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NUCLEAR-RENEWABLE HYBRID ENERGY SYSTEM TO SUPPLY ELECTRICITY AND HYDROGEN TO DECARBONIZE STEEL INDUSTRY: A CASE STUDY IN BRAZIL

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ABSTRACT

This research offers an overview of the challenges and developments on the decarbonization of the steel industry in Brazil, through the utilization of hydrogen for iron reduction and electricity from a Nuclear-Renewable Hybrid Energy Systems (N-RHES) for electricity supply and hydrogen production. This analysis compares 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, providing hydrogen for the H-DRI process reducing the CO_2 emissions. The electricity needed for the hydrogen production, or the electric arc furnace (EAF) are supplied completely by a N-HRES system. The outputs show promising results for the viability of the H-DRI considering the coal cost, CO_2 emission fee and the electrolyze efficiency.

1. INTRODUCTION

The utilization of non-renewable fuels has increased due to changes in energy demand since the industrial revolution. Since then, the population and comfort levels have increased, leading to a high demand for electricity, heating, and transportation, which is mostly fueled by fossil fuels.

As energy access has increased recently, the high cost of electricity, CO_2 emissions, and energy security are the main concerns in any country worldwide. Fuel prices, availability, political issues, and commodity trades are all factors that have influenced the cost of energy. [1] The integration of alternative energy sources into the energy mix is currently a primary challenge given the context. Renewable energy sources are being heavily discussed in order to achieve a carbon-free transition. Nonetheless, their limitations are due to their dependence on weather and seasonality.

During this transition, nuclear energy is a reasonable alternative to support renewable energy. The integration with renewables is crucial due to nuclear generation's seasonal flexibility and load-following ability. The nuclear-renewable hybrid energy system (N-RHES) can not only provide electricity reliably, but it can also be used for cogeneration purposes. [2]

The energy consumption and CO_2 generation of industries in general are among the highest in the world. The steel industry has an extremely high emission rate among all of them. Only 7% of global emissions are due to the sector alone. [3]. At the moment, steel production using blast furnace/blast oxygen furnace route (BF/BOF) releases about 1.9 tCO_2/tsteel. [4].

In order to avoid those emissions, numerous projects for the steel industry are being developed worldwide. The alternative is to replace coal with hydrogen, which implies a direct reduction of iron ore (DRI) using 100% low carbon hydrogen (H-DRI). [4]

2. METODOLOGY

2.1. DESCRIPTION OF THE ENERGY SYSTEMS

This work compared two scenarios, one of which is a conventional steel plant producing 2 million tons per year through the blast furnace route (BF-BOF route), as depicted in Fig. 1. As depicted in Fig. 2, another scenario involves a plant in Ceara State, Brazil that uses hydrogen as the primary component for steel reduction and processes (H-DRI route) as shown in Fig. 2.

The energy required to produce steel using the BF-BOF route is 17.4 GJ/tsteel [5]. The primary fuel utilized in this situation is coal, which is turned into coke for metal reduction and also utilized in the thermal power plant to produce electricity. This route is responsible for emitting approximately 1.9 tCO_2/tsteel, which is equal to 3.8 $MtCO_2$ per year. With a 60-year project life-time, it has the potential to reach 228 $MtCO_2$.

In order to decarbonize the industry, the H-DRI proposal utilizes a N-RHES to supply electricity and produce free-carbon hydrogen for the steel making process, as shown in Fig. 2. In this instance, hydrogen is used to replace the coal, and it's produced by an electrolyzer that uses electricity from the N-RHES. The plant will receive electricity directly from the energy systems for other processes.

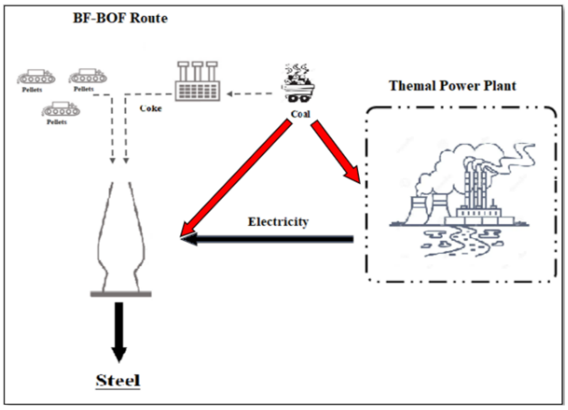

Fig. 1 Steel production through BF-BOF route (source: author)

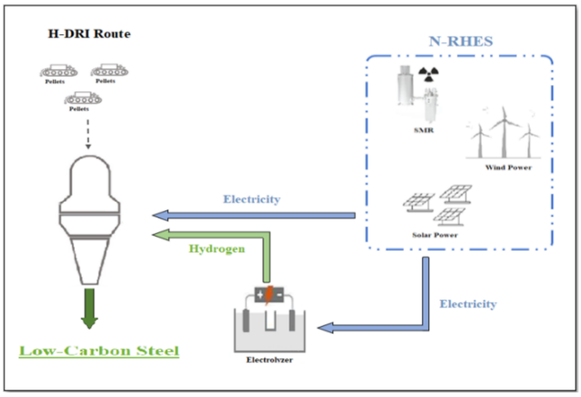

Fig. 2 Low-carbon steel production through H-DRI route (source: author)

2.2. SYSTEMS PREMISES

Some assumptions are made to simplify the calculations:

- Both steel plants will be built from the beginning, considering that the BF-BOF and the H-DRI have similar investment values.
- Electricity and fuel are the only energy inputs needed to produce steam.
- The base scenario assumes that coal represents 90% of the energy input (17.4 GJ/tsteel) and electricity represents 10%.

Tab. 1 demonstrates the initial premises that were adopted to estimate the demand.

Total Demand Premises		
Anual production	2000000	ton of steel
Coal demand	770	kg/t
Electricity demand BF-BOF Route	483.33	kWh/t
H2 demand	70	kgH2/t
Electricity demand H-DRI Route	383.33	kWh/t

Tab. 1 Demand Premises

2.3. N-HRES MODEL

A system with three components was initially proposed to meet the demand for electricity and hydrogen.

- Small modular reactor
- Wind power plant
- Photovoltaic power plant

The development of multiple models led to the discovery of a competitive levelized cost of energy (LCOE). Because of the daily radiation in the area, the photovoltaic power plant was not a viable option compared to the other two options and it was causing an increase in overall costs. Consequently, the system that was modeled includes a small modular reactor (SMR) and a wind power plant.

2.4 SMALL MODULAR REACTOR

The SMR chosen for this case study was the XE-100, which was developed by X-Energy, a US company, as shown in Fig 3. The project is comprised of modular reactors that provide 80MW each, and it is possible to combine four modules to produce 320MW. Additionally, the plants are designed to deliver steam at a high temperature of 565°C. [6]

Considering all the low-carbon sources available, nuclear energy is one of the few that can produce electricity, heat, and hydrogen today. Furthermore, to guarantee all three without being dependent on weather conditions or seasonality. [7]

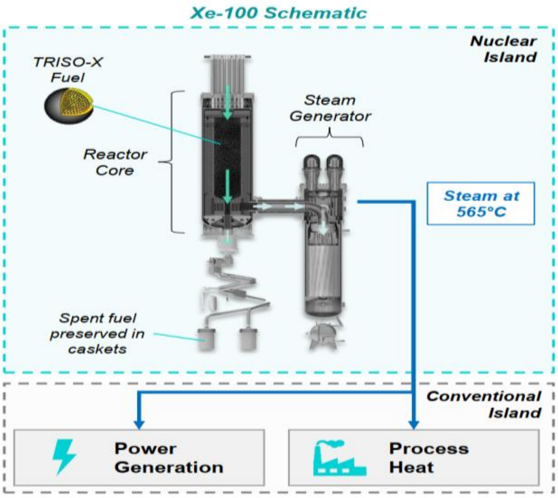

Fig. 3 Xe-100 Schematic (X-Energy 2022)

2.5 WIND POWER PLANT

HOMER Pro [8] was used to model wind power using NASA's Prediction of World Energy Resource data base to estimate its potential. There is an average wind speed of 8.5 m/s in this area.

In light of this, Fig. 4 illustrates the predicted turbine output throughout a year at various times of the day.

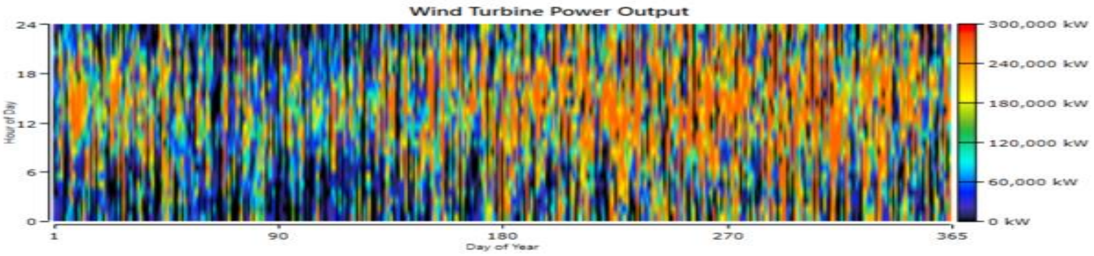

Fig. 4 Turbines output over the year (HOMER Pro)

3. RESULTS

The calculations were initially based on conservative values for both systems. The thermal power plant and the N-RHES have been calculated using the LCOE, as depicted in Tab. 2 and 3 and the Eq. (1). Afterwards, the value is utilized to determine the total annual expenditure for each system.

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

with

CIt = capital investment expenditures at year t;
O&Mt = O&M expenditures at year t;
Ft = fuel expenditures at year t;
Pt = net electrical power of the plant under consideration at year t;

r = discount rate;
8760 = numbers of hours in a year;
Lft = load factor of the plant;
tstart = beginning of project (start of the first construction period);
tend = end of the project (lifetime of the plant).

Levelized cost calculation		
Coal Power Plant		
Capacity	MW	200
Total investment	Million US$	310.45
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	1401600
Fuel costs	Million US$	29.11
LCOE	**US$/MWh**	**51.13**

Tab. 2. Financial analyses for coal power plant

Levelized cost calculation			
		SMR	**Wind Power**
Capacity	MW	640	280.46
Total investment	Million US$	2250.24	336.55
Discount rate	percent	8.0%	8.0%
Variable & Fixed O&M costs	US$/kW/Year	62.5	100
Variable & Fixed O&M costs	Million US$/year	40	28.05
Capacity factor	fraction of year	0.95	0.45
Energy Generation	MWh	5326080	1103116
LCOE	**US$/MWh**	**59.64**	**61.81**

Tab. 3. Financial analyses for N-RHES

The methodology used resulted in the LCOE for the coal power plant, SMR, and wind power plant being 51.13 US$MWh, 59.64 US$MWh, and 61.81 US$MWh, respectively. The calculation of the final amount spent on each route requires those values.

The electricity expenses for both systems were calculated using the LCOE. To conclude the annual cost for the BF-BOF route, it was necessary to include additional values for coal supply. By calculating the total expenditure on energy inputs in dollars per year, both systems can be compared as detailed in Tab. 4 and 5.

The first analysis was conducted with a conservative attitude towards the topics below.

- Coal price (0.138 U$/kg)
- Emissions fee (no fee)
- Electrolyzer productivity (46 kWh/kgH_2)

BF-BOF Route		
Electricity demand	kwh/tsteel	483.33
	TWh	0.966
Coal demand	kg/tsteel	770
	t	1540000
Emissions	tCO_2/tsteel	1.9
	tCO_2	3800000
Electricity cost	$/MWh	51.13
	Million US$	49.42
Coal cost	$/kg	0.138
	Million US$	212.52
Total	**Million US$**	**261.95**

Tab. 4. Financial analyses for BF-BOF Route

H-DRI Route		
Electricity demand	kwh/tsteel	383.33
	TWh	0.766
H_2 demand	kgH_2/tsteel	70
	t H_2	140000
Electrolizer demand	kWh/kgH_2	46
	TWh	6.44
Total electricity demand	TWh	7.21
Electricity cost (N)	$/Mwh	59.64
Electricity cost (W)	$/Mwh	61.81
Total	**Million US$**	**433.87**

Tab. 5. Financial analyses for H-DRI Route

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 U$/kW, with coal price at 180$/t, no emissions fee, and an electrolyzer efficiency of 46 kWh/kgH_2. As shown in Tab. 4 and 5, the total amount spent for BF-BOF would be MUS$ 261.96 and for HDRI MUS$ 433.87, the HDRI route is about 65% more expensive than the conventional one.

The HDRI system could become feasible if the conservative values were slightly modified. Fig. 5, 6, and 7 demonstrate a sensitive analysis based on a fluctuation in coal prices. The cost of producing 1 ton of CO_2 is between US$60 to US$420, and CO_2 emission fees range from 0 to US$50 per ton of CO_2 and the efficiency of the electrolyzer is 46 to 24 kWh per kilogram of H_2 generated.

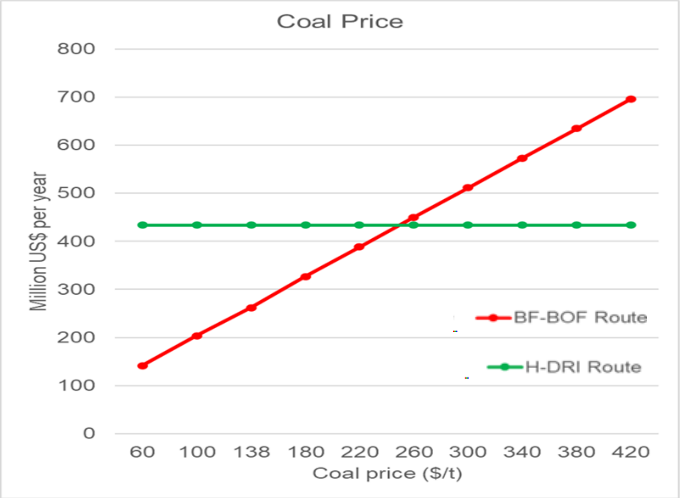

Fig. 5. Variation of coal price

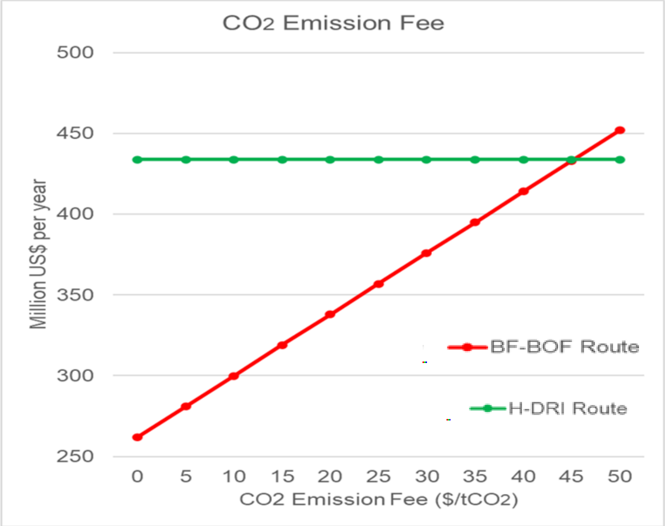

Fig. 6. Variation of CO2 emission fee

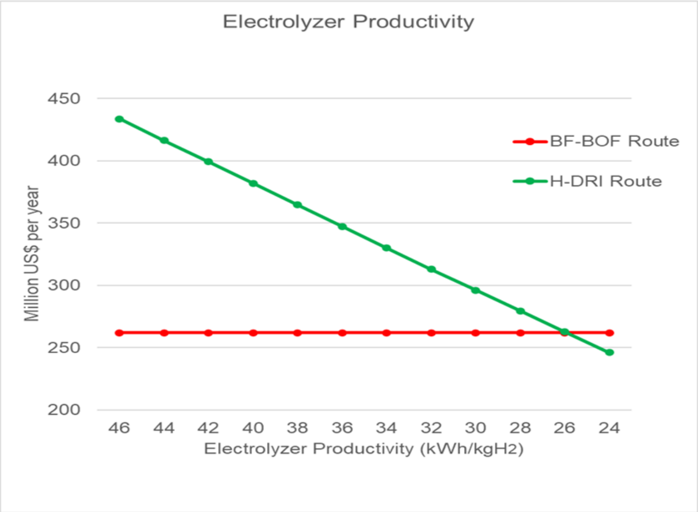

Fig. 7. Variation of electrolyzer productivity

The turning point for HDRI viability, given the individual aspects, occurs when the coal price goes up to US$260/t, the carbon price goes up to US$48/t$CO_2$ or the electrolyzer efficiency goes up to 26kWh/kgH_2.

4. CONCLUSION

After this research, it can be concluded that the H-DRI route using N-RHES is only a matter of time before it becomes viable. Despite the financial aspect, the proposed system may still be expensive, but when GHG emissions and energy security are taken into account, it can easily become suitable.

The second scenario's viability is determined by three factors: coal price, CO_2 emission fee, and electrolyzer's productivity. The financial feasibility of H-DRI with N-RHES can be determined by analyzing each factor separately. If the coal price rises to US$260/t, the carbon price rises to US$48/t$CO_2$, or the electrolyzer efficiency reaches 26kWh/kgH2, the H-DRI with N-RHES will be financially viable.

These three parameters are expected to change simultaneously and under less conservative conditions, taking into account: coal price 180 US$/t, CO_2 emission fee 10 $/t$CO_2$ and electrolyzer productivity 38 kWh/kgH_2, the total spent with energetics input was 364 million US$ per year, for both scenarios, this means that the H-DRI route would be already financially viable.

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