Proof-of-Concept and Feasibility of Green Steel within the United States through Hydrogen Direct Reduced Iron and Electronic Arc Furnace method

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Acknowledgments

List of Acronyms, Symbols

CO2 Carbon Dioxide

DOE Department of Energy

EAF Electronic Arc Furnace

GW Gigawatt

H2 Hydrogen

H2O Water

HDRI Hydrogen Direct Reduced Iron

HOPP Hybrid Optimization and Performance Platform

HYBRIT Hydrogen Breakthrough Ironmaking

IRR Internal Rate of Return

kWe Kilowatt electrical

LCOE Levelized Cost of Electricity

LCOH Levelized Cost of Hydrogen

LCOS Levelized Cost of Steel

M1 Iron ore pellets entering HDRI furnace

M10 Hydrogen exiting electrolyzer

M11 Hydrogen entering heater

M12 H2O entering condenser

M13 Liquid H2O to electrolyzer

M14 Oxygen from electrolyzer

M2 Reduced iron leaving HDRI furnace, entering EAF

M3 Liquid steel leaving EAF

M4 Hydrogen stream entering HDRI

M5 Exhaust stream leaving HDRI

M6 Carbon entering EAF

M7 Lime/slag formers entering EAF

M8 Slag stream leaving EAF

M9 CO2 exhaust exiting EAF

MW Megawatt

MWh Megawatt hour

NPV Net Present Value

NREL National Renewable Energy Laboratory

O2 Oxygen

PMT Payment per period

TLS Metric Tonne of Liquid Steel

Executive Summary

Climate change is becoming an overwhelming issue. Many industries are aiming to curb their emissions to slow climate change while maintaining current production volumes. Global steel companies have been exploring processes to lower their carbon emission as they are, relatively, one of the largest emission producers. One process that is gaining traction is Hydrogen Direct Reduced Iron (HDRI). The common way to reduce iron was with carbon monoxide and the byproduct was carbon dioxide. With replacing carbon monoxide with hydrogen, the byproduct in a HDRI system is water instead of carbon dioxide. Current pilot plants in the Europe have paired HDRI with an Electronic Arc Furnace (EAF) to produce Green Steel, steel produced with renewable energy. EAFs utilize electricity as means of energy transfer, instead of heat, to melt iron. Older blast furnaces rely on the burning of coal to introduce energy and the byproducts were carbon dioxide. Steelmaking, as of now, cannot be entirely carbon-free because many compositions of steel require carbon. An HDRI-EAF process does yield emissions but not at the scale that older steel techniques. The questions of financial feasibility of a HDRI-EAF begin to arise as energy is growing through a transitional phase A techno-economic analysis of an HDRI-EAF system within the United States was performed using renewable energy modeling from NREL’s HOPP on four scenarios. The results show a promising future for the HDRI-EAF. The steel plant modeled is considered a small steel plant, but the plant returned net present values around $200 million over 20 years assuming a $0 initial investment. Levelized cost of steel average $475/tls compared to a market selling price of $700/tls. All four scenarios returned profits with the ability to improve. Analysis has shown that electricity pricing is the major financial factor in an HDRI-EAF plant. The study found that a reduction of $1/MWh corresponds to a decrease of $3.5/tls that corresponds to a $35/tls decrease for ¢0.1/kWh. These parameters and results in this report act as a baseline for the rates renewable energy need to meet help reduce emissions among the steel industry.

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1. Introduction

Steel production is, and has been, a major world industry; currently totaling around $124.1 bn in the United States and $861.64 bn globally sourcing a wide variety of other industries. Steel has been a cornerstone for the global market. With a projected market growth of 2.6% to 2025, the industry will continue to be a major factor in the world economy and subsequently the world’s emissions. Currently, the steel industry contributes 7-8% of the world’s emissions (McKinsey & Company 2020). The Net Zero Emissions by 2050 report set by the International Energy Agency identifies that crude steel production needs to reduce its CO2 emission by 4% a year to 0.9 tonnes CO2 per metric tonne liquid steel (tls) to reach net zero (IEA n.d.). The Steel Industry is facing a technological revolution as of late to meet these goals. Steel produced with hydrogen is looking to be a promising technology in tackling emissions. Steel has typically been made with coal, but coal can be substituted with hydrogen. Then, hydrogen can be produced with renewable energy. This pairing of hydrogen and renewable energy to produce steel has been dubbed Green Steel. There have been plans for many Green Steel demonstration and pilot plants, but none have been set for in the United States (Leadit 2021). A common Green Steel concept is a Hydrogen Direct Reduced Iron shaft paired with and Electronic Arc Furnace (HDRI-EAF). Basically, this is a process where hydrogen reduces iron and then the iron is melted in an electric furnace. It is a fairly newer concept that has faced some resistance. The lack of adaptation is mainly due to high electricity and hydrogen prices, the two major components in Green Steel (Edwards-Evans 2020) (Burgess 2022). However, with the current advancements in hydrogen production and renewable energy, Green Steel may become competitive to current steel production methods in the United States.

Diagram

Description automatically generated

Figure Centralized Hydrogen Direct Reduced Iron-Electronic Arc Furnace concept (Green Steel)

Production of steel is an energy intensive process. Historically, many steel producers relied on the use of metallurgical (or coking) coal to introduce the energy needed for production. Coal, in general, has been the cheapest way for many industrial plants to generate energy. Coal-fired power plants, aluminum production and even transportation have relied heavily on coal as means of energy. However, there has been large volatility in coal prices. Earlier in 2022, coal hit a high of $650 per tonne, up 200% from its average over the last three years (De Clercq, Doyle and Voet 2022). There has also been instability in many other operational costs associated with steel. Electricity prices have been inconsistent. Major steel producers in Texas and Missouri have built their own power systems because of local electricity pricing and instability (Douglas 2019). Proposed wind farms off the Gulf of Mexico are planned to power industrial plants in the region (Ferman 2022). The integration of onsite electrical generators has become more common in the industry, more specifically renewable energy generators.

Diagram

Description automatically generated

Figure Onsite Electrical Generation Concept

Onsite renewable generators and the new HDRI-EAF concept have become intriguing for larger steel companies trying to meet emission goals. HDRI-EAF allows for a majority of the coal to be substituted with electricity almost reducing all of the emissions in steel making. An overview of the system can be seen in Figure 1. How financially feasible is his system? Replacing a majority of the coal with electricity will be more expensive but the question is how expensive. What parameters would there need to be in place to make an HDRI-EAF system competitive? What would be the levelized cost of steel? A thermodynamic breakdown and techno-economic analysis of the system has been developed to answer these questions.

This paper reviews the methodology and results of the thermodynamic and techno-economic analysis of Green Steel through a HDRI-EAF. The methodology and results are in Section 2 and 3 respectively. The analysis is derived from thermodynamic energy/mass equations of each component. The results, cost reduction methodologies, plant scalability, and current Green Steel projects are discussed in Section 4. Conclusions of the paper are presented in Section 6.

1. Methodology

The methodology in this paper is influenced and built by the work previously done by Abhinav Bhaskar in his paper *Decarbonizing primary steel production: Techno-economic assessment of a hydrogen based green steel production plant in Norway* and his accompanying model and codes. To start, electrical and hydrogen generation was developed using the tools from National Renewable Energy Laboratories’ software Hybrid Optimization and Performance Platform (HOPP). Second, a thermodynamic model was developed to help understand and analyze the flow of energy and mass throughout the HDRI-EAF system. This model was broken down into iron production in the HDRI, the steel production in the EAF and the hydrogen production in the electrolyzer. The model’s energy and mass demands are in reference to production of one metric tonne of liquid steel (tls). Further accessories were modeled as well to meet desired temperatures in the system. Next, a financial model was developed of the system consisting of capital costs, operational costs and other important costs like electricity costs and emissions costs.

Using Python, computational scripts were developed based off these models. These scripts have been named Hydrogen Ammonia and Green Steel (HAGS)[[1]](#footnote-1). HOPP is also a Python based software allowing HAGS to be called into HOPP. Also, open-source computation software NumPy and NumPy Financial were utilized in generating and storing the financial outputs. With these financial totals, levelized costs can be determined.

* 1. Integration with Hybrid Optimization and Performance Platform

The main purpose of this model is to incorporate hydrogen production by renewable energy with a steel making process. Hydrogen produced with renewable energy, Green Hydrogen, is a growing industry. European countries are developing gigawatt (GW) scale wind farms with GW electrolyzers for the sole purpose of producing hydrogen for industrial use (SeaH2Land n.d.). Open-source software Hybrid Optimization and Performance Platform (HOPP) computationally models the combination of hybrid plants and electrolyzers. HOPP is developed by the National Renewable Energy Laboratory, NREL, and is described as “a software tool that enables detailed analysis and optimization of hybrid power plants” [NREL WEB]. Using high-resolution wind and solar maps from national databases, HOPP generates performance data of hybrid plants of different sites within the United States. In addition, HOPP utilizes other NREL-developed-tools like ReOpt, SAM, and WISDEM to optimize the hybrid plants down to the component level. In addition to Green Hydrogen, HAGS also has the option to be powered completely by the renewable energy. In this report, the HDRI-EAF plant will be powered by electricity from the models provided by HOPP. This report applies the performance data from HOPP as inputs into HAGS. HAGS utilizes HOPP’s yearly electric production, the levelized cost of energy and the yearly hydrogen production as inputs. The input parameters HOPP used are in Table 3 and 4.

HOPP also has an electrolyzer model but a new one was created in HAGS for purpose of simplification and incorporation. The model assumes that the associated costs of the electrolyzer are incorporated with the steel plant, not the hybrid plant. The parameters and values of HAGS’s electrolyzer model has a deviation of <1% compared to HOPP’s model. More in-depth discussion of the electrolyzer is in Section 2.2.3.

Diagram

Description automatically generated

Figure Hybrid Optimization and Performance Platform modeling capabilities

* 1. Thermodynamic Model

To fully model an HDRI-EAF system, a thermodynamic breakdown of the system is required. Each individual component can be subdivided into the basic thermodynamic energy conservation law. This law states that energy cannot be created nor destroyed, only transferred. To simplify the system even farther, it is safe to assume that the entire system, apart from the EAF, is a closed system. Therefore, mass conservation can be applied as well. The conceptual model is illustrated in Figure 3. Each “**M**”value corresponds to a different state, either a change in temperature or change in substance. Further sections describe each state in more detail. A full list of variables and their definitions can be found in Table 5.

To determine energy transfer, the enthalpy of each substance at the desired temperatures is vital in determining energy gained or loss in each process. Shomate’s equation, equation (1), is used to determine enthalpies and the corresponding coefficients were grabbed from the NIST Chemistry WebBook, SRD 69 (Chase 1998). Molecular weights used in this model are also taken from the NIST WebBook. The weights were used to determine total enthalpies at each stage. Temperatures matched the values of Abhinav’s work to determine validation (Bhaskar, Mohsen and Homam, Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen 2020).

(1)

(2)

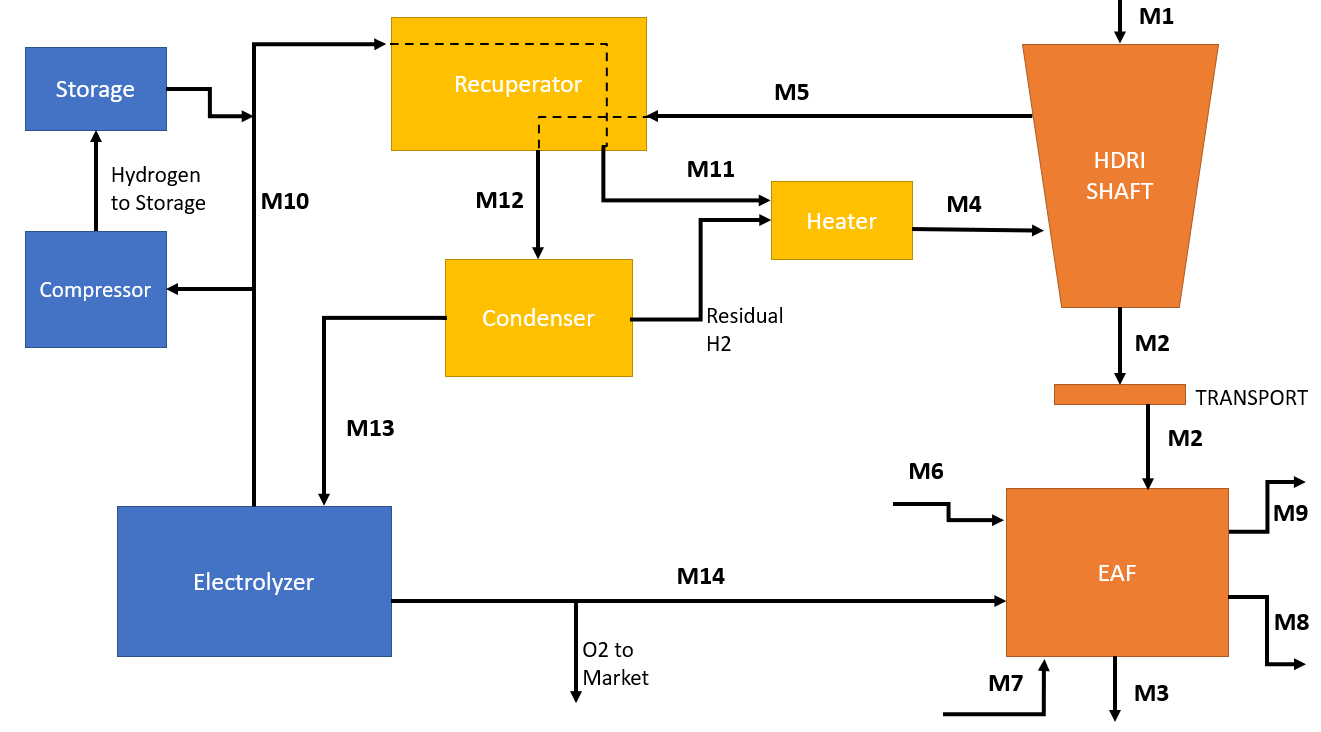


Figure Thermodynamic Model of Entire System

* + 1. Hydrogen Direct Reduced Iron Shaft System

The main process of iron reduction in an HDRI-EAF system is the HDRI shaft. The two main producers of DRI systems are MIDREX and Energiron (International Iron Metallics Association n.d.). Each company has differences in their design, but the main reduction process is the same. Iron ore enters a shaft furnace and is reduced by a reducing agent. Reducing agents are substances, usually gases, that bond with the oxygen in the ore. Through this process, hematite (Fe2O3) reduces through many stages but finalizes itself as pure iron (Fe), also known as sponge iron. In an HDRI system, the reducing agent is hydrogen. The chemical reactions of hydrogen reduction can be seen in equations (3), (4) and (5) (Patisson and Mirgaux 2020).

(3)

(4)

(5)

Reduction rates with hydrogen are higher than that of carbon gas mixes. In addition, higher hydrogen temperatures and pressures lead to increased reduction rates (El-Geassy and Rajakumar 1985). The model in this report assumes that the hydrogen was not pressurized; it remains at atmospheric pressure. The temperature of the hydrogen is assumed to be at 1173 K. Work done previously exhibits that these parameters are satisfactory but can be more efficient (Sato, Ueda and Yasunori 1986).

Chart, funnel chart

HDRI System with two inputs and outputs

Figure Model of Hydrogen Direct Reduced Iron system

The conceptual model of the HDRI system is shown in Figure 4. It consists of two main inlets and two outlets. Iron ore, **M1**, consists of hematite and impurities. These impurities can consist of many elements. Most of the impurities are other metallic oxides like CaO and SiO2. This model assumes that the impurities of the ore only consist of SiO2 and Al2O3. The other inlet in the model is the hydrogen as **M4.** There is a stoichiometric amount required to reduce all the iron ore. However, a higher flow rate of hydrogen should be achieved as a buffer as some of the hydrogen will re-oxidize (Duarte and Pauluzzi 2019). To accommodate for this, the actual flow rate of the model is 20% higher than the stoichiometric requirement. The outlets in the system are the reduced iron ore, **M2**, and the exhaust of the hydrogen, **M5**. The amount reduced iron is dependent on the metallization rate of the HDRI shaft. MIDREX shafts claim to have a metallization rate of 92%-96% (Midrex Technologies, Inc. 2018) (Sanjal 2015). This model assumes a metallization rate of 94% with a temperature 973 K. The exhaust consists of excess hydrogen and water, a product of reduction. The total mass of the water produced can be determined with the molecular weight ratios and mol ratios. It is assumed that all the stoichiometrically required hydrogen is consumed and the resulting temperature is 573 K.

The following are additional assumptions of the HDRI system:

* No heat loss in the reduced iron from the HDRI shaft to the EAF
* Hydrogen apparent activation energy is 35 KJ/mol (Bhaskar, Mohsen and Homam, Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen 2020)
* 100% hydrogen is fed into the HDRI shaft
* Iron Pellets are not preheated
  + 1. Electronic Arc Furnace System

The EAF acts as the primary steelmaker in the production process. The concept of an EAF system is related to that of welding. Large electrodes in the EAF run high-voltage open currents between them generating large amount of heat. Most steel plants depend on the EAF to be the primary melting process. Alloys are then added in secondary metallurgy processes to control the chemical composition of the steel. The most common secondary metallurgy in the modern industry is ladle metallurgy (Nutting, Wondris and Wente 2019). Secondary metallurgy of any kind is not modeled in this report, but details of ladle metallurgy is discussed further below.

The reduced iron from the HDRI, **M2**, enters the EAF at a temperature of 973 K. The model assumes that there is no heat loss in the transition of HDRI Shaft and the EAF. Once in the furnace, the iron is heated to 1923 K and becomes molten. The molten stream, **M3**, leaves the furnace at the same temperature. Coke, lime, and oxygen are also added to the EAF to help reduce the FeO2, form a layer of slag, produce carbon-steel, and provide extra energy. The coke, **M6**, performs additional reduction in the EAF, contributing about 4.4% more steel. However, the model does not take the excess into account financially and turns it into a buffer to accommodate of 4.4% steel loss. Coke is also added to increase the carbon composition of the steel. The added lime, **M7,** is usually some sort of chemical compound containing calcium or magnesium and oxygen. It acts as a slag former as the calcium bonds with the impurities in the iron stream. This slag layer acts as an insulator, extracts unwanted impurities, and extends the electrode life (National Lime Association 2022). Slag leaves the system as **M8** at a temperature of 1923 K. For sake of simplicity, the added energy from inputted oxygen, **M14**, commonly known as oxyfuel, was not considered. The addition of oxyfuel would decrease the required electricity demand of the EAF and change the percent carbon in the steel. With these additions, there is unfortunately some sort of emissions produced. However, the emissions produced are extremely low compared to traditional routes.

Diagram

Electronic Arc Furnace thermodynamic model

Figure Model of Electronic Arc Furnace

The main reactions in the EAF are the following (Hornby and Brooks 2021):

(4)

(5)

(6)

These are the major reactions of most primary steel making processes. The secondary metallurgy process is where the composition of the steel is formed. Depending on the desired composition of the steel, other materials and elements are added into the ladle furnace. These can include the elements Si, Mn, P, S, Cr, Ni, Mo, and Cu (Camdali and Tunc 2016). These reactions look like the following (Yu, et al. 2021):

(7)

(8)

This model did not take account in the secondary metallurgy process and subsequently these reactions. It is important to note the energy needed to facilitate these reactions varies depending on the desired compositions. Further work should be done to thermodynamically model the secondary metallurgy of each steel composition, but the scope of this work attains to a generalization of the EAF process.

As mentioned earlier, the reactions of the coke, lime and oxygen were not thermodynamically modelled. Instead, assumptions were made on minor reactions in the EAF. The following assumptions are based off the assumptions Abhinav Bhaskar made in his work to determine validation (Bhaskar, Abhishek, et al. 2022).

* 10 kg/tls of coke are injected
* 50 kg/tls of lime are injected
* 208 kg/tls of oxygen are injected
* .113 tCO2/tls are generated

Other assumptions of the EAF include:

* No scrap involved, 100% pellet fed
* 4.4% steel loss
* EAF electrical efficiency is 60%
  + 1. Electrolyzer System

The base of the electrolyzer system is modeled by NREL’s H2A production models. The H2A models alkaline, polymer electrolyte membrane, and solid oxide electrolyzers. Currently, the cheapest and most efficient is the alkaline electrolyzer. A case study performed by NREL found that a Norsk Atmospheric Type No.5040 electrolyzer could achieve a 44.7 kWh/kg specification by 2025 (Ramsden and Ruth 2011). Further research reinforces advancements in efficiency to be achievable (Taibi, et al. 2020).

The base equation of an electrolyzer is shown in Equation (9). The electrical energy required correlates to the kWh/kgH2 specification, or the efficiency.

(9)

Chart, diagram

Description automatically generated

Figure Model of Electrolyzer system

The electrolyzer model in HAGS is driven entirely by yearly hydrogen output and an achievable efficiency specification. The yearly hydrogen is calculated by H2A and HOPP. The efficiency specification relates to a kWh/kgH2 value that is achievable in the near future. It is a broad generalization of the dynamics in an electrolyzer. HAGS, however, determines the amount of electricity needed for the amount of hydrogen H2A calculates. Another aspect of the HAGS model is the recycling of water produced by the reactions in the HDRI shaft. This in-flow of water is distinguished by **M13** in the conceptual model in Figure 6. The reuse of water in the exhaust allows for less water to be introduced in the system. In addition, **M10** represents the hydrogen flow leaving the electrolyzer and **M14** equates to the oxygen produced.

For this model, the following assumptions are made:

* The electrolyzer efficiency is 44 kWh/kgH2 to match the standards set by the DOE (Hydrogen and Fuel Cell Technologies Office n.d.) and NREL’s case study (Ramsden and Ruth 2011).
* 60% of the oxygen produced is sold to market
* Low heating value of hydrogen is 120.1 MJ/kg (Essom Co., LTD n.d.)
* Electrolyzer Stack Lifetime is 90,000 hours (Bareiß, et al. 2019)
  + - 1. Storage and Compressor model

HAGS has the infrastructure to model compressed hydrogen storage. More specifically underground pipe storage of compressed gaseous hydrogen. For the purposes of this report, adding storage adds insignificant amount of costs at this scale. Models of larger scale electrolyzers will need storage and compressors to help buffer varied electrical inputs from renewable sources.

Financials of the compressors and storage pipes have been added to this report but are not reflected in the results.

* + 1. Models of Auxiliary processes

In the conceptual diagram, Figure 3, there includes a recuperator, a heater, and a condenser. These processes are crucial in acquiring the desired temperature at each state.

The recuperator is a heat exchanger that requires no added energy. In this model, the recuperator exchanges heat from **M5** and **M10**. The resulting states are **M12** and **M11** respectively. The thermodynamic energy/mass equation based on the temperatures calculates about a 58% efficiency in the recuperator. According to Kelvion, their heat exchangers can reach up to 90% (Kelvion n.d.).

HAGS assumes a temperature in **M11** of 30 K into the heater. The model then determines the required energy to heat the hydrogen stream to 1173K, **M4,** using the energy/mass equation. The electrical efficiency of the heater is assumed to be 60% to account for all energy losses from the heater itself to the transformers in the electrical grid.

The condenser was not modeled in HAGS as it does not necessarily need energy to condense steam to liquid water. The condenser is more a place holder to show steam returning to the electrolyzer as liquid water.

Temperatures of all these states at these auxiliary processes can be found in Table 5

* 1. Financial Model

After calculating all the physical outputs and energy demands in a HDRI-EAF system, a financial analysis of the system is needed to determine economic feasibility of the system. Capital, operational, emission, labor, maintenance, and tax costs were used to determine financial parameters.

HAGS conducted a cash flow analysis to determine internal rate of return and net present values. In addition, a levelized cost of production was calculated. The analysis utilized NumPy financial codes pmt, irr, and npv. Further information on these calculations can be found in section 2.3.5.

The analysis performed in this model assumed a startup timeframe of two years. Steel was not produced until the third year of the plant life.

|  |  |
| --- | --- |
| HDRI | $80 per tls/yr |
| EAF | $140 per tls/yr |
| Electrolyzer | $300 per kW |
| H2 Storage | $560 per kg-container |
| Storage Compressor | ~$171,710 per year |

* + 1. Capital Costs

Table Additional Capital Costs

A manufacturing plant of this magnitude requires a large investment. The large investment includes the purchase of the physical assets of the plants, the erection of the plant and the associated costs that are assumed with construction. This large investment is typically paid off through loans. The interest rate assumed for these loans in HAGS is a 7% rate. The capital costs of the assets in the system can be broken down into components, this is reflected in Table 1. HAGS then employs the Lang Factor method to estimate all associated costs with construction. The Lang Factor is a multiplier of the capital costs of all considerable components that projects final costs of plant. The techno-economic analysis done by Abhinav Bhaskar inferred a Lang factor of 3 (Bhaskar, Abhishek, et al. 2022). In other reports, a factor of 3.1 should be considered for solid plants and 3.63 for solid-fluids plants (Wain 2014). For this report a Lang Factor of 3 is considered for verification purposes.

The total capital costs of a HDRI-EAF system are determined by the production rate the plant intends to achieve. On average, the system was found to have a combined capital cost of $220/tls-yr (Energy Technology Systems Analysis Programme 2010). It was then split into each component in Table 1. The electrolyzer was described to have a capital cost related to its electrical capacity. With technological advancements, the cost per kW will decrease. The HAGS model has assumed a cost of $300 per kW from the DOE technical target report (Hydrogen and Fuel Cell Technologies Office n.d.). This $300 per kW also applies to the stack replacement needed during the plant lifetime.

The capital costs of the compressed pipe storage were not assumed in this analysis. However, capital costs assumptions were made for future work with HAGS. The pipe storage itself has a simple capital cost of $560 per kg-container (Papadias and Ahluwalia 2021). The compressor capital cost model is more complicated. The equation to determine capital investment costs is followed:

(10)

For simplification, a compressor rating of 802 kWe was selected and the total cost was divided by the plant life.

Along with Table 1, capital cost assumptions include:

* Plant life of 20 years
* Interest rate of 7%
* Lang factor of 3
* Plant Operates 95% of the year

Since the plant does not contain secondary metallurgy capabilities, capital costs of the ladle furnace and finishing processes were not considered. HAGS has the framework for these costs, but more work needs to be done to adequately adapt these processes.

* + 1. Operational Costs

Operational costs of industrial processes include many variables and can be hard to estimate especially for a 20-year plant life. Prices vary due to many factors: inflation, electricity costs, market pricing. These variables, in this report, were considered fixed because of their volatility over 20 years.

Table Additional operating costs

|  |  |
| --- | --- |
| HDRI | $13 per t/yr |
| EAF | $32 per t/yr |
| Electrolyzer | $0 |
| H2 Storage | 2.85% capex |
| Storage Compressor | $245,509 per year\* |

The operational costs in HAGS consist of material, electricity, labor, maintenance, tax, emission and depreciation. Material costs and electricity costs will be covered in further sections. Labor costs in industrial applications depend on the intensity of the labor needed, local labor rates and the efficiency of the processes. A labor cost of $40/tls is considered (Bhaskar, Abhishek, et al. 2022). This can vary from State to State; however, this value is believed to be on the higher end. Maintenance costs of the plant are related to the capital costs. The model assumed a maintenance cost of 1.5% of total capital costs. Tax costs also vary depending on state. Rates range from 21-28% within the United States. With the Biden Administration’s corporate tax proposal, the average tax rate is 25.8% (York and Wilson 20201). This analysis inferred a tax rate of 25%. Carbon emission pricing is still relatively new in the United States. Only four states- California, Oregon, Washington, and Massachusetts- have implemented carbon taxes with no federal tax being implemented (World Bank n.d.). Majority of steel plants in the United States do not operate in these States. Therefore, in this model, a carbon tax cost of $0 was implemented. Depreciation costs in HAGS was simplified to the total capital cost of the plant divided over the plant life assuming the assets of the plant have no worth after the decommission of the plant.

A buffer of operational costs was implemented as well. These costs can be seen in Table 2. As previously said, HAGS has the capability to determine operational costs of compressed pipe storage but was not included in this report. These buffer values act as additional operational costs for specific maintenance costs for the DRI and EAF. These maintenance costs cover replacements of electrodes, conveyer belts, etc.

* + 1. Electricity Costs

HAGS is the incorporation of electricity from renewable energy sources powering a primary steel plant. Therefore, the levelized cost of electricity is determined by the costs associated with the hybrid renewable plant. HOPP modeled a hybrid plant from the parameters shown in Table 3 and 4 and returned a levelized cost of electricity for each scenario.

Table Hybrid Plant Physical Parameters

| Scenario Name | Location lat,long | Tower Height | Rotor Diameter | Turbine Rating | Wind Size MW | Solar Size MW | Storage Size MW,MWh |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Georgia 2030 Advanced | 33.162, -83.8 | 110 | 150 | 7 | 100 | 1 | 1 |
| Georgia 2030 Moderate | 33.162, -83.8 | 120 | 175 | 7 | 100 | 1 | 1 |
| Georgia 2030 Conservative | 33.162, -83.8 | 135 | 200 | 7 | 100 | 1 | 1 |
| Texas 2030 Conservative | 36.103, -102.27 | 110 | 150 | 7 | 100 | 1 | 1 |

Table Hybrid Farm Financial Parameters

| Scenario Name | Wind Cost kW | Solar Cost kW | Storage Cost kW | Storage Cost kWh | Electrolyzer Cost kW |
| --- | --- | --- | --- | --- | --- |
| Georgia 2030 Advanced | 958 | 598 | 97 | 104 | 300 |
| Georgia 2030 Moderate | 910 | 598 | 97 | 104 | 300 |
| Georgia 2030 Conservative | 671 | 598 | 97 | 104 | 300 |
| Texas 2030 Conservative | 958 | 598 | 97 | 104 | 300 |

The electricity costs from these scenarios can be seen in Table 7. Electrical production of all four hybrid plant scenarios was limited to 437,950,000 kW per year. This ensures that the different levelized cost of electricity of each scenario is dependent on the associated costs and not the electrical production amount.

* + 1. Market Pricing

A major contributor to operational costs is the costs of raw materials. In the HDRI-EAF process, raw materials include iron ore, coke, lime, and hydrogen- depending on how hydrogen is produced. Market pricing for these raw materials is volatile and could vary substantially over the plant life. These material prices were fixed as well in this study. They are fixed at the following prices:

* Iron ore cost of $90 per tonne (Mercier, Hijikata and Burrai 2020)
* Coking Coal cost of $120 per tonne (Mercier, Hijikata and Burrai 2020)
* Lime cost of $112 per tonne (IndexBox, Inc. 2022)

The market also has effect on the revenues of the steel plant. Steel has many compositions and finished forms of finishing. For example, the market prices of hot rolled steel averaged $1,065 per metric tonne while standard plate averaged $2,059 per metric tonne (SteelBenchmarker 2022). HAGS in this report does not model secondary casting and metallurgy; the market price needs to reflect rebar product because it is a basic form of steel product. Market price for rebar, as of February 2020, sits around $700 per metric tonne and fluctuates around that price (Mercier, Hijikata and Burrai 2020) The model also assumed a market oxygen price of $40 per tonne from a University of Pennsylvania report (Dorris, et al. 2016).

* + 1. Financial Calculations

The four main financial calculations identified by HAGS were Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Steel (LCOS), Levelized Cost of Hydrogen (LCOH)

NPV was calculated through NumPy Financial’s numpy\_financial.npv code. It requires inputs of the cash flow of the system and the interest rate. The return is the Net Present Value of the system.

IRR was similarly calculated using numpy\_financial.irr. The cash flow series is needed as an input for the Internal Rate of Return.

The levelized cost calculations were based off yearly costs and yearly productions.

Yearly total cost in the levelized cost of steel equation is a combination operational, electricity, material, labor, emission, and maintenance costs plus payments against loan, plus interest, of capital costs.

The levelized cost of hydrogen does not include all the processes in the HDRI-EAF system. Hydrogen production only relates to the costs of the electrolyzer. This includes the maintenance, electricity cost and loan payment of the capital. It does not include the price of water as water rates range vastly State to State. In addition, the cost is insignificant. At the average rate of $3.38 for 1000 gallons of water in the United States, the cost of water only adds $0.01 per kgh2.

1. Results

HAGS ran base mass energy flow calculations and used the results as the basis for the integration with HOPP. The following section reviews the resulting data.

* 1. Mass Energy Flow

The mass energy flow results are shown in Table 5. Values with N.A. (Not Applicable) are not necessary in determination final financial values. All the results are in terms of per metric tonne liquid steel and are scalable.

Table System's Mass Energy Flow

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Definition | Mass kg/tls | Temperature K | Enthalpy kWh/tls |
| M1 | Iron ore pellets entering HDRI furnace | 1601.08 | 298 | N.A. |
| M2 | Reduced iron leaving HDRI furnace, entering EAF | 1019.19 | 973 | 125.69 |
| M3 | Liquid steel leaving EAF | 1000.00 | 1923 | 355.85 |
| M4 | Hydrogen stream entering HDRI | 64.87 | 1173 | 231.42 |
| M5 | Exhaust stream leaving HDRI | 494.72 | 573 | 110.31 |
| M6 | Carbon entering EAF | 10 | 298 | 0.00 |
| M7 | Lime/slag formers entering EAF | 50 | 298 | 114.22 |
| M8 | Slag stream leaving EAF | N.A. | 1923 | N.A. |
| M9 | CO2 exhaust exiting EAF | 50 | 1773 | N.A. |
| M10 | Hydrogen exiting electrolyzer | 64.87 | 343 | 117.15 |
| M11 | Hydrogen entering heater | 64.87 | 443-413 | 177.15-151.03 |
| M12 | H2O entering condenser | 494.72 | 393 | 47.38 |
| M13 | Liquid H2O to electrolyzer | 494.72 | 343 | N.A. |
| M14 | Oxygen from electrolyzer | 519.81 | 298 | N.A. |

* 1. Outputs of Hybrid Optimization and Performance Platform Driven Green Steel Plant

HAGS ran the four scenarios in HOPP and returned physical production values, electrical demands, and financials of each scenario. The following presents these results.

* + 1. Physical Production

All the physical productions values can be found in Table 6.

Hydrogen production was constant among all four scenarios. 7,228,798 kg of hydrogen are produced yearly in each scenario. Steel production was 119,948 tonnes per year in each plant. The electrical power demand of all plants was about a 50 MW per year system and the energy demand per tonne of steel was about 3.5 MWh.

Table Physical Outputs

| Scenario Name | H2 produced kg/yr | Steel produced tls/yr | Emissions tCO2/yr | Power Demand MW/yr | Energy Demand MWh/tls |
| --- | --- | --- | --- | --- | --- |
| Georgia 2030 Advanced | 7,228,798 | 118,948 | 0.233 | 49.9 | 3.49 |
| Georgia 2030 Moderate | 7,228,798 | 118,948 | 0.233 | 49.9 | 3.49 |
| Georgia 2030 Conservative | 7,228,798 | 118,948 | 0.233 | 49.9 | 3.49 |
| Texas 2030 Conservative | 7,228,798 | 118,948 | 0.233 | 49.9 | 3.49 |

* + 1. Financial Outputs of Plant

Based off the calculations and methods covered in the methodology, Table 7 presents the financial results of HAGS integrated with HOPP. The scenarios from HOPP return electricity prices ranging from $30.6-49.3 per MWh. Assuming linearity, the results show an electricity price reduction of $1/MWh corresponds to a decrease of $3.5/tls. $1/MWh is equal to ¢0.01/kWh. Net present values and Internal Rate of Return values are based off a $700/tls; however, today market prices of rebar have ranged from $630-551/tls in the month of July,2022 (Daily Metal Prices 2022).

Table Financial Outputs

| Scenario Name | Electricity Price $/MWh | Levelized Cost Hydrogen $/kg | Levelized Cost of Steel $/tls | Levelized Cost of Oxygen $/kg | Net Present Value $mill | Internal Rate of Return % |
| --- | --- | --- | --- | --- | --- | --- |
| Georgia 2030 Advanced | 36.1 | 1.58 | 462 | 0.20 | 192 | 27% |
| Georgia 2030 Moderate | 45.5 | 2.00 | 495 | 0.25 | 165 | 24% |
| Georgia 2030 Conservative | 49.3 | 2.17 | 508 | 0.27 | 153 | 23% |
| Texas 2030 Conservative | 30.6 | 1.35 | 443 | 0.17 | 208 | 28% |

1. Discussion

The values at each state in the conceptual model reflect the theoretical results based on thermodynamics. The assumption of an entirely closed system is improbable and in-field experimentation is needed to validate the data. However, the results found by Abhinav Bhaskar are similar to those found in this analysis (Bhaskar, Abhishek, et al. 2022). In his report as well, a sensitivity analysis was conducted. The analysis found that electricity price was the driving factor financially. The preliminary results in this report support these claims as the HDRI-EAF system is an electric intense process. Among the four scenarios, the only changing variable was the electricity price. The resulting financial variations are directly related to the variations in electricity pricing. Any reduction in electricity cost or increase in plant efficiency would improve financials substantially

Even at these parameters, the model yields a profitable plant with a large area of growth. With an assumed market price of $700/tls, all four scenarios developed profits. The profits ranged from $238-198/tls sold. This does not include the profits from sold oxygen. The financial potential of the HDRI-EAF plant is largely based on energy efficiencies and pricing. Smaller but substantial contributors include market material costs and electrolyzer capital costs.

One important note is that a steel plant of this size is considered extremely small in the industry. Most American steel plants produce .5-4 million tonnes of steel per year and this plant resembles a .1 million tonne per year plant. To model a larger plant, hydrogen production would need to increase at a scalable rate. The electrolyzer in this model resembles a 3.5-MW electrolyzer compared to the GW electrolyzers in proposed hydrogen projects. HAGS has the capability to model these GW electrolyzers with an HDRI-EAF system and further work will need to be done at these larger scales. In addition to increasing capacity, advancements in electrolyzer efficiency would yield higher steel productions. HAGS has an assumed efficiency of 75% which correlates to a 44 MWh per kg H2. Any increase in efficiency would return higher steel productions as well.

The energy demand of 3.49 kWh/tls lands it in the lower portion of reported power demands of a HDRI-EAF plant. From multiple reports and articles, a power demand of 3.2-4.4 MWh/tls is standard (Holling and Gellert 2018) (Hoffman, Van Hoey and Zeumer 2020) (Kushnir, et al. 2020). In HAGS, the energy demands of individual components are also similar to reported. As well, the emissions in the system of 23.3 kg/tls closely matches HYBRIT’s value of 25 kg (Pei, et al. 2020). Efficiency advancements will lower these energy demand values in the future. Many current plants melt up to 50% scrap steel in their furnaces along with iron pellets. Furnaces with scrap require less inputted energy to melt compared to iron pellets. Introduction of scrap into this model would lower the energy demand of the plant as this report assumed zero scrap. Another operation some DRI plants utilize is preheating iron ore pellets going into the shaft. Not much work has been done on the effects preheating has. Thermodynamically, preheating would decrease the time to reduce iron ore. The largest factor of efficiency in the HDRI-EAF plant is the electrical efficiency of the components. In this model, efficiency was 60%. An increase in the efficiency of the steel plant’s electrical grid to 80% or higher would decrease the total electrical demands. This increase of efficiency is feasible on its own. The final goal of HAGS is to incorporate a dedicated on-site hybrid farm for industrial uses to reduce energy losses that are associated with the power grid. Another intention is to have one controller for the whole system instead of controllers for individual components.

Diagram

Description automatically generated

Figure Main Controller Diagram

With dedicated hybrid plants, electricity costs have the potential to be reduced even further. Energy Rush Hour and high price volatility would be mitigated with dedicated power grids and return more stable and predictable forecasts. Renewable energy does have the likelihood of inconsistent electrical outputs so a large battery or energy storage would be required for a large HDRI-EAF plant. HOPP does have battery storage incorporated but will need to be scaled larger to meet the demands of a standard size steel plant. In addition, hydrogen-based batteries are being developed and could prove useful in a Green Steel project. However, renewable energy will be competitive with most other energy sources within the next 10 years and advancements may reap cheaper electricity in the future.

Pelletization of iron ore for HDRI use is commonly done by the mining company after the physical mining of the ore. This process is also energy intensive and should be another focus of researchers. Fossil fuels have been the main source to power pelletization. However, in the HYBRIT program, pelletization has been completely powered by 100% renewable bio-oil (HYBRIT n.d.). Iron ore market pricing can reduce with technological advancements in biofuels as well.

Steel prices have varied remarkably over the last 10 years. In 2016, hot-rolled band steel had a price around $400 compared late 2021 where it had a price of $2100 (SteelBenchmarker 2022)[[2]](#footnote-2). The steel markets vary internationally as well. The USA has a larger market price on average than the rest of the markets i.e., China, Western Europe, and World Export. It is hard to predict the pricing but the global demand for steel had an increase of 3.9% while production decreased (Mercier, Hijikata and Burrai 2020). It is a safe assumption that price of steel will gradually increase in the future.

Chart, histogram

Description automatically generated

Figure SteelBenchmarker Report of Hot Rolled Band price (SteelBenchmarker 2022)

Electrolysis is crucial to the transition to Green Steel. In addition to the efficiency, the capital costs of the electrolyzer can prove help improve profitability. Currently, costs of electrolyzers range from $650-1000 per kW depending on the manufacturer and type of electrolyzer (Taibi, et al. 2020). However, the DOE has set a goal of $300 per kW to be reached soon (Hydrogen and Fuel Cell Technologies Office n.d.) and could reach a range of $130-307 per kW by 2050 with 1-5 TW capacities (Taibi, et al. 2020). These dollar amounts and capacities could thoroughly benefit Green Steel making capabilities.

It is crucial to understand the relationship between electricity cost and levelized cost of steel. The relationship found in this study is a reduction of $1/MWh relates to a decrease of $3.5/tls. This may not seem significant at first. However, most plant productions are in the millions per year. A reduction of $3.5/tls would theoretically correspond to millions in savings a year and consequently tens of millions over the lifetime of the plant.

Governmental policy is another route to make Green Steel more profitable. It may be soon that the United States implements a carbon tax on CO2 emissions. In the steel making process, it is inevitable that CO2 is produced. Policy can allow that these emissions to be taxed or waived as the .233 tCO2/tls is considerably lower than the target of .900 tCO2/tls set by the IEA. Another option is carbon capture program. The CO2 emitted during the EAF process can theoretically be reused as a carbon source to produce steel. Carbon capture is a relatively new technology, and a cost analysis needs to be done to determine associated costs compared to a carbon tax. There are multiple avenues the government can use to achieve economic viability of HDRI-EAF systems.

American steel producers should also look to European producers. Steel producers in Europe are currently in the process of completing 11 projects related to green hydrogen and steel production. The HYBRIT program is currently an operating plant in Sweden (Leadit 2021). It is a joint conjecture between SSAB, Vattenfall and LKAB. Most of the details are not public information but HYBRIT is an HDRI-EAF plant maintained by SSAB. The energy for the plant is produced through renewable energy, from power company Vattenfall, and the iron ore supplied is mined and pelletized by LKAB (HYBRIT n.d.). HYBRIT is just a demonstration of the capabilities of HDRI-EAF and has been instrumental in the proposal of larger projects. Steel manufacturer ArcelorMittal has invested heavily in SeaH2Land in the North Sea. The basic concept of SeaH2land is a 2-GW offshore wind farm connected to 1-GW electrolyzer system for the purpose of producing hydrogen. The hydrogen produced will be split among residential and industrial use. It is important to note that Europe traditionally has expensive energy compared to the United States. Operation of HYBRIT in the United States would most likely be more profitable solely based on electricity pricing and market steel pricing.

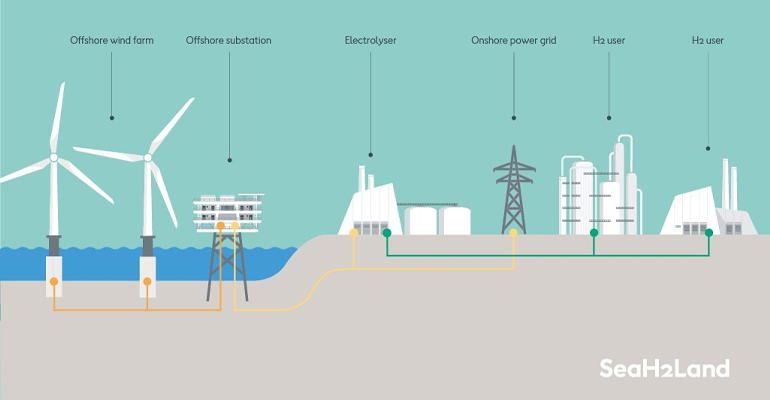


Figure SeaH2Land Proposal Concept

1. Conclusion

The main purpose of this analysis was to determine how feasible Green Steel production would be within the United States. Through the thermodynamics of an HDRI-EAF plant, HAGS determined the required power to produced one tonne of steel (3.49 MWh/tls). After integrating HOPP, financial analysis was performed with the associated costs and the results seem promising. With a levelized cost of around $475/tls, the plant modeled proved to be profitable over the lifetime of 20 years. Future advancements and analysis of physical HDRI-EAF systems will decrease levelized costs and develop Green Steel to be more competitive. The model also reinforced previous claims that electricity pricing is vital to the profitability of Green Steel.

For the United States to maintain a share in the steel market, American producers need to invest and start a transition into Green Steel. Like previously mentioned, European steel producers have invested into 11 projects regarding Green Steel. Most of these projects are planned to be completed by 2030. In the United States, US Steel Corp. is the lone company with any proposed plan. The plan has no completion date, and it is not even regarded as Green Steel production. The steel industry is currently going through a revolution and the United States is lagging behind. Green Steel has the capability to become cheaper than modern techniques. American producers risk losing their market share.

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1. HAGS has the capability of a parallel process of producing ammonia but was not utilized in this process [↑](#footnote-ref-1)
2. SteelBenchmarker did not have reported rebar pricing for U.S. market [↑](#footnote-ref-2)