaneously generating electricity, heat, potable water and hydrogen. This unique capability is particularly advantageous as it ensures independence from weather conditions or seasonality, providing a reliable and versatile energy solution [40].

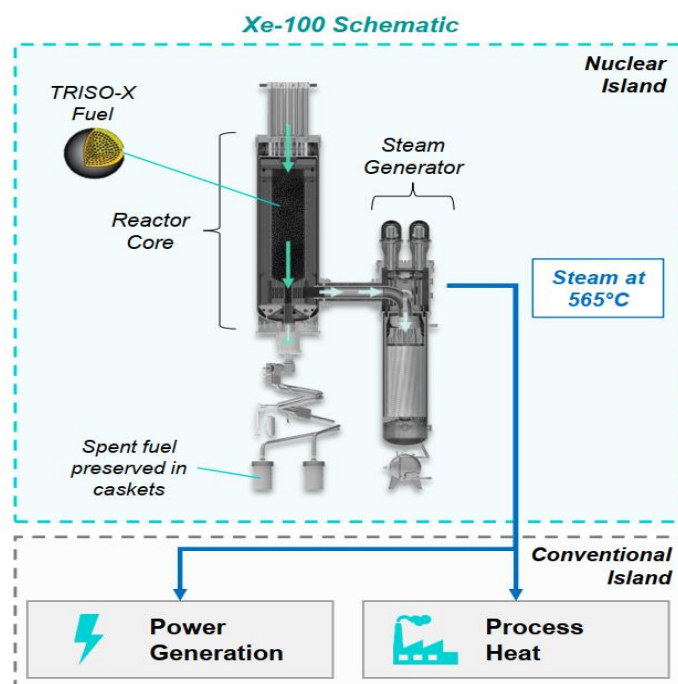


Figure 11 – The SMR Xe-100 schematic [39]

Given the vast diversity in SMR models, sizes, and capacities, coupled with the potential impact of technological advancements on installation costs over time, a sensitivity analysis has been conducted. This analysis aims to illustrate the viability curve for varying reactor prices, acknowledging the dynamic nature of the SMR landscape considering just the electricity production.

3.1.2. Wind Power Plant

Wind power was simulated using HOMER Pro Software, leveraging the NASA Prediction of World Energy Resource database to assess the wind potential. HOMER Pro is a software tool used for optimizing the design of microgrids, off-grid, and grid-connected renewable energy systems. The software is widely used in energy systems modeling, particularly for hybrid power systems that combine renewable energy sources with conventional generation. As depicted in Figure 12, the average wind speed in the specified area of Guararu, Caucaia - CE, Brazil, reaches up to 8.5 m/s during certain months, with an annual average of approximately 6.87 m/s, [41] as shown in Figure 12.

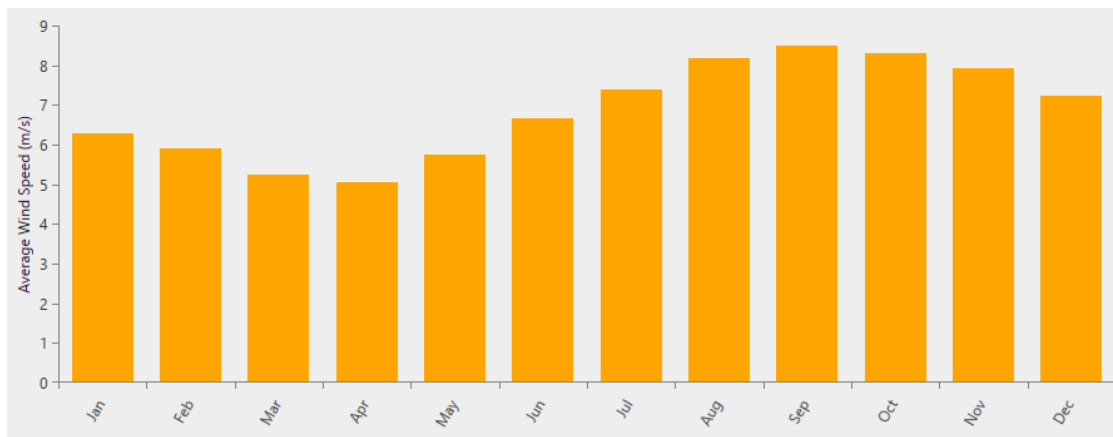


Figure 12 – Average wind speed [41]

The computation of wind turbine power output in HOMER involves a three-step process. Initially, it determines the wind speed at the hub height using the logarithmic law, as defined in Eq. (1) [42]. For the scope of this work, the calculations were performed using the ENERCON E-126 turbine, known for its hub height of 135 meters [43].

$$U_{hub} = U_{anem} \cdot \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{anem}}{z_0}\right)} \quad (1)$$

With:

U_{hub} = the wind speed at the hub height of the wind turbine [m/s]

U_{anem} = the wind speed at anemometer height [m/s]

z_{hub} = the hub height of the wind turbine [m]

z_{anem} = the anemometer height [m]

z_0 = the surface roughness length [m]

Once the hub height wind speed is established, HOMER utilizes the wind turbine's power curve to compute the anticipated power output, considering standard conditions of temperature and pressure. The calculated power curve, provided by the supplier, for this study is depicted in Figure 13.

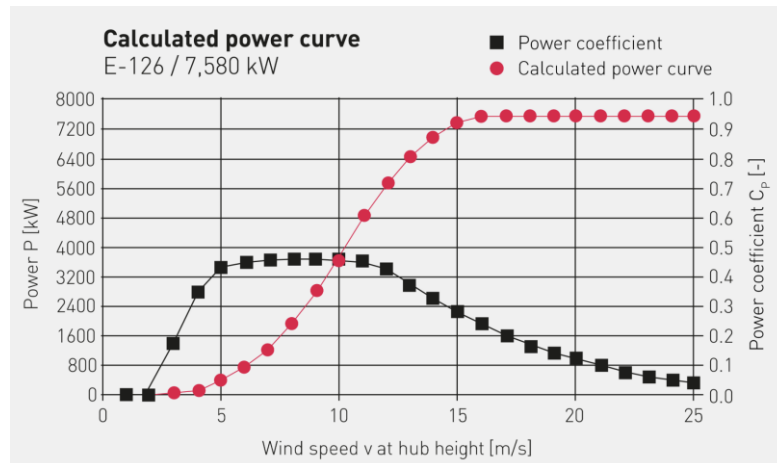


Figure 13 – Calculated power curve E-126 [44]

Finally, the power output value is adjusted considering the actual air density. To correct the value, the power predicted by the power curve is multiplied by the air density ratio, according to Eq. (2).

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) \cdot P_{WTG,STP} \quad (2)$$

With:

P_{WTG} = the wind turbine power output [kW]

$P_{WTG,STP}$ = the wind turbine power output at standard temperature and pressure

[kW]

ρ = the actual air density [kg/m^3]

ρ_0 = the air density at standard temperature and pressure ($1.225 \text{ kg}/\text{m}^3$)

Considering the calculation methodology explained, Figure 14 shows the expected turbines power output over a year during the hours of the day. This data was obtained directly from HOMER output.

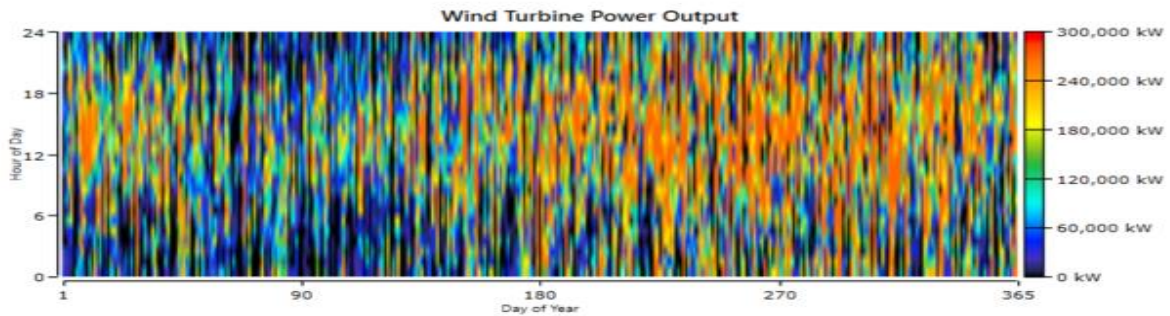


Figure 14 – Wind turbine power output [45]

Utilizing the anticipated output illustrated in Figure 7 alongside the power rating of the wind turbines, we calculated the average capacity factor, a crucial parameter applied in subsequent calculations.

3.2. Levelized Cost of Electricity calculation

The calculations initially relied on conservative values for both systems. Subsequently, sensitivity analyses were conducted calculating the LCOE to evaluate most favorable scenario using Python programming to facilitate the analysis, the script is presented on Annex A.

The initial step involved calculating the levelized cost of electricity (LCOE), defined as the ratio of total lifetime expenses to the total expected output [46], for both power plants. The Eq. (3) is used to calculate the LCOE:

$$LCOE = \frac{\sum_{t_{start}}^{t_{end}} \frac{CI_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t_{start}}^{t_{end}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} \quad (3)$$

with

C_{t} = capital investment expenditures at year t ;

$O\&M_{t}$ = O&M expenditures at year t ;

F_{t} = fuel expenditures at year t ;

P_{t} = net electrical power of the plant under consideration at year t ;

r = discount rate;

8760 = numbers of hours in a year;

L_{f} = load factor of the plant;

t_{start} = beginning of project (start of the first construction period);

t_{end} = end of the project (lifetime of the plant).

Due to the BF-BOF route relies totally on coal either for electricity or coke for iron reduction, which needs 770 kilograms of coal for each ton of produced steel, the expenses depend mostly on coal market prices. As the price of coal depends on international trading, it is used an average value between the trade market fluctuations from October 2020 to October 2023, which has minimum value of 37.87 and maximum value of 420.45 USD/t, respectively [47].

For the coal power plant, an installed capacity of 200 MW was assumed, with an investment of MUS\$ 310.45. The fixed and variable costs were detailed in Table 2. It was also assumed that the plant will operate at an 80% capacity factor.

Table 2 – Financial analyses for coal thermal power plant

Levelized cost of energy – Coal Power Plant		
Capacity (MW)		200
Total Investment	Million US\$	310.45
Construction time	Years	5
Life time	Years	45
Discount rate	Percent	8.0%
Fixed O&M Cost	US\$/kW/year	31.44
Variable O&M Cost	US\$/MWh	0.017
Capacity Factor	Fraction of year	0.8
Energy Generation	MWh	1,401,600
Fuel Cost	Million US\$	29.11

The calculation of the levelized cost of energy (LCOE) for the Nuclear-Renewable Hybrid Energy System (N-RHES) is presented in two parts, as detailed in Table 3. One section focuses on the Small Modular Reactor (SMR), while the other addresses wind power.

For the investment per installed kilowatt, the values are US\$ 3,516 for SMR and US\$ 1,200 for wind power. Notably, SMR demonstrates a high-capacity factor of 0.95, indicating it operates nearly continuously. In contrast, the wind power plant has a capacity factor of 0.449, reflecting the variability of wind resources in the region. The overall operation and maintenance (O&M) costs for both systems are outlined in Table 3.

Table 3 – Financial analyses for N-RHES

Levelized cost of energy			
		SMR	Wind Power
Capacity	MW	640	280.46
Total Investment	US\$/kW installed	3516	1200
Construction time	Years	6	3
Life time	Years	60	25
Discount rate	Percent	8.0%	8.0%
Fixed and Variable O&M Cost	US\$/kW/year	62.5	100
Fixed and Variable O&M Cost	Million US\$/year	40	28.05
Capacity Factor	Fraction of year	0.95	0.449
Energy Generation	MWh	5,326,080	1,103,116

4. RESULTS

Starting from conservative values, the calculations for both systems were initially based on cautious estimates. Following this, sensitivity analyses were carried out to assess more optimistic scenarios, aided by the development of a Python code for streamlined analysis, presented in Annex A. The LCOE was then computed, in accordance with Eq. (3), for both the coal power plant and the N-RHES, with the results presented in Tables 4.

Table 4 – Levelized cost of energy

Levelized cost of energy (US\$/MWh)	
Coal Power Plant	51.12
SMR	59.60
Wind Power Plant	60.10

For the coal power plant, the financial analysis indicates a Levelized Cost of Electricity (LCOE) of US\$ 51.13 per MWh, considering the costs on Table 2.

The financial analysis indicates that the LCOE is US\$ 59.6 per MWh for SMR and US\$ 60.1 per MWh for wind power, highlighting the competitive pricing of both technologies in the current energy landscape.

Utilizing the LCOE, the electricity expenditure for both systems was determined. In the case of the BF-BOF route, supplementary values accounting for the coal supply were essential to conclude the annual energetic cost. The total expenditure on energetic inputs was calculated in dollars per year, facilitating a comparative analysis of both systems, as detailed in Table 5 and Table 6.

Table 5 – Annual Energetics Input Cost - BF-BOF Route

Annual Energetic Cost - BF-BOF Route		
Electricity demand	kWh per ton of steel produced	483.33
	TWh	0.966
Coal demand	kg of coal per ton of steel produced	770
	ton of coal	1,540,000
Emissions	ton of CO ₂ per ton of steel produced	1.9
	ton of CO ₂	3,800,000
Electricity cost	\$/MWh	51.13
	Million US\$	49.41
Coal cost	\$/kg	0.18
	Million US\$	277.2
Emission fee	\$ per ton of CO ₂	0
	Million US\$	0
TOTAL	Million US\$	326.69

Table 6 – Annual Energetics Input Cost - HDRI Route

Annual Energetic Cost - HDRI Route		
Electricity demand	kWh per ton of steel produced	383.33
	TWh	0.766
H ₂ demand	kg of H ₂ per ton of steel produced	70
	ton of H ₂	140,000
Electrolyzer demand	kWh per kg of H ₂ produced	42
	TWh	5.88
Total electricity demand	TWh	6.65
Electricity cost	\$/MWh (SMR)	59.6
	\$/MWh (WPP)	60.1
TOTAL	Million US\$	397.03

The analysis indicates that the viability of the HDRI route might be questionable, particularly given the assumed conservative values: an investment cost for the SMR at 3516 US\$/kW, coal price at 180\$/t, no emissions fee, and an electrolyzer efficiency of 42 kWh/kgH₂. However, even with these conservative values, slight improvement in the four mentioned aspects could become the system feasible.

4.1 – Sensitivity Analysis

4.1.1 – Sensitivity analysis for BF-BOF

The coal price has a huge impact on determining the system's viability, especially for the BF-BOF route, which relies heavily on it. As previously mentioned, the international trading dynamics significantly influence coal prices, with fluctuations ranging from 37.87 to 420.45 US\$/t [47]. Although Brazil still does not have any fees for carbon emissions, one of the main proposed Amendment to the Constitution (PEC 45/2019) discusses the possibility of carbon fees in Brazil [48]. Nonetheless, this is a common practice in other countries to ensure the low carbon transition. Therefore, by the global trends seem that sooner or later Brazil should implement this kind of policy to ensure sustainability.

However, it is really difficult to set a price for the Brazilian context, then, the sensitivity analysis explores how the variation of the CO₂ emission fee from 0 to 60 US\$ could affect the steelmaking industry. For this analysis it was considered the electrolyzer efficiency as 42 kWh/kg of H₂ produced, and the SMR cost US\$ 3,516 per kW installed, an average of the models found, it was considered the base case of this study.

Figure 15 illustrates the total cost variation based on coal price and emissions fee. The H-DRI route is more profitable for coal prices above US\$0.23/kg, otherwise the CO₂ emission fee should increase to make the H-DRI route economically feasible. For instance, for the US\$ 15/tCO₂ emission fee the HDRI is economically viable for a price of US\$0.19/kg. While the HDRI route remains constant (US\$ 397.00M), unaffected by fluctuations in coal prices and emissions fees, the BF-BOF route is heavily reliant on both factors. Even minor changes in coal costs can result in a substantial increase in the energetic input expenses for the conventional process.

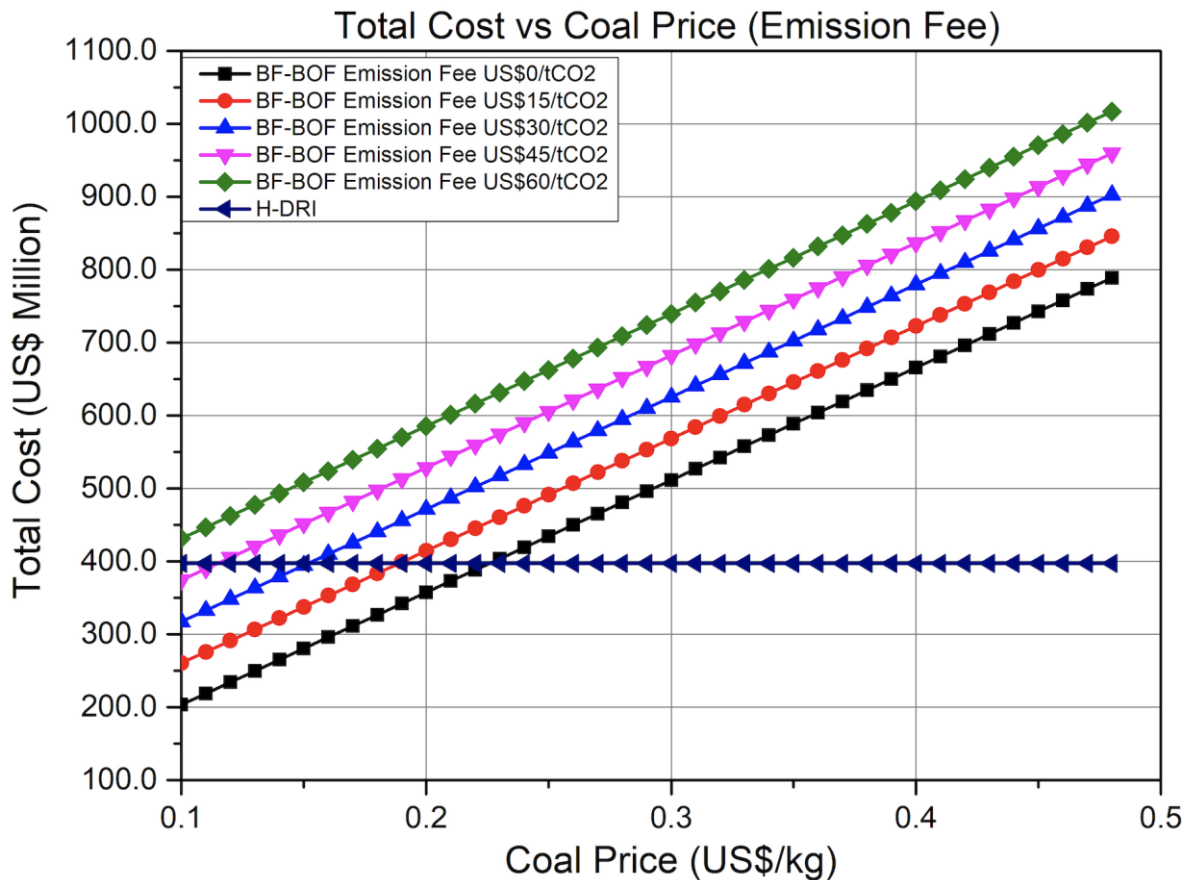


Figure 15 – Coal Price and Emissions Fee Sensitivity Analysis

4.1.2 – Sensitivity analysis for H-DRI

Other two factors could influence the expenses in the H-DRI route. The first factor is the investment cost on SMR and the second factor is the electrolyzer efficiency. Nowadays, many kinds of SMR are being developed with different power output, steam temperatures, investment cost, among other features. Generally, after the first of a kind model, prices in nuclear reactors tend to reduce over 55% from the initial price. The viability of this project is resemblance mostly in the SMR price and the electrolyzer efficiency for hydrogen production.

For this analysis it was considered the coal price at US\$ 0.18 per kg and no emissions fee, and the electrolyzer efficiency has been assumed to be between 24 and 48 kWh/kgH₂, the BF-BOF remains constant at US\$327.00M as it can be seen in Figure 16. For instance, when the SMR investment cost is US\$3650/kWh the price needed to

become the N-HRES feasible the electrolyzer efficiency should be about 32 kWh/kgH₂. If the prices of SMR could not be decreased another possibility is to improve the electrolyzer efficiency. In this analysis, the investment cost varies within the range of 2000 to 4000 US\$/kW installed for the electrolyze efficiency between 24 and 48 kWh/kgH₂.

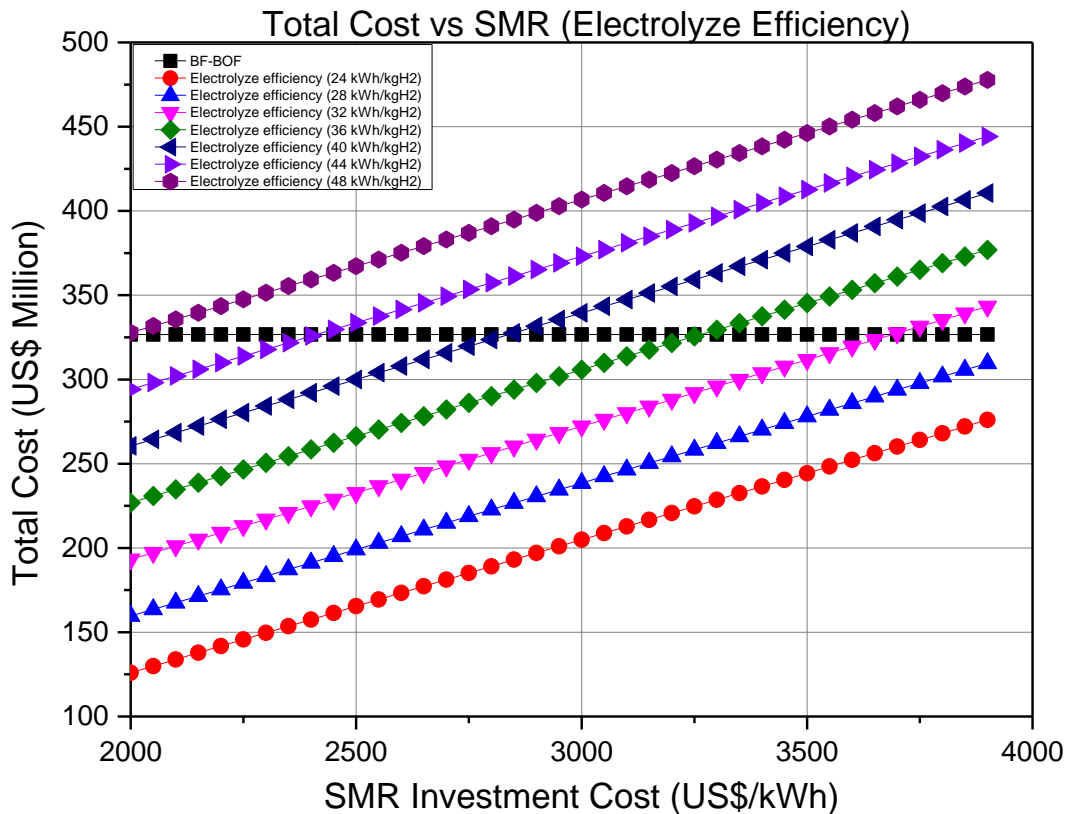


Figure 16 – SMR cost and electrolyze efficiency sensitivity analysis

4.1.3 – Carbon taxes

The carbon taxes are being discussed since many years ago but its rise over the past few years could make alternative solutions financially viable [49]. As previously shown, even with considerably low coal prices, a small tax would make the HDR1 system profitable. This topic aims to show that the proposed system will become more attractive with time in many countries.

The countries that taxed emissions in 2004 can be seen in Figure 17. This year, only Norway, Denmark, Slovenia, Finland, Estonia, Latvia, and Poland were charging fees for every ton of CO₂ emitted. The fees were relatively low comparing to 2024, Norway

led the group with approximately 80 US\$/tCO_{2e}, followed by Denmark with 16 US\$/tCO_{2e}. [50]

Price of carbon around the world, 2004

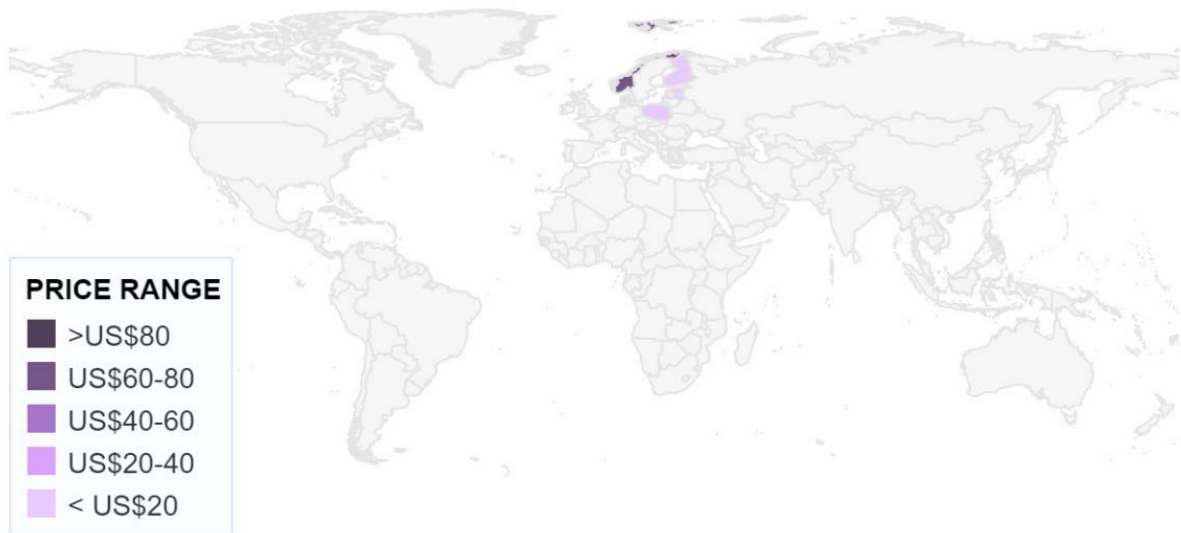


Figure 17 – Price of carbon emitted, 2004 [50]

There are currently more than 30 countries that charge for emissions, and Europe is still the region with the most supporters. Uruguay is the top-ranked country with fees that range from 165 US\$/tCO_{2e}, followed by Switzerland and Liechtenstein with rates that are roughly 132 US\$/tCO_{2e}. A huge difference is noted between Figures 17 and 18, in 20 years the number of countries on the list increased considerably and so the price.

Price of carbon around the world, 2024

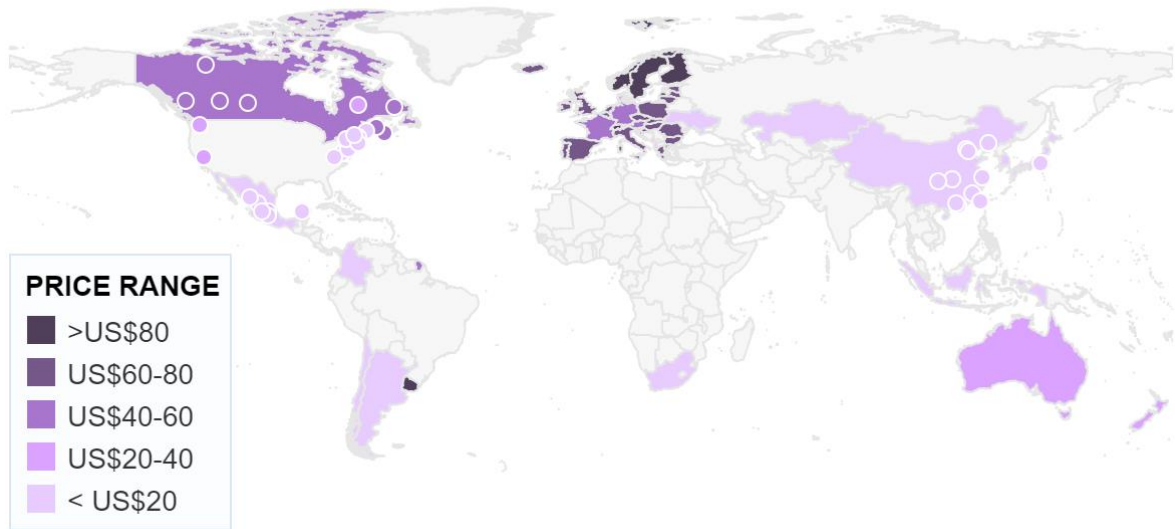


Figure 18 – Price of carbon emitted, 2024 [50]

Even though in Brazil there is no emissions fee, the HDRI route when compared with BF-BOF would be very profitable in many countries, specially on those with carbon price higher than 40 US\$/tCO_{2e}.

5. CONCLUSION

Upon completion of this study, it becomes evident that the feasibility of the H-DRI route employing N-RHES is a matter of time. Solely considering the financial aspect, it may currently appear as a relatively costly technology; however, when factors such as greenhouse gas emissions and energy security are taken into account, the proposed system swiftly transforms into a viable and attractive option.

The viability of the second scenario depends basically on the four parameters discussed in the sensibility analyses: SMR investment cost, coal price, CO₂ emission fee, and the electrolyzer's efficiency. Analyzing each of them individually, when the SMR investment cost drop to 2,625.20 US\$/kW installed the coal price increases to 225.27 US\$/t or the carbon price rises to US\$ 18.50 per ton of CO₂ or the electrolyze efficiency reach 33.63 kWh/kgH₂, then the H-DRI with N-RHES will become financially suitable.

Nevertheless, it is anticipated that these four parameters will change simultaneously over the years, evolving with technological improvements under less conservative conditions. This change is simulated in the sensitivity analysis.

Therefore, in this work has been assessed the impact in the price of the BF-BOF route by varying the coal prices and the emission fee for a case study considering different scenarios. Concluding that the H-DRI become feasible, considering no emission fee, at coal price of US\$0.23/ton. Notably, in regions where the emissions fee exceeds US\$ 60.00/tCO₂, the cost of coal becomes irrelevant, the HDRI route becomes economically viable for all scenarios.

In contrast, for the H-DRI route, the cost of BF-BOF remained fixed at approximately US\$M 327.00. The viability of the H-DRI become feasible if the electrolyze efficiencies increases, as an example at 32 kWh/kgH₂ the investment cost from SMR should be above US\$3650.00, considering, that the current electrolyze efficiency is around 33.3 kWh/kgH₂, the minimum price for the SMR should be around US\$3650.00.

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ANEXO A – PYTHON CODE

1. Input:

```
{  
    "Annual_P": 2000000,  
    "Electr_Cost_BF": 0.52,  
    "Emiss_Fee": 0,  
    "SMR_Cap": 640,  
    "SMR_Cost": 3516,  
    "SMR_CT": 6,  
    "SMR_ST": 1,  
    "SMR_LF": 60,  
    "SMR_FOM": 62.5,  
    "SMR_VOM": 0,  
    "SMR_CF": 0.95,  
    "WPP_Cap": 280,  
    "WPP_Cost": 1200,  
    "WPP_CT": 3,  
    "WPP_ST": 1,  
    "WPP_LF": 25,  
    "WPP_FOM": 100,  
    "WPP_VOM": 0,  
    "WPP_CF": 0.449  
}
```

2. Calculations:

```
class Calculations:  
    def __init__(self):  
        #Variáveis de ENTRADA  
        self.ED_BF = None  
        self.Coal_D = None  
        self.CO2_E = None
```

```
self.Coal_C = None
self.Disc_RT = None
self.ED_HDRI = None
self.H2_D = None
self.Electrolyzer_D = None
self.Electrolyzer_C = None
self.Annual_P = None
self.Electr_Cost_BF = None
self.Emiss_Fee = None
self.SMR_Cap = None
self.SMR_Cost = None
self.SMR_CT = None
self.SMR_ST = None
self.SMR_LF = None
self.SMR_FOM = None
self.SMR_VOM = None
self.SMR_CF = None
self.WPP_Cap = None
self.WPP_Cost = None
self.WPP_CT = None
self.WPP_ST = None
self.WPP_LF = None
self.WPP_FOM = None
self.WPP_VOM = None
self.WPP_CF = None

#Variáveis de SAÍDA
self.T_Elec = None
self.T_Coal = None
self.T_Emiss = None
self.T_BF = None
self.LCT_CNS = None
self.LCT_OPR = None
self.SMR_COST_LT = None
```

```
self.LEG_LT = None
self.SMR_LCOE = None
self.LCTWPP_CNS = None
self.LCTWPP_OPR = None
self.WPP_COST_LT = None
self.LEGWPP_LT = None
self.WPP_LCOE = None
self.TT_ED_HDRI = None
self.TC_HDRI = None
```

```
#Métodos GET para variáveis de ENTRADA
```

```
def get_ED_BF(self):
    return self.ED_BF
```

```
def get_Coal_D(self):
    return self.Coal_D
```

```
def get_CO2_E(self):
    return self.CO2_E
```

```
def get_Coal_C(self):
    return self.Coal_C
```

```
def get_Disc_RT(self):
    return self.Disc_RT
```

```
def get_ED_HDRI(self):
    return self.ED_HDRI
```

```
def get_H2_D(self):
    return self.H2_D
```

```
def get_Electrolyzer_D(self):
    return self.Electrolyzer_D
```

```
def get_Electrolyzer_C(self):  
    return self.Electrolyzer_C
```

```
def get_Annual_P(self):  
    return self.Annual_P
```

```
def get_Electr_Cost_BF(self):  
    return self.Electr_Cost_BF
```

```
def get_Emiss_Fee(self):  
    return self.Emiss_Fee
```

```
def get_SMR_Cap(self):  
    return self.SMR_Cap
```

```
def get_SMR_Cost(self):  
    return self.SMR_Cost
```

```
def get_SMR_CT(self):  
    return self.SMR_CT
```

```
def get_SMR_ST(self):  
    return self.SMR_ST
```

```
def get_SMR_LF(self):  
    return self.SMR_LF
```

```
def get_SMR_FOM(self):  
    return self.SMR_FOM
```

```
def get_SMR_VOM(self):  
    return self.SMR_VOM
```

```
def get_SMR_CF(self):
    return self.SMR_CF

def get_WPP_Cap(self):
    return self.WPP_Cap

def get_WPP_Cost(self):
    return self.WPP_Cost

def get_WPP_CT(self):
    return self.WPP_CT

def get_WPP_ST(self):
    return self.WPP_ST

def get_WPP_LF(self):
    return self.WPP_LF

def get_WPP_FOM(self):
    return self.WPP_FOM

def get_WPP_VOM(self):
    return self.WPP_VOM

def get_WPP_CF(self):
    return self.WPP_CF

#Métodos SET para variáveis de ENTRADA
def set_ED_BF(self, value):
    self.ED_BF = value

def set_Coal_D(self, value):
    self.Coal_D = value
```

```
def set_CO2_E(self, value):  
    self.CO2_E = value
```

```
def set_Coal_C(self, value):  
    self.Coal_C = value
```

```
def set_Disc_RT(self, value):  
    self.Disc_RT = value
```

```
def set_ED_HDRI(self, value):  
    self.ED_HDRI = value
```

```
def set_H2_D(self, value):  
    self.H2_D = value
```

```
def set_Electrolyzer_D(self, value):  
    self.Electrolyzer_D = value
```

```
def set_Electrolyzer_C(self, value):  
    self.Electrolyzer_C = value
```

```
def set_Annual_P(self, value):  
    self.Annual_P = value
```

```
def set_Electr_Cost_BF(self, value):  
    self.Electr_Cost_BF = value
```

```
def set_Emiss_Fee(self, value):  
    self.Emiss_Fee = value
```

```
def set_SMR_Cap(self, value):  
    self.SMR_Cap = value
```

```
def set_SMR_Cost(self, value):
```

```
self.SMR_Cost = value
```

```
def set_SMR_CT(self, value):
```

```
    self.SMR_CT = value
```

```
def set_SMR_ST(self, value):
```

```
    self.SMR_ST = value
```

```
def set_SMR_LF(self, value):
```

```
    self.SMR_LF = value
```

```
def set_SMR_FOM(self, value):
```

```
    self.SMR_FOM = value
```

```
def set_SMR_VOM(self, value):
```

```
    self.SMR_VOM = value
```

```
def set_SMR_CF(self, value):
```

```
    self.SMR_CF = value
```

```
def set_WPP_Cap(self, value):
```

```
    self.WPP_Cap = value
```

```
def set_WPP_Cost(self, value):
```

```
    self.WPP_Cost = value
```

```
def set_WPP_CT(self, value):
```

```
    self.WPP_CT = value
```

```
def set_WPP_ST(self, value):
```

```
    self.WPP_ST = value
```

```
def set_WPP_LF(self, value):
```

```
    self.WPP_LF = value
```

```
def set_WPP_FOM(self, value):
    self.WPP_FOM = value

def set_WPP_VOM(self, value):
    self.WPP_VOM = value

def set_WPP_CF(self, value):
    self.WPP_CF = value

#Metodos GET para variáveis de SAÍDA
def get_T_Elec(self):
    return self.T_Elec

def get_T_Coal(self):
    return self.T_Coal

def get_T_Emiss(self):
    return self.T_Emiss

def get_T_BF(self):
    return self.T_BF

def get_LCT_CNS(self):
    return self.LCT_CNS

def get_LCT_OPR(self):
    return self.LCT_OPR

def get_SMR_COST_LT(self):
    return self.SMR_COST_LT

def get_LEG_LT(self):
    return self.LEG_LT
```

```
def get_SMR_LCOE(self):
    return self.SMR_LCOE

def get_LCTWPP_CNS(self):
    return self.LCTWPP_CNS

def get_LCTWPP_OPR(self):
    return self.LCTWPP_OPR

def get_WPP_COST_LT(self):
    return self.WPP_COST_LT

def get_LEGWPP_LT(self):
    return self.LEGWPP_LT

def get_WPP_LCOE(self):
    return self.WPP_LCOE

def get_TT_ED_HDRI(self):
    return self.TT_ED_HDRI

def get_TC_HDRI(self):
    return self.TC_HDRI

def verificar_variaveis(self):
    variaveis_nulas = []
    variaveis = [
        ("ED_BF", self.ED_BF), ("Coal_D", self.Coal_D), ("CO2_E", self.CO2_E),
        ("Coal_C", self.Coal_C), ("Disc_RT", self.Disc_RT), ("ED_HDRI",
self.ED_HDRI),
        ("H2_D", self.H2_D), ("Electrolyzer_D", self.Electrolyzer_D),
        ("Electrolyzer_C", self.Electrolyzer_C), ("Annual_P", self.Annual_P),
        ("Electr_Cost_BF", self.Electr_Cost_BF), ("Emiss_Fee", self.Emiss_Fee),
```

```

        ("SMR_Cap", self.SMR_Cap), ("SMR_Cost", self.SMR_Cost), ("SMR_CT",
self.SMR_CT),
        ("SMR_ST", self.SMR_ST), ("SMR_LF", self.SMR_LF), ("SMR_FOM",
self.SMR_FOM),
        ("SMR_VOM", self.SMR_VOM), ("SMR_CF", self.SMR_CF), ("WPP_Cap",
self.WPP_Cap),
        ("WPP_Cost", self.WPP_Cost), ("WPP_CT", self.WPP_CT), ("WPP_ST",
self.WPP_ST),
        ("WPP_LF", self.WPP_LF), ("WPP_FOM", self.WPP_FOM), ("WPP_VOM",
self.WPP_VOM),
        ("WPP_CF", self.WPP_CF)
    ]

```

```

for nome_variavel, var in variaveis:

```

```

    if var is None:

```

```

        variaveis_nulas.append(nome_variavel)

```

```

if variaveis_nulas:

```

```

    raise ValueError(f"\n\nPor algum motivo as seguintes variáveis não foram
preenchidas: {' '.join(variaveis_nulas)}\n")

```

```

def calc(self):

```

```

    self.verificar_variaveis()

```

```

    #calculating the BF-BOF Route Annually Cost1

```

```

    self.T_Elec = (self.Electr_Cost_BF * self.ED_BF * self.Annual_P)/1000

```

```

    self.T_Coal = (self.Coal_D * self.Coal_C * self.Annual_P)

```

```

    self.T_Emiss = (self.CO2_E * self.Emiss_Fee * self.Annual_P)

```

```

    self.T_BF = (self.T_Elec + self.T_Coal + self.T_Emiss)

```

```

    #calculating LCOE for NRHES - SMR

```

```

    self.LCT_CNS = self.SMR_Cap*self.SMR_Cost

```

```

    #Levelized cost

```

```

for contruction period

```

```

self.LCT_OPR = 0 #Levelized cost operation period

for i in range((self.SMR_CT + 1), (self.SMR_CT + self.SMR_LF + 1)):
    self.LCT_OPR += (((self.SMR_FOM +
self.SMR_VOM)*self.SMR_Cap))/((self.Disc_RT + 1) ** (i - 0.5))
    self.SMR_COST_LT = self.LCT_CNS + self.LCT_OPR
    self.LEG_LT = 0 #Levelized energy generated during life -
discounted

for i in range((self.SMR_CT + 1), (self.SMR_CT + self.SMR_LF + 1)):
    self.LEG_LT += ((self.SMR_Cap*self.SMR_CF*8760))/((self.Disc_RT + 1) ** (i
- 0.5))
self.SMR_LCOE = self.SMR_COST_LT/self.LEG_LT

#calculating LCOE for NRHES - wind power plant
self.LCTWPP_CNS = self.WPP_Cap*self.WPP_Cost #Levelized
cost for contruction period
self.LCTWPP_OPR = 0 #Levelized cost operation period

for i in range((self.WPP_CT + 1), (self.WPP_CT + self.WPP_LF + 1)):
    self.LCTWPP_OPR += (((self.WPP_FOM +
self.WPP_VOM)*self.WPP_Cap))/((self.Disc_RT + 1) ** (i - 0.5))

self.WPP_COST_LT = self.LCTWPP_CNS + self.LCTWPP_OPR
self.LEGWPP_LT = 0 #Levelized energy generated during life -
discounted

for i in range((self.WPP_CT + 1), (self.WPP_CT + self.WPP_LF + 1)):
    self.LEGWPP_LT += ((self.WPP_Cap*self.WPP_CF*8760))/((self.Disc_RT +
1) ** (i - 0.5))
self.WPP_LCOE = self.WPP_COST_LT/self.LEGWPP_LT

#calculating the HDRJ Route Annually Cost
self.TED_HDRJ = self.ED_HDRJ * self.Annual_P

```

```

self.THED_HDRI = self.H2_D*self.Electrolyzer_D*self.Annual_P
self.TT_ED_HDRI = self.TED_HDRI + self.THED_HDRI
self.TC_HDRI    = (self.SMR_LCOE*self.SMR_Cap*self.SMR_CF*8760)  +
((self.TT_ED_HDRI - (self.SMR_Cap*self.SMR_CF*8760))*self.WPP_LCOE)

```

3. Outputs:

```

import sys
import os
import matplotlib.pyplot as plt
import calculations
import json
#Para gerar mapa:

os.system('clear')

def pontro_neutro(objeto, inicio, fim, precisao, variavel):
    variacao = inicio                #Variavel variaçãõ começa com valor de inicio
    while 1:
        if variavel == "Coal_C":      #Altera o valor da variável dentro de obj_calc
            objeto.set_Coal_C(variacao)
        elif variavel == "Emiss_Fee":
            objeto.set_Emiss_Fee(variacao)
        elif variavel == "Electrolyzer_D":
            objeto.set_Electrolyzer_D(variacao)
        elif variavel == "Disc_RT":
            objeto.set_Disc_RT(variacao)
        else:
            raise ValueError("\n\nVariavel de sensibilidade errada: ", variavel, "\n")

    objeto.calc()                    #Refaz os calculos

```

```

diff = abs(objeto.get_TC_HDRI()-objeto.get_T_BF())
#print(variavel, "\t", objeto.get_T_BF(), "\t",objeto.get_TC_HDRI(),"\t", diff,"\t",
variacao)
if diff<precisao:
    return variacao
if variacao>fim:
    print("ERRO",variavel)
    return
variacao+=diff*abs(fim-inicio)*0.000000001

def analize_sensibilidade(objeto, inicio, fim, passo, variavel, pasta):
    indice = 0
    vetor_X = []
    vetor_Y1 = []
    vetor_Y2 = []
    variacao = inicio                #Variavel variação começa com valor de inicio

    #FAZER BACKUP DO VALOR ORIGINAL
    if variavel == "Coal_C":        #Salva o valor original da variável para
posteriormente resetar
        vlr_original = objeto.get_Coal_C()
    elif variavel == "Emiss_Fee":
        vlr_original = objeto.get_Emiss_Fee()
    elif variavel == "Electrolyzer_D":
        vlr_original = objeto.get_Electrolyzer_D()
    elif variavel == "Disc_RT":
        vlr_original = objeto.get_Disc_RT()
    else:
        raise ValueError("\n\nVariavel de sensibilidade errada: ", variavel, "\n")

    #CALCULAR VALORES
    while variacao < fim:            #E só para quando variação chegar ao valor
de fim
        if variavel == "Coal_C":    #Altera o valor da variável dentro de obj_calc

```

```

    objeto.set_Coal_C(variacao)
elif variavel == "Emiss_Fee":
    objeto.set_Emiss_Fee(variacao)
elif variavel == "Electrolyzer_D":
    objeto.set_Electrolyzer_D(variacao)
elif variavel == "Disc_RT":
    objeto.set_Disc_RT(variacao)
else:
    raise ValueError("\n\nVariavel de sensibilidade errada: ", variavel, "\n")

objeto.calc()                #Refaz os calculos
vetor_X.append(variacao)     #Adiciona variável em um vetor para salvar
o histórico
vetor_Y1.append(objeto.get_T_BF())    #Adiciona T_BF em um vetor para
salvar o histórico
vetor_Y2.append(objeto.get_TC_HDRI()) #Adiciona TC_HDRI em um vetor
para salvar o histórico
variacao+=passo             #Incrementa variacao com o valor de passo
indice+=1                   #Incrementa o indice em 1 e finalmente repete o
loop

#ACHAR PONTO NEUTRO
pnt_neutro = pontro_neutro(objeto, inicio, fim, 1, variavel)

#GERAR TABELA
with open('./+pasta+/tabela-'+variavel+'.txt', "w") as arquivo:
    arquivo.write("#Sensibility analysis - " + variavel + "\n\n")
    arquivo.write("Ponto neutro: " + f"{pnt_neutro}" + "\n\n")
    arquivo.write(variavel + "\tT_BF" + "\tTC_HDRI\n")
    for indice2 in range(0, indice - 1):
        linha = f"{vetor_X[indice2]}\t{vetor_Y1[indice2]}\t{vetor_Y2[indice2]}\n"
        arquivo.write(linha)

#GERAR GRÁFICO

```

```

plt.figure(variavel)
plt.plot(vetor_X, vetor_Y1, label='Carvão', color='black')
plt.plot(vetor_X, vetor_Y2, label='Hidrogênio', color='green')
plt.xlabel(variavel)
plt.ylabel('Custo final')
plt.title('Sensibilidade a variação de '+variavel)
plt.legend()
plt.savefig('./'+pasta+'/grafico-'+variavel+'.pdf', format='pdf')

#VOLTAR VALOR ORIGINAL
if variavel == "Coal_C":                #Volta o valor da variável dentro de obj_calc
para o valor original
    objeto.set_Coal_C(vlr_original)
elif variavel == "Emiss_Fee":
    objeto.set_Emiss_Fee(vlr_original)
elif variavel == "Electrolyzer_D":
    objeto.set_Electrolyzer_D(vlr_original)
elif variavel == "Disc_RT":
    objeto.set_Disc_RT(vlr_original)
else:
    raise ValueError("\n\nVariavel de sensibilidade errada: ", variavel, "\n")

def ler_arquivo():
    # Verificar se o nome do arquivo foi passado como argumento na linha de comando
    def msg(strg):
        print(strg,"Favor informar conforme abaixo:\n")
        print("{} <nome_do_arquivo_de_entrada>\n".format(sys.argv[0]))
        print("Ou:\n")
        print("{}                                <nome_do_arquivo_de_entrada>
<nome_da_pasta_de_saida>\n".format(sys.argv[0]))

    if len(sys.argv) < 2:

```

```

    msg("Não foi informado um arquivo de entrada...\n")
    return 1
elif len(sys.argv) > 3:
    msg("Formato de linha de comando inválido...")
    return 1

# Obter o nome do arquivo a partir do primeiro argumento
nome_arquivo = sys.argv[1]

try:
    # Abrir o arquivo em modo de leitura
    with open(nome_arquivo, 'r') as arquivo:
        return json.load(arquivo)
except FileNotFoundError:
    print("O arquivo '{}' não foi encontrado.\n".format(nome_arquivo))
    return 1
except Exception as e:
    print("Erro ao ler o arquivo:", e)
    return 1

#####
##### MAIN #####
#####

def main():
    print("#####\n### EnergySyst ###\n#####\n")
    input_data = ler_arquivo()
    if input_data == 1:
        return

nome_pasta = "output_EnergySyst" # Nome padrão da pasta de saída
if len(sys.argv)==3:

```

```

nome_pasta = sys.argv[2]
if not os.path.exists(nome_pasta):
    os.makedirs(nome_pasta)
else:
    raise ValueError("\n\nA pasta já existe: ", nome_pasta, "\n")
else:
    if not os.path.exists(nome_pasta):
        os.makedirs(nome_pasta)

# Objeto obj_calc recebe classe Calculations que está dentro do arquivo
calculations
obj_calc = calculations.Calculations()

# Inputs from user
obj_calc.set_Annual_P(input_data["Annual_P"])
obj_calc.set_Electr_Cost_BF(input_data["Electr_Cost_BF"])
obj_calc.set_Emiss_Fee(input_data["Emiss_Fee"])
# Inputs for NRHES - SMR LCOE
obj_calc.set_SMR_Cap(input_data["SMR_Cap"])
obj_calc.set_SMR_Cost(input_data["SMR_Cost"])
obj_calc.set_SMR_CT(input_data["SMR_CT"])
obj_calc.set_SMR_ST(input_data["SMR_ST"])
obj_calc.set_SMR_LF(input_data["SMR_LF"])
obj_calc.set_SMR_FOM(input_data["SMR_FOM"])
obj_calc.set_SMR_VOM(input_data["SMR_VOM"])
obj_calc.set_SMR_CF(input_data["SMR_CF"])
# Inputs for NRHES - wind power plant LCOE
obj_calc.set_WPP_Cap(input_data["WPP_Cap"])
obj_calc.set_WPP_Cost(input_data["WPP_Cost"])
obj_calc.set_WPP_CT(input_data["WPP_CT"])
obj_calc.set_WPP_ST(input_data["WPP_ST"])
obj_calc.set_WPP_LF(input_data["WPP_LF"])
obj_calc.set_WPP_FOM(input_data["WPP_FOM"])
obj_calc.set_WPP_VOM(input_data["WPP_VOM"])

```

```

obj_calc.set_WPP_CF(input_data["WPP_CF"])
#Default values BF-BOF Route
obj_calc.set_ED_BF(484)      # kwh per ton of steel
obj_calc.set_Coal_D(770)    # kg per ton of steel
obj_calc.set_CO2_E(1.9)     # ton of CO2 per ton of steel
obj_calc.set_Coal_C(0.18)   # US$/kg
obj_calc.set_Disc_RT(0.08)  # 8% Discount rate
#default values HDRI Route
obj_calc.set_ED_HDRI(384)   # kwh per ton of steel
obj_calc.set_H2_D(70)       # kg of H2 per ton of steel
obj_calc.set_Electrolyzer_D(42) # kwh per kg of H2
obj_calc.set_Electrolyzer_C(1300) # US$ per kW installed

#Depois de todas variáveis setadas, realiza os calculos
obj_calc.calc()

with open('./'+nome_pasta+'/output', 'w') as arquivo_saida:
    arquivo_saida.write("#####\n###                               EnergySyst
###\n#####\n\n\n")
    arquivo_saida.write(f"Total    electricity    cost    for    BF-BOF    Route
is:\nU$ {obj_calc.get_T_Elec()}\n\n")
    arquivo_saida.write(f"Total    coal    cost    for    BF-BOF    Route
is:\nU$ {obj_calc.get_T_Coal()}\n\n")
    arquivo_saida.write(f"Total    emissions    fee    cost    for    BF-BOF    Route
is:\nU$ {obj_calc.get_T_Emiss()}\n\n")
    arquivo_saida.write(f"Total    spend    annually    in    BF-BOF    Route
is:\nU$ {obj_calc.get_T_BF()}\n\n")
    arquivo_saida.write("Total                                discounted                                SMR
construction:\n{:.2f}\n\n".format(obj_calc.get_LCT_CNS()))
    arquivo_saida.write("Total                                discounted                                SMR
operation:\n{:.2f}\n\n".format(obj_calc.get_LCT_OPR()))
    arquivo_saida.write("Total
discounted:\n{:.2f}\n\n".format(obj_calc.get_SMR_COST_LT()))
    arquivo_saida.write("Total                                discounted                                energy

```

```

generated:\n{:.2f}\n\n".format(obj_calc.get_LEG_LT()))
    arquivo_saida.write("SMR                LCOE                in
U$/kWh:\n{:.4f}\n\n".format(obj_calc.get_SMR_LCOE()))
    arquivo_saida.write("Total                discounted                WPP
construction:\n{:.2f}\n\n".format(obj_calc.get_LCTWPP_CNS()))
    arquivo_saida.write("Total                discounted
operation:\n{:.2f}\n\n".format(obj_calc.get_LCTWPP_OPR()))
    arquivo_saida.write("Total
discounted:\n{:.2f}\n\n".format(obj_calc.get_WPP_COST_LT()))
    arquivo_saida.write("Total                discounted                energy
generated:\n{:.2f}\n\n".format(obj_calc.get_LEGWPP_LT()))
    arquivo_saida.write("Wind                power                plant                LCOE                in
U$/kWh:\n{:.4f}\n\n".format(obj_calc.get_WPP_LCOE()))
    arquivo_saida.write("Total                electricity                needed
HDRI:\n{:.2f}\n\n".format(obj_calc.get_TT_ED_HDRI()))
    arquivo_saida.write("Your total annually amount for HDRI route
is:\n{:.2f}\n\n".format(obj_calc.get_TC_HDRI()))

# Comparing routes
if obj_calc.get_T_BF() > obj_calc.get_TC_HDRI():
    arquivo_saida.write("THE TOTAL SPEND ANNUALLY IN HDRI ROUTE IS
LESS THAN YOUR CURRENT BF-BOF\n\n")
else:
    arquivo_saida.write("THE TOTAL SPEND ANNUALLY IN YOUR CURRENT
ROUTE IS LESS THAN HDRI ROUTE\n\n")

print("Arquivo de saída 'output' gerado!\n")

#sensitivity analysis - coal price
analize_sensibilidade(obj_calc, 0.1, 0.5, 0.01, 'Coal_C',nome_pasta)

#sensitivity analysis - CO2 fee
analize_sensibilidade(obj_calc, 0, 100, 1, 'Emiss_Fee',nome_pasta)

```

```
#sensitivity analysis - electrolyzer efficiency
analize_sensibilidade(obj_calc, 24, 46, 0.5, 'Electrolyzer_D',nome_pasta)

#sensitivity analysis - discount rate
analize_sensibilidade(obj_calc, 0, 0.1, 0.005, 'Disc_RT',nome_pasta)

print("Gráficos e tabelas gerados com sucesso!! \n\nEnergySyst finalizado com
sucesso!\n")

if __name__ == "__main__":
    main()
```