Sustainable Steel Production in the Desert: Economic and Technical Assessment of a Hydrogen-Powered Steel Plant in Mauritania

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***Abstract*—The global steel industry is a major contributor to climate change and faces challenges in achieving a carbon-neutral production, hinging on the availability of cost-effective hydrogen produced by renewable energy. Mauritania, with its exceptional solar and wind resources, offers some of the most competitive conditions globally for hydrogen production. Instead of focusing on hydrogen exports, this study explores the technical feasibility and economic viability of establishing a renewable-powered steel plant in Mauritania, utilizing the country's abundant iron ore reserves. The findings suggest that sustainably produced steel in Mauritania could be cost-competitive with current European prices. With ongoing declines in investment costs for emerging renewable technologies, Mauritania has the potential to become one of the world's most cost-effective steel producers.**

***Index Terms*—hydrogen, green steel, Mauritania, sustainable steel, hydrogen integration**

I. Introduction

The global steel industry is a vital ingredient of modern infrastructure and economic development, yet it produces more emissions than all global road freight combined [1]. In the face of increasing environmental concerns and the urgent necessity to address climate change, it is important to look for cost-effective solutions for some of the largest CO_2 emitters. Accounting for approximately 7 % of global energy-related CO_2 emissions, the steel sector is one of the largest carbon emitters, primarily due to its reliance on coal and natural gas for traditional blast furnace - basic oxygen furnace (BF-BOF) processes [1]. Producing one ton of steel typically results in the emission of around 1.87 tons of CO_2 [2]. This number is alarming, especially since it has been predicted that global steel production will increase by more than one third by 2050, primarily driven by the demands of developing countries [1].

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The shift to green steel production, replacing carbon with hydrogen as a reducing agent, represents a promising pathway and cuts CO_2 emissions by more than 97% [2]. In this process, iron ore is reduced by hydrogen to direct reduced iron (DRI) and then further melted to steel in an electric arc furnace (EAF). Currently, the first green steel plants are being developed as pilot plants in Sweden and Germany. However, for them to become economically competitive with traditional processes, the availability of low-cost and large-scale renewable energy sources is critical.

Mauritania, located in northwest Africa, presents a unique opportunity in this global effort due to its abundant natural resources. For instance, its lowest solar irradiation measurements compare to Europe's peak solar resources. In the northern region of Mauritania, wind energy can be harnessed onshore at wind conditions which are usually only comparable to high-performance offshore conditions. Solar and wind power generation costs are estimated to be low, at around 20-25 US$/MWh and 22-29 US$/MWh, respectively. This could enable hydrogen production to be among the cheapest globally, anticipated to be between 1.7 and 2 US$/$kg_{H_2}$ by 2035. [3]

One of the major obstacles is the long-distance transport and storage of hydrogen, which can be both technically complex and expensive. In the context of Mauritania, hydrogen could instead be directly used within the country to produce steel or DRI, a precursor in the production of green steel. The country's strategic geographic location, coupled with its status as Africa's second-largest iron ore producer, positions it as a prime candidate for the development of a hydrogen-based steel industry.

This paper seeks to explore the technical and economic feasibility of establishing a hydrogen-based steel plant in Mauritania. A key component of this research involves the simulation of steel production in selected locations using an existing GAMS (General Algebraic Modeling System) model. This aims to optimize the integration of renewable energy to identify the most cost-effective configuration. It aims to propose a viable plant layout, assess the potential production cost of green steel, and evaluate its competitiveness against conventional steel. The study also offers technical optimization measures to improve the plant's efficiency and sustainability.

II. Materials and Methods

To outline the technical and economic requirements necessary for green steel in Mauritania, a potential plant and supply chain design was developed, conceptualized as three interconnected sub-plants: (1) renewable energy production and conversion, (2) seawater desalination and cooling systems, and (3) electrolysis and steel production. The energy and water plants are considered auxiliary, providing feedstock to the main plant which produces hydrogen and green steel.

The technical and economic parameters of the main plant are modeled based on a GAMS optimization model developed by Devlin, Kossen, Goldie-Jones and Yang (2023) at the University of Oxford [4]. The model was solved using the NEOS server for numerical optimization by the University of Wisconsin and various other hosts [5]. Both auxiliary plants are excluded from the model to reduce complexity. Instead, their input parameters will be calculated separately. This model was selected due to its detailed approach and was slightly adapted to Mauritania's specific conditions, offering a comprehensive view of the entire production process, from iron ore crushing to steel casting.

For the economic assessment, a project lifetime of 20 years is assumed. The model is designed to minimize energy usage and costs, offering detailed insights into the project's capital expenditures (CAPEX) and operational expenditures (OPEX). A Weighted Average Cost of Capital (WACC) of 8% is used for most scenarios to reflect base financing costs, while a high-capital-cost scenario assumes a 15% WACC to represent elevated financial risk in developing countries. A plant size with a yearly production rate of 1 million tons of liquid steel (tLS) is considered. Fixed CAPEX costs are applied to the steel plant infrastructure components such as the EAF, while investment costs for emerging technologies (e.g., electrolyzers) are projected to decline over the coming decades [4]. OPEX include resource costs, maintenance (estimated at 2% of infrastructure CAPEX [6]), and labor costs. Labor costs were based on a reference wage (4.38 US$/hour), derived from SNIM (National Industrial and Mining Company) workers' wages, and scaled according to labor intensity for steelmaking (4.29 US$/tLS) and ironmaking (1.93 US$/t of DRI). For the Germany comparison scenario, default costs from the Devlin, Kossen, Goldie-Jones and Yang study are used [4].

A. Investigated Scenarios

Four main scenarios are investigated in this thesis.

1) **Nouadhibou**: This primary location (21°15'54.4"N 16°43'11.8"W) benefits from its proximity to the iron ore railway, the Boulenouar Wind Power Station, a 225 kV transmission line, and the port of Nouadhibou. It offers high solar and wind energy potential, making it an optimal site for renewable energy integration. Its coastal position enables seawater desalination as a water source. The selection of Nouadhibou leverages existing infrastructure, reducing logistical complexities and transportation costs.
2) **Zouérat**: Located near key mining operations and connected to the port by railway (22°38'57.2"N 12°43'14.8"W), this desert region features similar solar potential to Nouadhibou but slightly reduced wind resources. Challenges include ensuring adequate water supply for cooling and overcoming logistical constraints during construction and operation.
3) **High-Capital Cost Case**: This scenario, again set in Nouadhibou, investigates the cost increase per ton of steel for a high-capital-cost case with a WACC of 15%. Unfortunately, financing costs are typically higher in developing countries due to higher associated economic and political risk factors.
4) **Reference Scenario**: This scenario simulates the same plant for an existing steel plant location of thyssenkrupp Steel Europe AG in Bochum, Germany (51°28'26.6"N 7°10'11.7E) with adjusted labor costs and WACC. Costs of land are not included in any scenario.

Within each scenario, the model calculates optimal production capacities for starting dates in 2030, 2040, and 2050. Scrap steel usage scenarios of 0%, 25%, and 50% are included, resulting in 36 distinct combinations. These scenarios account for anticipated improvements in technology efficiency and cost reductions over time, as well as varying availability of recycled materials (scrap).

B. Renewable Energy Production and Conversion

For electricity generation, a combination of solar photovoltaic (PV) and wind energy is chosen due to their synergistic effects and their low levelized costs of electricity. Renewable Energy (RE) generation was modeled using the online database Renewables Ninja [7] and the MERRA-2 dataset for 2019.

- **Solar PV**: The panels are tilted at 25° and oriented southward, achieving a mean capacity factor of about 22% in Zouérat and Nouadhibou, including a 10% system loss. The daily mean output is approximately 0.2 kW/kWp over the course of one day. Only a few days exhibit a low mean output, and on the worst day the mean output was still 0.08 kW/kWp.
- **Wind Energy**: For wind energy, the Vestas V164 7000 turbine has been selected at a hub height of 150 m due to its similarities with currently installed wind turbines and considering the growing sweep area in coming years. In

Nouadhibou, the mean capacity factor for wind of 55.1% is significantly higher than for solar, peaking at 75.86% in June. However, wind energy shows greater variability than solar. In Zouérat, wind energy production remains high but lower than in Nouadhibou, with a total mean capacity factor of 42.6%.

The renewable energy system operates as an islanded smart grid, balancing variability in generation with the variable demands of the electrolysis and steel production processes. Key flexibility components include:

- **Lithium-Ion Batteries**: Energy storage with a cycle efficiency of 92% to manage short-term fluctuations.
- **Hydrogen Storage**: Aboveground steel tanks storing compressed hydrogen at 200 bar, providing medium-term storage capacity.
- **Fuel Cells**: Converting stored hydrogen into electricity during low renewable energy periods, with efficiency improvements projected over the model's timeline.
- **Operational Flexibility**: Oversizing of production capacity allows for operations to synchronize with RE availability during peak energy periods.

The layout of the electricity generation plant is displayed in Figure 1. Power generated by wind energy and solar PV enters a distribution system which, depending on the current demand, decides whether the power is directly consumed, inverted, or curtailed. An inverter efficiency of 95% is assumed. Surplus DC power can also be stored in the lithium-ion battery and then be discharged either back to DC or inverted to the AC grid. The fuel cell, converting hydrogen stored in storage tanks, can also direct power to the AC grid. Smart grid systems are used to balance the numerous and time-dependent input sources and consumers.

Almost all electrical systems operate on AC power. Their specific consumption is set by the default values of the model [4]. It is furthermore assumed that the electrolyzers are powered by DC, even though it remains industry standard to double convert solar energy from DC to AC and back to DC. It is assumed that direct DC - DC implementations will be made for large-scale projects in the future since it reduces costs for inverters and energy losses.

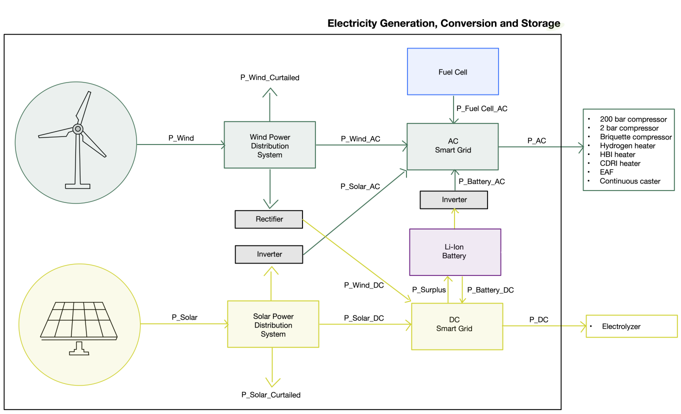

Fig. 1. Design of the Renewable Energy Production Auxiliary Plant

C. Seawater Desalination and Cooling System

In an effort to supply freshwater to the electrolyzer and the cooling system of both the electrolyzer and the EAF, a reverse osmosis seawater desalination plant is planned next to the sea. Water can then be supplied by existing train infrastructure or by pipeline to the main plant. Evaporative cooling methods are chosen for both cooling systems due to their lower water consumption; however, once-through cooling methods would also be possible. The cooling system consists of a closed loop connected to a heat exchanger on one side and a cooling tower on the other side. Investment costs of reverse osmosis plants are assumed at about 1600 US$/m^3/d [8].

To avoid further complicating the steel plant model, water demand and cost are calculated by hand to 3.72 m^3 per tonne of steel. For a production of 1 Mt of steel per year, this equivalates to an average daily demand of freshwater of 10,192 m^3/day. To add flexibility to the plant and to also enable the plant to support local civil water supply and agriculture, the plant can be oversized to a capacity of 15,000 m^3/day. This is still a relatively small plant, given that typical desalination plants have capacities of 100,000 m^3/day [9].

Total investment costs for the desalination plant are estimated to be 24 million USD. For each ton of steel produced, costs of water range between 3.72 US$ and 5.47 US$ depending on the quantity of water produced for civil purposes. Since this cost contribution is low, it is not directly included in the main economic model but will be added to the total costs afterwards.

D. Plant Design and Technical Modeling

The technical modeling of the main hydrogen and steel plant, based on the adapted Devlin, Kossen, Goldie-Jones and Yang model [4], is shown in Figure 2 and includes five sections:

1) **Input**: Feedstocks are pelletized iron ore and a variable share of scrap steel. Iron ore preparation involves crushing, screening, and pelletizing to achieve the required grade for direct reduction (assuming a 62% grade based on common Mauritanian exports [10]). For the operation of the electric arc furnace, further resources are needed such as lime, alloys, and carbon for graphite electrodes.
2) **Hydrogen Production and Storage**: Hydrogen is generated using an alkaline electrolyzer powered by RE and using purified water from the desalination plant as well as recycled water from the condenser. Surplus hydrogen can be stored or reconverted into electricity. Electrolyzer efficiency is projected to improve from 68% in 2030 to 75% in 2050, reflecting advancements in technology.
3) **Ironmaking**: In the shaft furnace reactor, iron ore is reduced to hot DRI using hydrogen as a reducing agent. It can either be stored or directly delivered to the EAF.
4) **Steelmaking**: The EAF melts a mix of DRI and scrap steel into liquid steel. Lime, alloys, and oxygen are

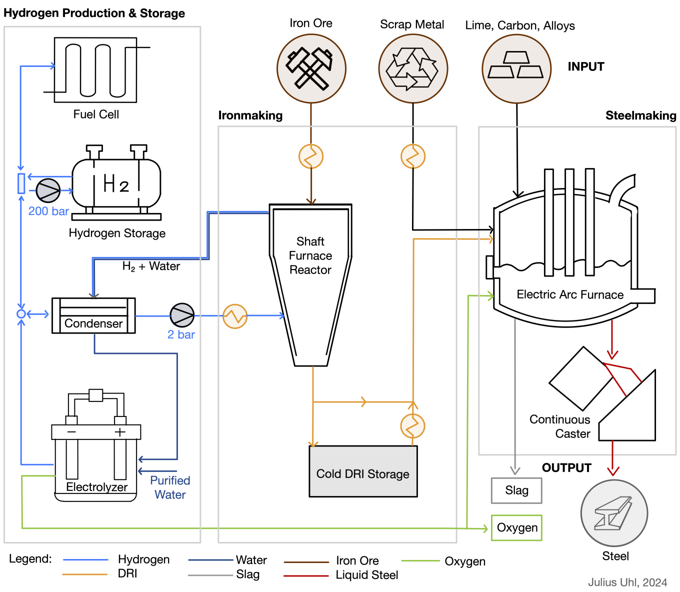

Fig. 2. Plant Design of the combined Hydrogen and Steel Plant

added throughout the process. The EAF operates in 60-minute cycles and can be synchronized with renewable energy generation to reduce operational costs.

5) **Output**: Semi-finished steel products are cast and prepared for export. By-products like slag and excess oxygen are not considered in this model but offer potential for additional revenue streams through secondary processing.

Factors not fully investigated by the model but acknowledged as influencing feasibility include skilled workforce availability, actual cost of capital beyond assumed WACC, government support, market demand, and economic/political stability. Also, the assumption of continuous EAF production in the model does not fully capture the requirements for handling its variable load profile with a smart mini-grid and should be further investigated.

III. Results

A. Optimal Steel Plant Layout

For the base case (Nouadhibou, 2030, 0% scrap), the model predicts a specific energy consumption of 5.71 MWh per ton of steel. The optimal energy mix includes a 1,285 MW solar PV park (majority supply) and a 564 MW wind energy installation (see Figure 3 (1)). The electrolyzer is the largest energy consumer, requiring a capacity of 709 MW. This corresponds to a 1.7 times oversizing compared to continuous operation, allowing for greater flexibility. Hydrogen storage capacity is 644 tons (21.2 GWh) while battery storage is modest at 35 MWh. Fuel cells are not included as economically unfeasible in this specific scenario. Most of the energy (3.08 MWh/tLS) is used for electrolysis while the EAF is the second-largest consumer at 750 kWh/tLS. Approximately 12% (630 GWh/year) of the produced renewable energy is curtailed. Mining and preparation energy (500 kWh/t) is supplied externally.

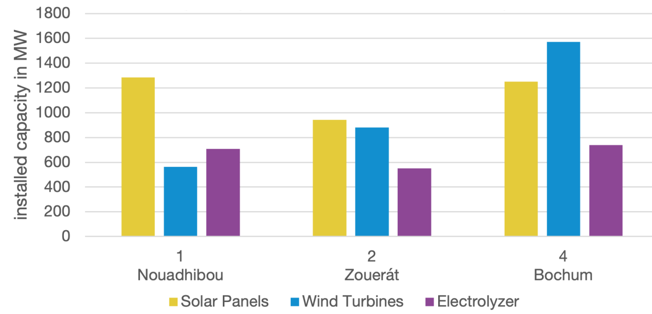

Fig. 3. Hydrogen Production Capacity for Scenarios (Nouadhibou, 2030, 0%), (Zouérat, 2030, 0%) and (Bochum, 2030, 0%)

Optimal plant layout changes with time and scrap percentage. By 2050, predicted cost reductions for future technologies lead to a greater economic advantage in oversizing solar PV. Electrolyzer oversizing increases to over 2.2 times nominal capacity by 2050, and fuel cells become economically feasible (5.9 MW). Hydrogen and battery storage capacities decrease considerably by about one-third and total energy consumption decreases slightly from 5.71 MWh/t to 5.38 MWh/t.

Increasing the scrap charge significantly reduces the demand for DRI, hydrogen, and renewable energy. With 50% scrap (vs. 0%, 2030), installed capacities for solar, wind, and electrolyzers decrease, as do storage capacities. Total specific energy consumption drops substantially from 5.71 MWh/t to 3.06 MWh/t.

Location also impacts the optimal layout as shown in Figure 3. Zouérat has a more balanced RE mix due to its resource profile with similar solar but slightly lower wind than Nouadhibou. This however reduces flexibility needs, resulting in lower electrolyzer capacity (550 MW, 1.34x oversizing), smaller battery and hydrogen storage, and inclusion of a 3.3 MW fuel cell. The comparison location in Bochum, Germany requires almost three times the wind capacity (1,250 MW) compared to Nouadhibou to compensate for less favorable resources, leading to slightly higher electrolyzer capacity (738 MW) and a larger fuel cell (6.5 MW) but lower battery storage. Total energy demand and curtailment rates are comparable across all locations.

B. Final Steel Price and Its Components

The modeled steel prices vary by scenario and are summarized in Figure 4. In 2030 (0% scrap), Zouérat offers the lowest price at 707 US$/t, followed closely by Nouadhibou at 720 US$/t. This is attributed to a more cost-efficient plant layout in Zouérat with lower capacities for solar PV, electrolyzers, and storage. The high-capital-cost scenario demonstrates that low capital costs are crucial for the success of renewable energy projects in Mauritania with prices increasing to 907 US$/t. The Bochum scenario results in the highest price at 925 US$/t, reflecting higher RE investment costs due to resource limitations.

To establish a steel plant powered by renewable energies in Nouadhibou in 2030, an investment of 1.4 billion US$

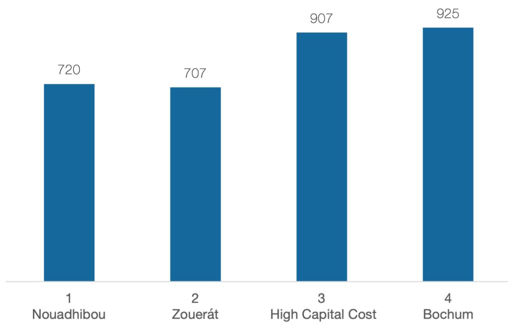

Fig. 4. Steel Prices for Scenarios (Nouadhibou, 2030, 0%), (Zouérat, 2030, 0%), (High Capital Cost, 2030, 0%) and (Bochum, 2030, 0%)

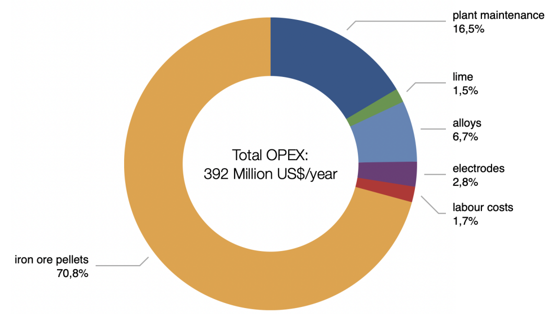

Fig. 6. Operational Expenditures of Modeled Steel Plant for Scenario (Nouadhibou, 2030, 0%)

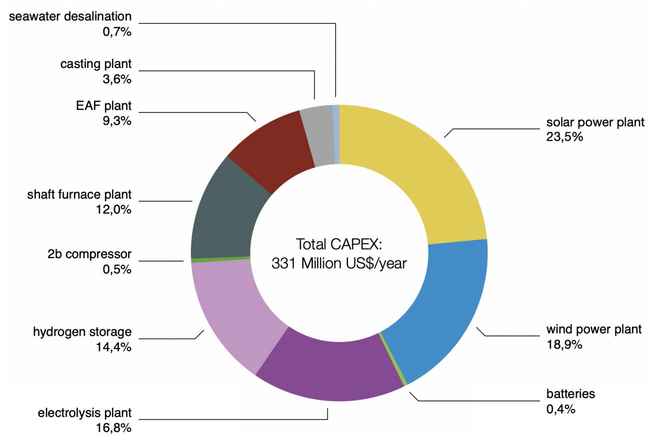

Fig. 5. Capital Expenditures of Modeled Steel Plant for Scenario (Nouadhibou, 2030, 0%)

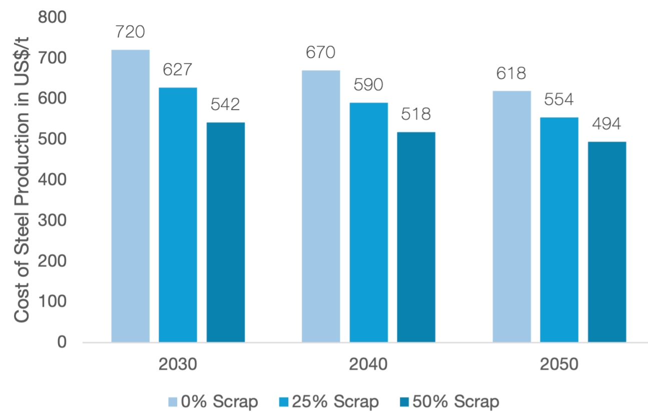

Fig. 7. Dependency of the Steel Price on the Installation Year and Scrap Share for Scenarios (Nouadhibou, 2030-2050, 0%-50%)

is required. The majority of this investment is allocated to the installation of renewable energy sources, accounting for 42.8% of the total costs (see Figure 5). Nearly one-third of the total investment are dedicated to electrolyzers and hydrogen storage. The steel plant infrastructure itself constitutes only a quarter of the initial expenses, while seawater desalination contributes a relatively minor 0.7%. Operational expenditures (OPEX) are primarily driven by iron ore costs (120 US$/t of ore), with additional costs for plant maintenance, resource procurement (lime, alloys, electrodes), and labor (see Figure 6).

Both a delayed production start and an increased scrap percentage lead to a nearly linear reduction in the steel price. Consequently, the lowest prices are achieved in the 2050 scenario with 50% scrap, reaching 494 US$/t. Figure 7 demonstrates the dependency of the steel price in Nouadhibou on the percentage of scrap used in 2030, 2040, and 2050.

IV. Discussion

Comparing the results to benchmarks, the modeled Mauritanian green steel prices (707-720 US$/t in 2030, 0% scrap) are slightly higher than current European hot-rolled coil (HRC) steel prices (around 690 US$/t in November 2023 [11]), but competitive with the two-year average European price (744 US$/t [12]). With 50% scrap, Mauritanian steel becomes potentially competitive with Chinese HRC steel priced at 496 US$/t at the London Metal Exchange in July 2024 [13]. However, if the cost of capital is excessively high, as seen in scenario 3, or if renewable resources are insufficient, as in Bochum in scenario 4, the cost of steel production increases significantly. Figure 8 compares the model results in 2030 with the mentioned steel price indices.

Beyond the core modeling, the integration of an EAF steel plant with desalination, electrolysis, renewable energy, and cooling systems offers multiple opportunities for efficiency improvements through process synergies. Key strategies include using waste heat from the EAF and electrolyzer to power the electrolysis itself using solid oxide electrolyzer cells or support thermal desalination. Alternatives such as air-based cooling with water recovery can cut evaporation losses by up to 35% [14]. Additionally, by-product oxygen from electrolysis can be utilized in the EAF or sold for revenue.

Reducing electrical conversion losses is another priority. DC integration between PV systems, electrolyzers, and potentially the EAF (using a DC electrode) can minimize energy losses from AC/DC conversions. Scheduling maintenance during low renewable generation periods could potentially reduce capacity oversizing requirements.

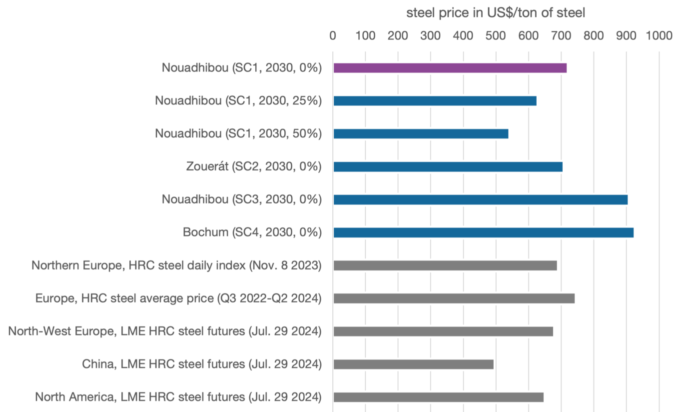

Fig. 8. Comparison of Steel Prices with Regional Steel Price Indices

Finally, connecting to a stable power grid can balance energy supply and demand and reduce energy curtailment. However, Mauritania's weak grid poses challenges. A potential solution involves linking with the European transmission network which actually extends all the way into Western Sahara [15], enabling grid balancing and limited electricity exports. For large-scale energy export however, hydrogen transport remains more cost-effective than electricity transmission. Providing excess energy and desalinated water to the local population could enhance regional stability and benefit the community.

V. Conclusion

The development of a hydrogen-powered steel plant in Mauritania represents a pioneering venture that integrates the latest advancements in sustainable energy technologies with the country's abundant natural resources.

Results indicate that by 2030, Mauritanian green steel could be produced at costs comparable with current average European prices. Projected cost reductions for renewable technologies and increased scrap utilization could lower the price significantly over time, potentially making it competitive with current Chinese steel prices. Despite substantial infrastructure investment costs of about 1.4 billion US$, the findings demonstrate that the project is far from a mere idealistic vision; instead, it has a solid foundation to become a key source of sustainable steel in the future.

It is not without cause that several major companies are investing in Mauritania, as evidenced by 140 GW of planned renewable energy installations [16]. This represents 285 times the country's current generation capacity and surpasses Italy's total power generation capacity. Although not all proposed projects may be executed, these initiatives position Mauritania as a leading potential producer of hydrogen and a crucial partner in Europe's clean energy transition.

The green steel production process outlined emits only a small fraction of the CO_2 compared to traditional methods, aligning with decarbonization goals like the European Green Deal. The produced green steel could command higher prices and supply industries aiming to minimize their carbon footprint.

Unlike other exploitative foreign operations on the continent, this project has the potential to add value to local products, generate employment, improve infrastructure, and strengthen both electricity and water stability in the region. In addition, it significantly reduces carbon emissions, paving the way for a greener future in the steel industry, one of the largest global CO_2 emitters.

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