Decarbonization of Steel and Comparative Analysis With Alternative Materials

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2023 by the
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ARIZONA STATE UNIVERSITY

May 2023

ABSTRACT

The purpose of this study was to comprehend the global warming potential (GWP), cost variability, and competitiveness of steel with rising carbon taxes. Aluminum, glass fiber composite, and carbon fiber composite were chosen as competing materials. In order to compare the aforementioned factors, the GWP of several processes to produce steel, aluminum, and fiber composites was examined. Cost analyses of various methods were also carried out to determine their viability. Energy consumption data for each of the paths under consideration were taken from the literature for the study. To get the consistent GWP for traditional and decarbonized scenarios, the required energy is multiplied with corresponding energy source (natural gas or electricity). Even after accounting for the carbon tax and the weight-reduction factor, the results show that steel still has the lowest production costs, followed by aluminum, while fiber composites remain the most costly. EAF- steel and secondary aluminum has least GWP followed by H_2-DRI (Hydrogen- Direct Reduced Iron)steel and NG-DRI (Natural Gas- Direct Reduced Iron) steel with carbon capture and storage (CCS). The state of art technology for glass fiber reinforced composite also emits less carbon dioxide but the cost of production is still high. Carbon fiber reinforced composite emits most carbon dioxide and is least economical.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Sridhar Seetharaman, for guiding me through the project and giving me valuable input and feedback. I would like to express my gratitude to Dr. Tetiana Shyrokykh and Dr. Tova Jarnerud for continuously helping me and improving the quality of the work. I would also like to thank Robert Stirling for teaching me cost analysis, proper use of MS excel and many important skills. I express my special thanks to TATA Steels Ltd. for providing me with this wonderful opportunity. Also, I would like to thank my friends and family for their constant support.

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1. INTRODUCTION

a. Brief background

Iron- and steel making industry is among the most important industries in the world. It has been a major contributor to the economic growth of many countries[1]. It is responsible for producing the raw materials used in various industries such as construction, manufacturing, automotive, aerospace, energy, and more. It also plays an important role in advancing technology by providing materials for research and development. After increasing by 0.1% in 2020, the World Steel Association (worldsteel) announced that steel demand increased by 4.5% in 2021 to reach 1,855.4 Mt. The demand for steel increased by 2.2% to 1,896.4 Mt in 2022[2].

According to Sun et al. [3], the iron and steel sector is one of the major contributors to global emissions, accounting for nearly 6% of all carbon dioxide emissions worldwide. The significant carbon dioxide emissions from this industry are a result of a number of factors, including the production method, the energy used in the production process, and the usage of coal as a fuel source. According to above mentioned report[3], emissions from steelmaking industry have grown dramatically since 1990, and more growth is anticipated over the following several decades. This is a serious issue since it has an enormous effect on climate change on a worldwide scale. In order to lessen the adverse effects on the environment, it is crucial to develop measures to reduce CO_2 emissions by implementing innovative technologies and energy-efficient practices. Moreover, governments ought to implement laws and rules that encourage the use of industrial methods and technology that are more environmentally friendly and effective.

According to a study by Wu et. al.[4], a large portion of iron and steel production’s carbon dioxide emissions are a result of energy consumption, with most of this energy being supplied by fossil fuels. To combat this, one way is utilizing renewable energy sources such as wind and solar power to replace fossil fuels and reduce emissions. The iron and steel industry's carbon dioxide emissions may be greatly reduced by these steps when used in conjunction with renewable energy sources. Moreover, financial incentives and governmental regulations may be significant in promoting such behaviors.

Technological advances help to decrease carbon dioxide emissions in the iron and steel industry with the help of their increased efficiency and ability to reduce energy consumption. To cut emissions, the steel sector has also been looking at alternative, low-carbon energy sources including hydrogen(from renewable energy) as reducing agent, renewable energy, and carbon capture and storage (CCS). Using recycled steel is another option to lower greenhouse gas (GHG) emissions from the manufacture of steel. The energy needed to create one tonne of virgin steel is approximately 22 gigajoules[5]. Recycled steel production uses a lot less energy than producing new steel from scrap, resulting in fewer greenhouse gas emissions. Recycled steel is being used increasingly often in manufacturing, which helps to lessen the environmental effect of steel production.

Another way to reduce carbon dioxide emissions is to use lightweight materials which gained popularity, mostly in the automotive industry. The benefits of replacing steel components with lighter materials such as aluminum and composites in automobiles as opposed to steel are as follows:

1. Increased Fuel Efficiency: A car's weight may be significantly reduced by using lightweight materials like aluminum and glass fiber composites increasing the efficiency and decreasing fuel consumption as well as reducing CO_2 emissions.

2. Improved Performance: By enabling greater acceleration, braking, and handling, the use of lightweight materials can increase a car's performance. With less mass to move, the vehicle can accelerate more swiftly and react to driver inputs quickly.

3. Improved Safety: By offering superior crash protection, lightweight materials can improve safety in automobiles. These materials have a greater capacity for energy absorption during collisions, which lessens the power of the impact on the car's occupants[6]. Furthermore, some lightweight materials, like composites, may be created to have special impact-resistant qualities, which makes them a better option for usage in safety-critical portions of the automobile[7].

4. Improved Sustainability: The use of lightweight materials can reduce the overall carbon footprint of a car by improving fuel efficiency and reducing emissions.

5. Creative Design: Designers may build novel, cutting-edge automotive designs with lightweight materials that are not achievable with conventional materials. For instance, using composites can result in distinctive forms and curves that provide better aerodynamic designs.

This research is focused on traditional steel production processes and decarbonization pathways of steel production, analyzing alternative lightweight materials such as aluminum and fiber composites. The aim was to investigate the feasibility of transitioning to a more sustainable steel production process while still achieving desired performance standards.

b. Motivation of study

The iron and steel industry's overall CO_2 emissions have grown during the past 10 years, largely as a result of growing steel demand and energy needs for manufacturing. According to worldsteel[8], 2020 saw the production of 1,860 million tonnes (Mt) of steel, with total direct emissions from the industry amounting to almost 2.6 billion tonnes, or between 7% and 9% of all anthropogenic CO_2 emissions worldwide. Every ton of steel produced in 2020, on average, resulted in the release of 1.89 tonnes of CO_2[8].

A carbon tax is a charge placed on activities that emit carbon in an effort to encourage the reduction of greenhouse gas emissions. According to the World Bank[9], in 2021 the average carbon tax in Europe was $42.29, highest being in Sweden at $137 and $0.30 as lowest in Ukraine. The imposition of carbon tax might have a considerable influence on the steel industry's operations. A carbon tax, on the other hand, may encourage the steel sector to innovate and invest in cleaner technology to reduce carbon dioxide emissions and improve sustainability.

The goal of this research was to determine the carbon dioxide emissions from the steel life cycle obtained via various routes, as well as the reliance of final commodity cost on the imposed carbon tax. Steel would become more costly to manufacture as a result of the tariff, perhaps reducing its ability to remain competitive with other materials. Different decarbonizing strategies and their associated production costs were investigated. The LCA and cost analysis were also done for additional lightweighting materials such as aluminum and fiber composites to further understand their competitiveness.

The goal of a life cycle analysis (LCA) is to evaluate the environmental impact of a product or process over the duration of its entire life cycle. This includes the entire process, from raw material extraction through manufacturing end product. An LCA is used to identify the life cycle stages with the greatest environmental effect, sometimes known as "environmental hotspots." LCA is also useful for identifying trade-offs between various environmental consequences. A product built to be extremely robust and long-lasting may have a high environmental effect during the manufacturing phase but a smaller impact during its lifespan because of the reduced need for replacement or disposal. This data may be utilized to make better-educated judgments regarding the most environmentally friendly design and manufacturing practices. Ultimately, the goal of LCA is to give a full knowledge of a product's or process' environmental effect and to suggest possibilities for enhancing its sustainability.

Examining the expenses related to a certain material, production method, and carbon tax's impact is the goal of performing cost analysis. Cost analysis entails the methodical gathering, examination, and interpretation of data pertaining to the expenses of a certain project or program. Cost analysis is done in order to maximize benefits and reduce expenses by assessing the relative costs and advantages of various solutions.

In summary, the goal of LCA and cost analysis is to gather precise and trustworthy data on the CO_2 emissions and costs related to producing steel, aluminum, and fiber composites so that they can be compared fairly, and resources can be spent effectively.

2. LITERATURE REVIEW

Many researchers have examined the life cycle impacts (LCAs) of the manufacturing of steel, aluminum, glass fiber, and carbon fiber reinforced composites, and these studies have repeatedly demonstrated that the manufacture of these items has a sizable environmental effect. The primary environmental effects of steel manufacturing are waste accumulation, water contamination, and greenhouse gas emissions.

The energy needed for the manufacturing process accounts for a significant portion of the environmental effect of the manufacture of steel, aluminum, and composite materials. These items are often produced using energy from non-renewable sources including coal, oil, and natural gas. High quantities of greenhouse gas emissions result from this, which fuels climate change.

The manufacturing process necessitates the use of enormous amounts of water, which can get polluted with contaminants such as heavy metals, sulfur dioxide, and nitrogen oxides. Serious water quality problems might result from this, which would be harmful to both human and aquatic life. Another big environmental consequence is waste creation. Large amounts of waste are produced by it, including solid, liquid, and gaseous waste. These waste products must be properly disposed of in order to reduce their negative effects on the environment and human health.

Many research investigations have looked at the life-cycle assessments (LCAs) of the manufacturing of steel, aluminum, glass fiber, and carbon fiber-reinforced composites. The following is an overview of the reported CO_2 emissions in those studies:

a. Steel

Steel production can occur through several pathways, including the blast furnace - basic oxygen furnace (BF-BOF) route, the electric arc furnace (EAF) route, and the direct reduced iron (DRI) route. According to IEA in 2019, 70% of steel was produced from commercial BF-BOF, 22% from scrap based EAF, 7% from DRI-EAF and 1% from smelting reduction - basic oxygen furnaces (SR-BOF)[10].

BF-BOF: The BF-BOF route is the traditional method for producing steel, and it involves the use of a blast furnace to produce pig iron from iron ore. The pig iron is then processed in a basic oxygen furnace to produce steel. This method is energy-intensive and produces significant greenhouse gas emissions, but it is also the most used method for producing steel. Several studies have been performed on the LCA of steel through BF-BOF. Neugebauer and Finkbeiner [11] , Burchart-Korol [12], Backes J &Suer J [13], Chisalita, and D.A. & Petrescu, L. [14] are some of the studies that derived results for LCA of integrated steel mill and considered system boundaries as cradle to gate. In these studies, the resulting GWP are reported in t $CO_{2\ eq}$/t steel produced. The lowest value of GWP in reported studies is 1.7 t $CO_{2\ eq}$/t steel[11] and 2.5 t $CO_{2\ eq}$/t [12]steel is the highest value, other reported value is 2.1 t $CO_{2\ eq}$/t steel [13,14]. This gives an average of 2.1 t $CO_{2\ eq}$/t steel from the BF-BOF pathway.

EAF (100% scrap): The EAF route involves the use of electric arcs to melt scrap steel, which is then used to produce new steel. This method is less energy-intensive and produces fewer greenhouse gas emissions than the BF-BOF route, but it is also produces lower quality steel. The compliance with high purity levels is sometimes only achieved by dilution of unwanted tramp elements as Pb, Cr, Ni, Cu, Sn, and Mo with highly pure substituting materials, i.e., direct reduced iron and hot metal to produce high-quality specialty steel grades from scrap with differing quality and chemical composition[15].

According to Huellen et. al.[16], the maximum residual content of Σ(Cu+Ni+Mo+Cr+Sn) in interstitial free steel can be 0.106%, therefore pure metal should be added to dilute the impurities. For this study, it is considered that sheets can be made with 100% scrap and all the tramp elements are removed at scrap house, which results in a higher cost than usual. Other possible scenarios are also discussed.

Scrap plays an important role in reducing industrial emissions and resource consumption; each tonne of scrap used for steel manufacturing saves 1.5 t of CO_2 emissions and 1.4 t of iron ore, 740 kg of coal, and 120 kg of limestone[17]. According to IEA[18] the CO_2 emissions from scrap-based steel production are reported to have an intensity of 0.3 t CO_2/t crude steel. Kirschen et. al[15] reported an emission of 0.35 t CO_2/t steel for steel production in the EAF when the raw material is 100% scrap. Birat et. al. reported 0.36 t CO_2/t steel[19], whereas 0.44 t CO_2/t steel is reported by [20] and 0.47 t CO_2/t crude steel by Kopfle & Metius[21].

DRI: The DRI process uses coal, natural gas, or hydrogen to directly reduce iron ore, yielding a high-purity iron product that can be employed to make steel. This approach uses less energy and emits fewer greenhouse gases than the BF-BOF route, but it is also less popular and more difficult than the other two ways. The coal gasifier DRI process emits 1.56 – 1.97 t $CO_{2\,e}$/t DRI[22]. For this study, coal DRI is not considered as it has high amounts of GWP from direct and indirect emissions. Because of the quantity of slag and the high sulfur content, DRI produced from iron ore using coal as the reducing agent is not appropriate for use in EAF. As a result, the primary use of the coal-based direct reduction method nowadays is for the treatment of steel mill dust[23].

On the other hand, on average, Natural Gas-Direct Reduced Iron followed by EAF emits 0.82 to 1.16 t CO_{2e}/ t DRI [22]. Several other studies on GWP from NG-DRI report the same results. Ameling et. al reports 1.3 t $CO_{2\,e}$/t DRI[24], Barati M states that the emission varies from 1.3- 1.5 t $CO_{2\,e}$/t DRI[25].

H_2-DRI, or hydrogen direct reduction iron, is a potential technique for making steel that substitutes hydrogen for the carbon monoxide typically utilized in the blast furnace process as a reducing agent. Because of the large reduction in carbon emissions, the H_2-DRI process is seen as a more environmentally friendly alternative to conventional steelmaking.

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (1)$$

$$FeO + H_2 \rightarrow Fe + H_2O \quad (2)$$

Iron ore is reduced to iron using hydrogen gas in the H_2-DRI process, which is subsequently melted and transformed into steel. Iron ore pellets and hydrogen gas are charged into a reactor vessel, where the reaction 1 and 2 is conducted. Pure iron and water vapor are formed when the hydrogen combines with the iron oxide in the ore. The reactor vessel releases the pure iron, which is then melted to create steel in an electric arc furnace.

Comparing the conventional BF-BOF method, the use of hydrogen in the manufacturing of steel has several benefits. The first benefit of the H_2-DRI process is that the sole waste is water vapor, which is readily caught and recycled. Second, the production of hydrogen is more environmentally friendly when it uses renewable energy sources like solar or wind energy.

Before implementing H_2-DRI technology, it must overcome considerable technological and financial obstacles. It is currently in the development stage. The primary obstacle is the price of hydrogen production, which is still costly when compared to alternative reducing agents like natural gas or coal. Another difficulty is the potential shortage of clean energy sources needed for hydrogen synthesis in some areas. Notwithstanding these difficulties, advancement and research efforts are being made to boost the H_2-DRI process's efficiency and save costs[26]. It has a lot of potential for the future of eco-friendly steel manufacturing.

Several studies have been conducted to see the total CO_2 emissions from H_2-DRI. A study published by Rechberger et. al. shows that the CO_2 emissions can vary from 0.1 t CO_2/t DRI when GWP from electricity is 0.01 kg CO_2/kWh to 1.1 t CO_2/t DRI when GWP from electricity is 0.3 kg CO_2/kWh[27]. According to Fan and Friedmann, it emits 0.38 t CO_2/ t DRI[28] when utilizing hydrogen that is produced through renewable electricity. For the sake of process and cost analysis, this study focuses on NG-DRI and H_2-DRI only.

b. Aluminum

The Hall-Héroult method, which electrolytically reduces aluminum oxide (alumina), is used to produce primary aluminum. Alumina is dissolved in a molten electrolyte, commonly cryolite, and an electric current is sent through the mixture. This results in the reduction of the aluminum ions that are present in the elemental aluminum, which gathers near the cathode and is eliminated as a solid. The Hall-Héroult process consumes a lot of energy, mainly for electrolytic reduction.

According to the aluminum association, in 2019 average CO_2 emissions from primary aluminum production in North America was 8.2 t CO_2/t Al demanding 38.19 kWh energy[29]. Whereas secondary aluminum emitted 0.55 t CO_2/t Al utilizing 2.5 kWh energy[29]. Another research article by Stolz & Frischknecht states that primary aluminum production emits 9.31 t CO_2/t Al and secondary aluminum production from old scrap emits 0.85 t CO_2/t Al[30]. In 2020, the International Aluminum Institute reported 11.2 t CO_2/t Al through primary aluminum production and 0.2 t CO_2/t Al through secondary aluminum production[31].

Determining the process's CO_2 emissions depends critically on the type of power utilized in the manufacture of primary aluminum. When electricity is produced using fossil fuels like natural gas or coal, the carbon intensity from the manufacture of primary aluminum is higher than when electricity is produced using renewable energies like solar, wind, or hydropower.

The CO_2 emission from the electrical grid used for manufacturing determines most CO_2 emissions from the production of primary aluminum. For instance, the carbon contribution of energy is high in areas where the electricity grid is predominately fueled via coal-fired power plants, leading to increased CO_2 emissions from the production of primary aluminum. On the other hand, in areas where the grid is powered by renewable resources like wind or hydropower, the carbon intensity of the electricity used is low, leading to low CO_2 emissions from the production of primary aluminum. According to [32], when using coal powered electricity 18.66 kg CO_2/kg Al is emitted, whereas when hydro powered electricity is used 3.82 kg CO_2/kg Al is emitted.

c. Glass fiber and Carbon fiber composite:

Reinforced polymer composites such as glass fiber composites and carbon fiber composites are employed in a variety of industries, such as aircraft industry, automobile, construction, and sports goods. Typically, these composites are produced using the following steps:

1. Producing fiber: Producing the reinforcing fibers is the initial stage in the creation of carbon fiber and glass fiber composites. Melting silica-based raw materials, including sand and soda ash, then pushing the molten substance through tiny nozzles results in glass fibers. Carbonized precursor materials, such as rayon or polyacrylonitrile (PAN), are used to create high-strength, high-modulus fibers that are subsequently used to create carbon fibers.
2. Composite fabrication: Fabricating the composite material is the following stage in the manufacturing process. This normally entails coating the reinforcing fibers with a polymer resin, like epoxy, polyester, or phenolic, then curing the resin to create a solid composite. Depending on the purpose, the composite may be extruded into a range of forms and sizes.
3. Finishing: Finishing is the last phase in the production process, and it usually includes cutting, sanding, and polishing the composite to create a completed product.

According to Tchana et. Al., glass fiber production emits 1.8-4.6 t CO_2/t glass fiber, 4.9 t CO_2/t resin[33]. Kawajiri & Sakamoto reports GWP of carbon fiber decreases as the production scale increases - it emits 43.32 t CO_2/t carbon fiber when the production scale is 500 TPY (ton per year) and 24.83 t CO_2/t carbon fiber when the production scale is 3000 TPY (ton per year)[34].

Composites made of carbon fibers and glass fibers each have certain benefits and characteristics of their own. While often less costly and simpler to manufacture than carbon fiber composites, glass fiber composites are less rigid, less powerful, and less thermally stable. Contrarily, carbon fiber composites are more expensive and challenging to produce, but they are also stronger, more rigid, and thermally stable.

The individual application requirements, including the desired qualities and budgetary restrictions, will determine whether glass fiber composites or carbon fiber composites should be used. Glass fiber composites are often utilized for applications requiring lower cost and easier processing, whereas carbon fiber composites are typically used for applications requiring great strength and stiffness.

d. Weight reduction potential and manufacturing costs:

According to the Vehicle Technologies Office, the weight of heavy steel sections can be reduced by 10–60% by using substitutes made of aluminum, or fiber-reinforced composites[35]. McKinsey & Company reported that 40% of the weight is reduced if steel is replaced with aluminum and 50% if replaced with carbon fiber composites[36]. [36] also provides cost estimates when steel is replaced with lightweight materials. Aluminum price is increased by 30% whereas for carbon fiber composites it is increased by 470%[36]. Dai et. al. suggests that CFRP can offer up to 60% weight reduction compared to steel[37]. The usage of aluminum alloys can reduce vehicle weight by 30% to 60%[38].

3. METHODOLOGY

a. Outline for LCA

International standards ISO 14040/44[13] are considered as a baseline for life cycle analysis. The concepts and recommendations offered by these standards, ISO 14040 and ISO 14044, can be used to undertake life cycle evaluations (LCAs) of goods, processes, and services. They create a standardized framework for carrying out LCA investigations that promotes standardization, comparability, and transparency of the findings. Although ISO 14040 provides the theoretical underpinnings and structure for LCA, ISO 14044 specifies the precise conditions and offers guidance for conducting LCA studies. To assess how products and services may affect the environment, many businesses and governments utilize ISO 14040 and ISO 14044.

In this study, the start point is the extraction of all the raw materials and the end point is a hot rolled sheet. It can also be called cradle-to-gate LCA. This analysis focuses on how a product or service affects the environment from the time of raw material extraction through the time it leaves the plant, or before it is dispersed to the final consumer. The life cycle stages of the product or service that take place prior to it leaving the manufacturing gate are all included in the cradle to gate LCA. This covers the collection of raw materials, delivery, production, and packaging. The usage and end-of-life stages of the item or service are not considered in the cradle to gate LCA.

b. Global warming potential from thermal and electrical energy

Production of thermal and electrical energy accounts for a sizable portion of greenhouse gas emissions, especially CO_2. As fossil fuels like coal, oil, and gas are used to produce heat and power, significant amounts of CO_2 are released into the atmosphere.

Several manufacturing methods utilizing various energy sources were looked at to analyze the diverse global warming potential induced by the production of various products. In this study, natural gas was taken into account as a source of energy for the process heat. It emits 0.202 kg CO_2/kWh_{th}[39]. The conventional electric power grid in the United States is made up of 61% fossil fuels (natural gas, coal, and pet roleum), 19% nuclear energy, and 20% renewable energy sources, according to the U.S. Energy Information Administration[40]. The asumed grid for renewable electricity is made up of 50% solar PV and 50% wind energy[41]. Table 1 gives the GWP of all the energy sources used in this analysis. The CO_2 embedded in the electricity grid is combined with direct emissions and additional process emissions to obtain the final CO_2 emission per kilogram of material. For current/non-decarbonized processes, the present US power grid is used, while for decarbonized processes, the assumed clean grid used.

Table 1 GWP of different energy sources

Energy Sources	GWP (kg CO_2 -eq /kWh)	References
Traditional electricity	0.385 kg CO_2 -eq /kWh_e	[42]
Renewable Electricity	0.032 kg CO_2 -eq /kWh_e	[41]
Natural gas	0.202 kg CO_2 -eq /kWh_{th}	[39]

c. Life cycle Analysis of various material production processes:

1. Steel Production

The life cycle of steel production through different routes is studied for this research. The start point of this study is mining and the end point is a hot rolled sheet. Steel sheet obtained through BF-BOF and NG-DRI is categorized in traditional steel making whereas the sheet produced through BF-BOF with carbon capture, EAF when input is 100% scrap and H_2-DRI is considered as a decarbonized process. As mentioned above the traditional process uses the current electricity grid and the decarbonized process uses renewable electricity grid.

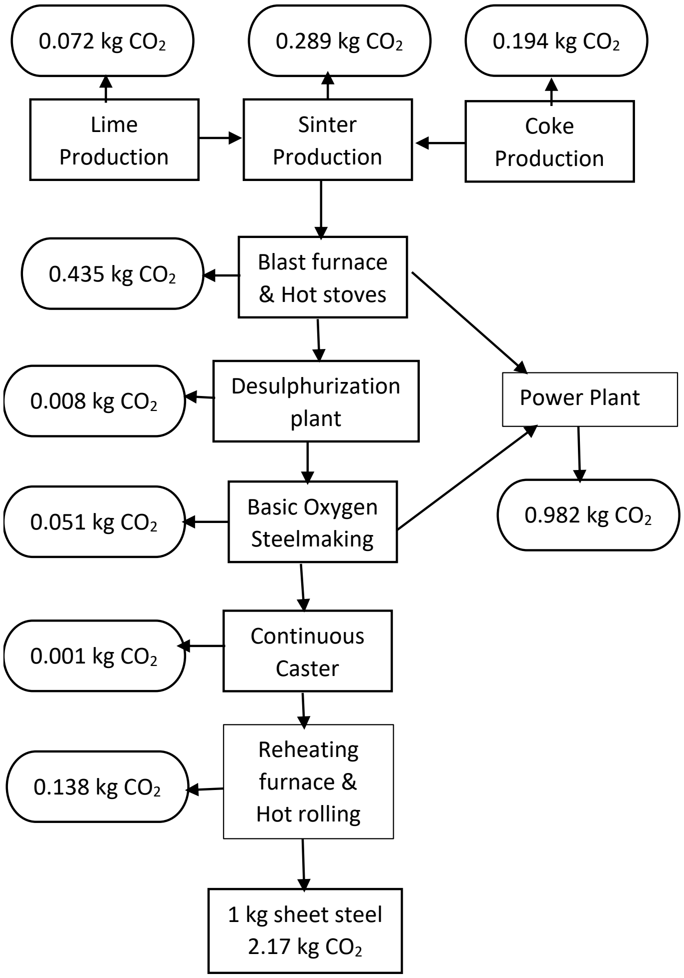

Figure 1 Steel Production through BF-BOF

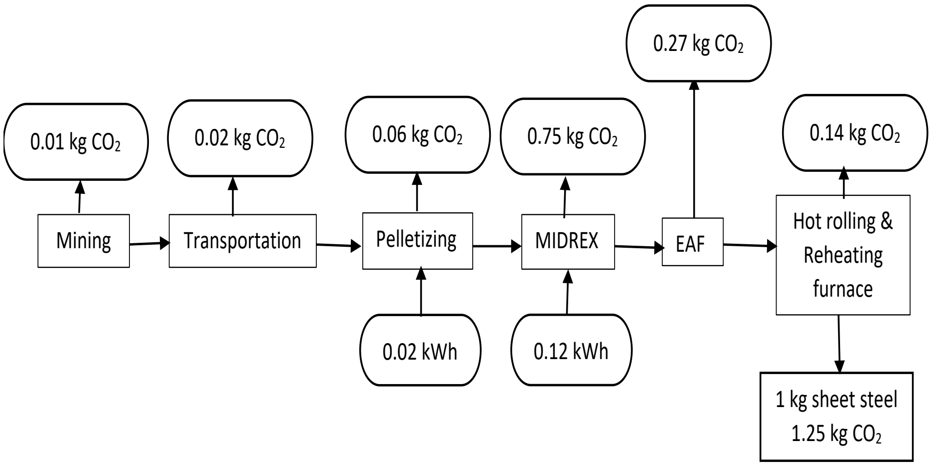

Figure 2 Steel Production through NG-DRI

The steel obtained through BF-BOF emits 2.19 kg CO_2/kg $_{\text{sheet steel}}$[43,44]. The process-wise emissions are shown in Figure 1. The majority of emissions come from power plants and hot stoves. Another traditional way to produce steel is through natural gas direct reduction. Figure 2 represents CO_2 emissions from each process. The total GWP of steel produced through NG-DRI is 1.25 kg CO_2/kg $_{\text{sheet steel}}$. The detailed calculations are provided in the appendix. The highest emission of 0.75 kg CO_2 is direct emission from DRI production.

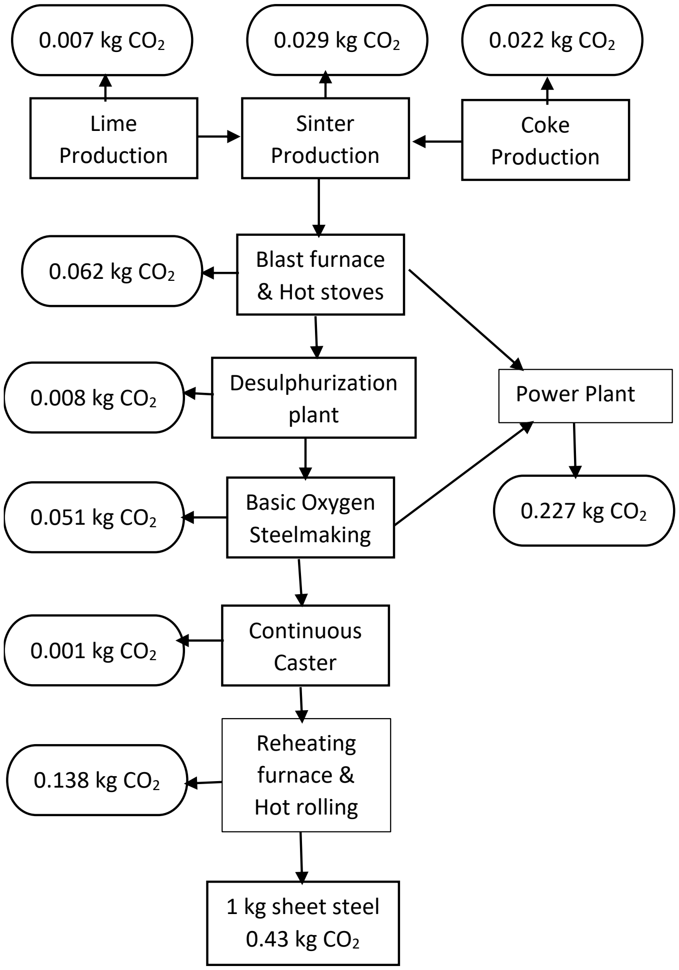

Figure 3 BF-BOF with carbon capture

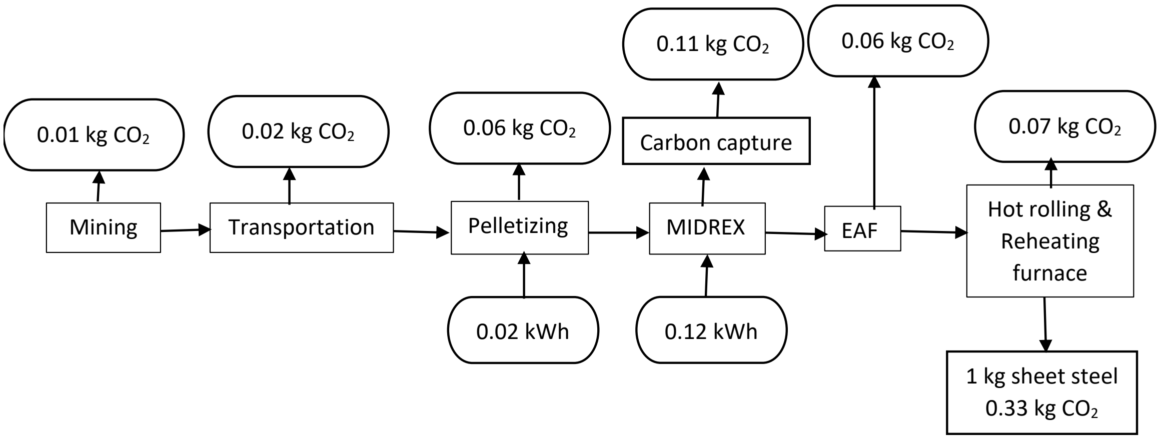

Figure 4 NG-DRI with carbon capture

One of the methods to reduce CO_2 emission is installing carbon capture and replacing current electricity grid with renewable electricity grid. Monoethanolamine (MEA) solvent is used for carbon capture and efficiency of 90% is considered[45]. Blast furnace, coking ovens, and heat/power plants are the main contributors to CO_2 emissions in BF-BOF-based steelmaking. CO_2 is captured and transported from lime production, sinter production, coke production, power plant, blast furnace and hot stoves. This brings down the final emissions to 0.43 kg CO_2/kg $_{\text{sheet steel}}$. Detailed process-wise emissions are shown in Figure 3. For NG-DRI as most of the emissions are from MIDREX process, CO_2 is captured from DRI process (Figure 4). Therefore, the final GWP of sheet obtained through NG-DRI with carbon capture and renewable electricity grid is 0.33 kg CO_2/kg $_{\text{sheet steel}}$.

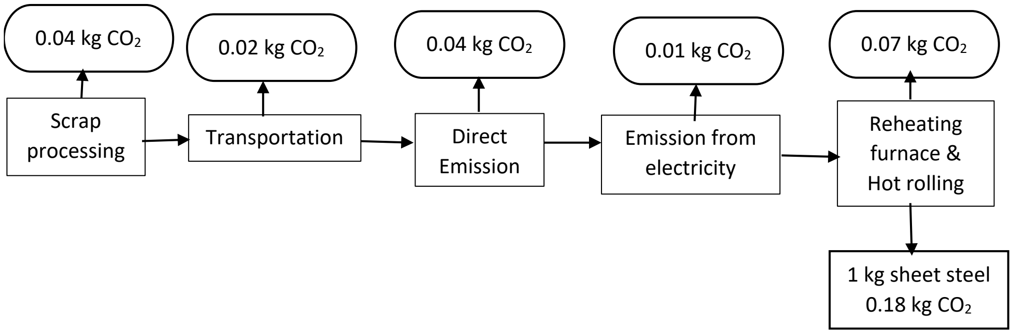

Figure 5 EAF steel using 100% scrap

As multiple research projects have shown that the steel obtained from EAF has relatively lower GWP than steel produced through BF-BOF, it can be reduced further when the input is 100% scrap steel. Even though high-end products like automotive sheet cannot be produced from 100% scrap, it can still be considered as a decarbonized pathway. Currently we might not have an economic way to remove all the tram elements from scrap, but if the economic barrier is passed there can certainly be a way to remove tramp elements at higher price. For the sake of this project, this study does not focus on secondary metallurgy but instead assumes the existence of such technology. For minimizing the GWP even more, renewable electricity grid is considered. Figure 5 shows the process-wise emissions from EAF when 100% scrap is used i.e., 0.18 kg CO_2/kg $_{\text{sheet steel}}$.

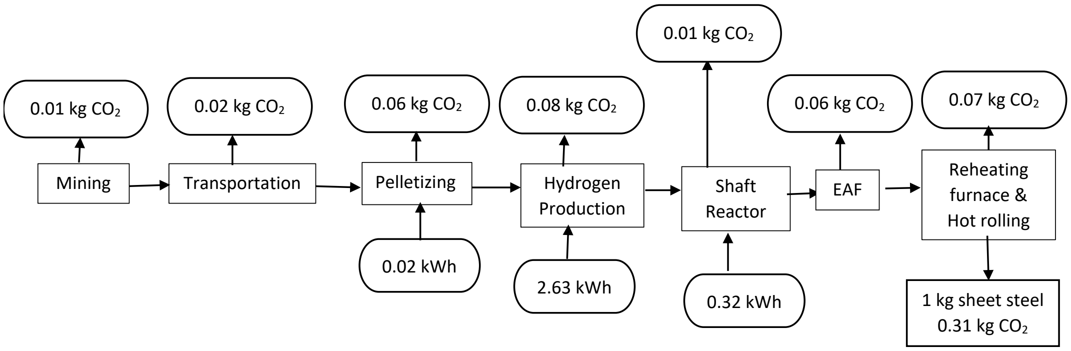

Figure 6 H_2-DRI

H_2-DRI is one of the latest technologies to produce steel. This process uses energy extensively for hydrogen production and that is why it's important that the energy comes from a cleaner source, so it gives less CO_2 emissions. The renewable electricity grid is utilized for this process and Figure 6 gives the flowchart and breakdown of total emissions. The GWP of steel obtained through this production process is as minimal as 0.31 kg CO_2/kg $_{\text{sheet steel}}$, where most of the CO_2 is from hydrogen production. Additional information about this method can be found in the results and discussion section.

2. Aluminum Production

Although aluminum is the third most abounded metal in the earth's crust, it cannot be found in its pure metallic form. It is generally extracted from bauxite ore. Aluminum production has three main steps:

1) Refining: Bayer's process

Blended and grounded bauxite and sodium hydroxide (NaOH) are added to a pressure vessel at temperatures 145-265 °C and pressure of 3.5 MPa. A solution of hot caustic soda (NaOH) is used to dissolve the aluminum-containing minerals present in bauxite (gibbsite, böhmite and diaspore) and create a highly concentrated sodium aluminate solution (equation 3, 5). Gibbsite can exist in $Al_2O_3 \cdot H_2O$ form as well, equation 4 shows its reaction with NaOH.

Gibbsite: $Al(OH)_3 + Na^+ + OH^- \rightarrow Al(OH)_4^- + Na^+$ (3)

Gibbsite alternative: $Al_2O_3 \cdot H_2O + 2NaOH \rightarrow 2NaAlO_2 + 4H_2O \rightarrow Al_2O_3 .3H_2O + 2NaOH$ (4)

Boehmite and diaspore: $AlO(OH) + Na^+ + OH^- + H_2O \rightarrow Al(OH)_4^- + Na^+$ (5)

The filter cake, a byproduct of the bauxite refining process, is then placed in calciners, and heated up to 1100 °C to remove any free moisture and water that is chemically bound. This process converts the filter cake into solid alumina. The reaction that occurs during calcination can be represented by the following equation:

$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$ (6)

2) Primary smelting

Alumina is then electrolyzed to produce aluminum metal. This process, called the Hall-Héroult process, involves dissolving the alumina in a molten electrolyte (usually cryolite) and passing an electric current through the solution. The alumina ions are drawn to the cathode, where they are reduced to aluminum metal. The aluminum is then cast into ingots or other shapes for further processing or use.

Aluminum reduction: $2Al_2O_{3(non\text{-}aqueous)} + 3C_{(s)} \rightarrow 4Al_{(s)} + 3CO_{2(g)}$ (7)

3) Secondary smelting

It is mainly recycling aluminum scrap. Depending on the desired output ratio, primary to secondary aluminum is mixed.

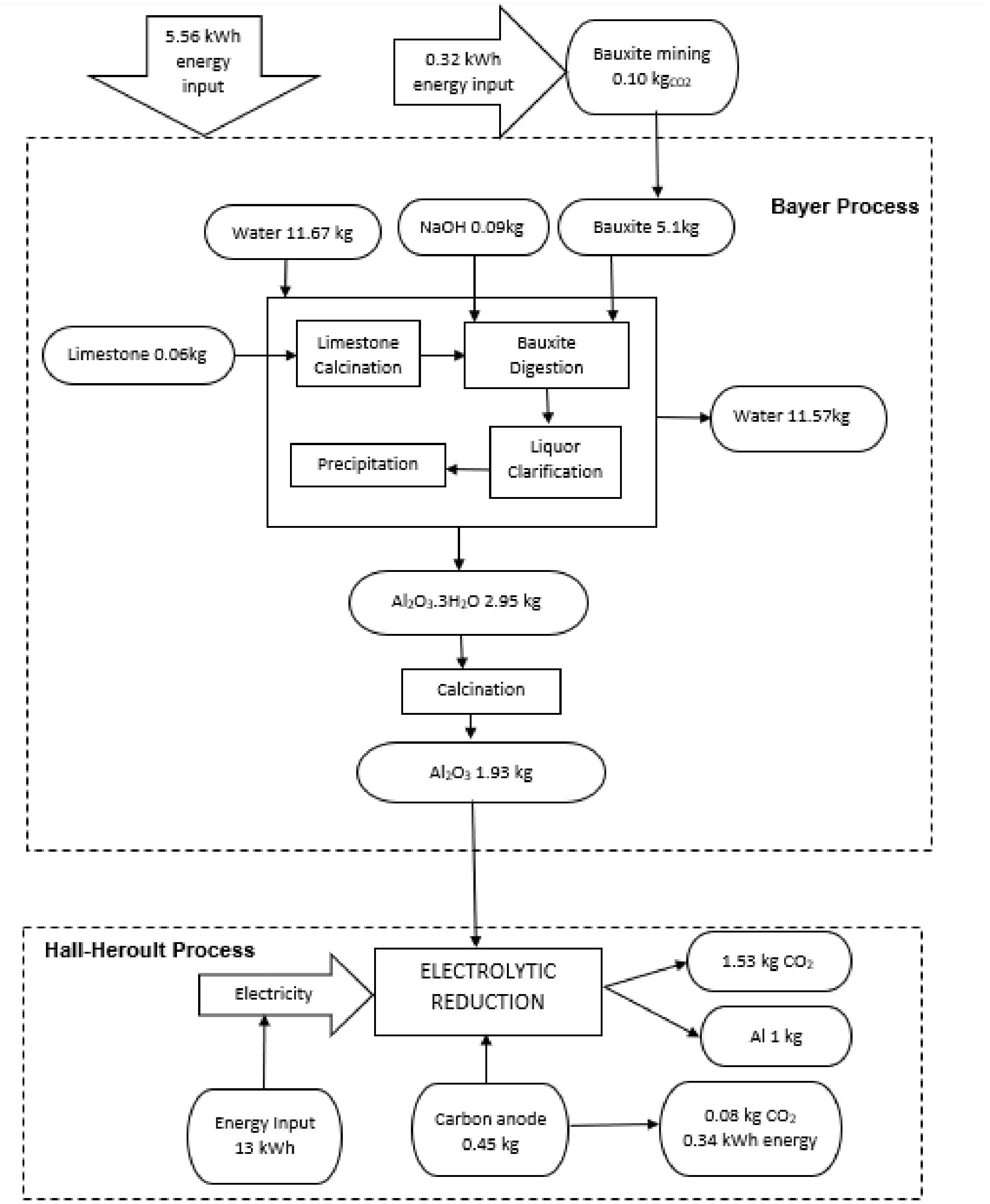

Figure 7 Primary aluminum production

The LCA of primary aluminum production considers all the sub- processes starting with mining of bauxite to sheet rolling. Therefore, the final product of this analysis is a hot rolled sheet. Traditionally sheet products are obtained through the primary aluminum route, but this study also focuses on decarbonized pathways. Decarbonized pathways include primary aluminum with carbon capture, primary aluminum production when electrical energy is used as an energy source for Bayer process along with inert anodes for electrolysis and making sheet from 100% scrap aluminum i.e. secondary aluminum production. As mentioned in earlier sections, the traditional route uses current electricity grid and all decarbonized routes uses renewable electricity grid.

The energy consumption is extensive in the manufacturing of primary aluminum. According to Figure 7 primary aluminum requires 19.22 kWh to produce 1 kg of liquid aluminum emitting 7.91 kg CO_2/kg $_{\text{Aluminum.}}$ Hot rolling of aluminum emits 0.31 kg CO_2/kg $_{\text{Aluminum}}$ with energy utilization of 1.04 kWh/kg$_{\text{Aluminum}}$. The breakdown of CO_2 emission and energy utilization is shown in Table 2 below.

Table 2 Energy utilization & CO_2 emission breakdown for primary aluminum production

Processes	Energy input (kWh/kg Al sheet)	Traditional electricity grid- USA (kg CO_2/ kg Al sheet)
Bauxite mining	0.32[46]	0.10
Bayer process (heat)	5.17 [47]	1.04
Bayer process (electricity)	0.39 [47]	0.15
Anode production (heat)	0.28 [47]	0.06
Anode production (electricity)	0.06 [47]	0.02
Electrolysis (Direct Emission)		1.53 [32]
Electricity for electrolysis	13.00 [47]	5.01
Sheet production (heat)	0.524[48]	0.11
Sheet production (electricity)	0.518 [48]	0.20
Total	20.27	8.22

It is critical that sources of emissions should be identified to decarbonize the manufacturing of aluminum. Several large emission sources are linked to the aluminum value chain, including:

- The use of industrial heat, steam, and electricity for refining

- Production of subsidiary materials for smelting and refining (e.g., anodes)
- Electricity generated from fossil fuels to run the electrolytic cell through melting
- Direct CO_2 emissions from the use of carbon anodes during electrolysis
- Thermal energy to provide steam and heat for aluminum casting and fabrication
- Waste removal and processing

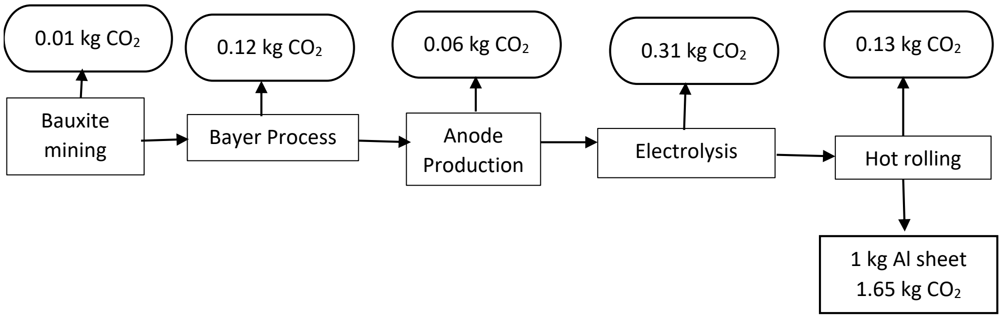

Figure 8 Primary Aluminum with carbon capture

It can be observed that during primary aluminum production, large amount of carbon dioxide is emitted(8.22 kg CO_2 /kg $_{\text{Auminuml sheet}}$). For reducing CO_2 emission, carbon capture unit is installed to capture CO_2 released from an electrolysis stack and from process heat generation used for Bayer process. The carbon capture unit has an efficiency of capture of 90% and uses MEA solvent for post-combustion capture with heat integration [49]. Flue gas contains 4% CO_2 by volume[50]. The traditional electricity grid is replaced with renewable electricity, final CO_2 emission is 1.65 kg CO_2 /kg $_{\text{Auminuml sheet}}$. Breakdown of these emissions is displayed in Figure 8.

The carbon dioxide equivalent (GWP) of 1 kilogram of aluminum sheet is 8.22 kg CO_2-eq, with the majority of this carbon dioxide coming from the regular electrical grid and process heat for Bayer process. The direct emissions from electrolysis, 1.53 kg CO_2/kg $_{\text{aluminum sheet}}$, can be eliminated by the inert anodes. In comparison to carbon anodes, inert anodes need more electricity since the potential differences between the reactants are greater. Inert anode needs 16 kWh/kg of aluminum sheet as opposed to carbon anode[51]. The inert anode is assumed to have 48.3% Fe_2O_3 and 51.7% NiO [52]. The results show that when renewable energy is employed as a source of energy for process heat in the Bayer process and an inert anode is used for electrolysis, a CO_2 emission of 1.16 kg CO_2/kg $_{\text{aluminum sheet}}$ is attained. In Table 3, CO_2 emissions from the production of conventional and decarbonized aluminum are compared.

Table 3 Comparison of decarbonized aluminum with conventional primary aluminum

Process	Conventional Aluminum ($kg_{CO2}/kg_{Al\ sheet}$)	Decarbonized aluminum ($kg_{CO2}/kg_{Al\ sheet}$)	Technologies
Bauxite mining	0.10	0.10	No Change
Bayer process	1.19	0.18	Thermal Energy from Renewable Electricity
Anode production	0.08	0.25	Inert Anodes
Electrolysis	6.54	0.51	Inert Anodes
Hot rolling	0.31	0.13	Renewable electricity
Total	8.22	1.16	

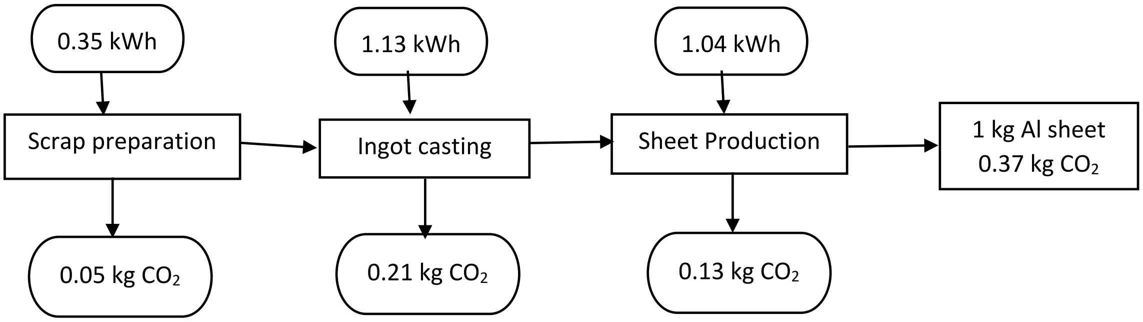

Figure 9 Secondary aluminum production

As stated before, 100% scrap cannot be used to make high end products, still secondary aluminum is considered as one of the decarbonized pathways to make aluminum sheet. Secondary aluminum requires just 9% of the energy required for primary aluminum production, 2.52 kWh/kg $_{\text{aluminum sheet}}$ (Figure 9). When renewable energy is employed, it emits less carbon dioxide than primary aluminum production, i.e., 0.37 kg CO_2/kg $_{\text{Aluminum sheet}}$. The energy utilization for secondary aluminum making is adapted from [48].

3. Fiber composites

Glass fiber is split into two categories:

- E-glass, textile glass fiber (used as reinforcing material for composites)
- Glass wool (used as insulation material for construction)

The American Society for Testing and Materials (ASTM) specifies that E-glass for common purposes should contain 52-62 wt.% SiO_2, 16-25 wt% CaO, 12-16 wt.% Al_2O_3, 0-10 wt% B_2O_3, 0-5 wt.% MgO, and 0-20 wt.% others[17].

As batch materials melt, they undergo decomposition and produce CO_2 through reactions 8, 9, and 10. During the melting process, the high temperature in the furnace causes nitrogen in the air to react with oxygen to produce thermal NO (reaction 11). At temperatures above 760°C, NO formation begins, and at temperatures above 1300°C, NO production reaches its maximum with the available oxygen. The thermal decomposition of Na_2SO_4 during the melting and refining process also causes SO_2 to be released (reaction 12).

$$CaCO_3 \rightarrow CaO + CO_2(g) \quad (8)$$

$$Na_2CO_3 \rightarrow Na_2O + CO_2(g) \quad (9)$$

$$CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2(g) \quad (10)$$

$$N_2(g) + O_2(g) \rightarrow 2NO(g) \quad (11)$$

$$2Na_2SO_4 \rightarrow 2Na_2O + 2SO_2(g) + O_2(g) \quad (12)$$

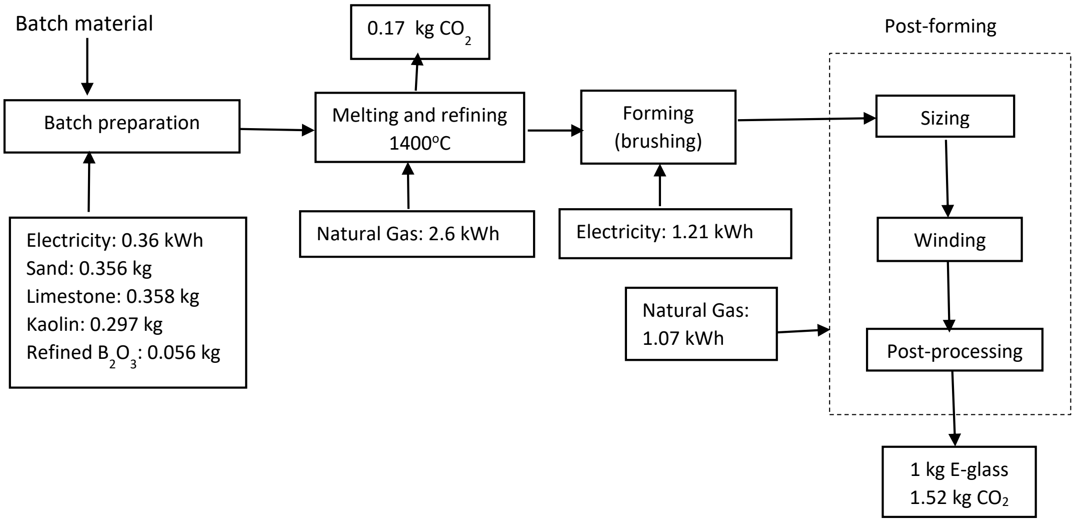

Figure 10 E-Glass fiber production

Figure 10 shows mass balance and energy utilization to produce 1 t E-glass. In order to use E-glass as sheets, it should be reinforced with a composite. Depending on the end product, there are various types of composite manufacturing procedures. Additive manufacturing, sheet molding compression, curing, filament winding, infusion, continuous process injection, and over molding are some of the molding techniques used to produce composites for auto parts. To create the composite, glass fabric and resin must be applied to the surface of the cloth. To produce fiber composites, there are five primary types of resins used in the automotive industry. In the automotive sector, phenolic and BMI cyanate resins are frequently used for the engine, engine compartment, and gearbox, while epoxy and thermoplastic resins are frequently used for automobile bodies. For this study, sheet molding compression (SMC) is considered as method of reinforcement and source of energy utilized is electrical energy. The composite considered is epoxy resin. The ratio of composite to fiber used is 50:50[53]. Table 4 gives the energy requirement for production of 1 kg GFRC. Resin production followed by refining and melting are the most energy intensive process steps. For refining and melting, natural gas is used as an energy source. CO_2 emission to produce 1 kg GFRC is 3.9 kg/kg$_{GFRC}$.

Table 4 Energy requirement for 1 kg GFRC

Processes	Energy (kWh/kg)

Batch preparation	0.18
Melting and refining	1.30
Forming	0.65
Post forming	0.54
Resin production [54]	10.56
Fabrication using SMC [55]	0.97
Total	14.15

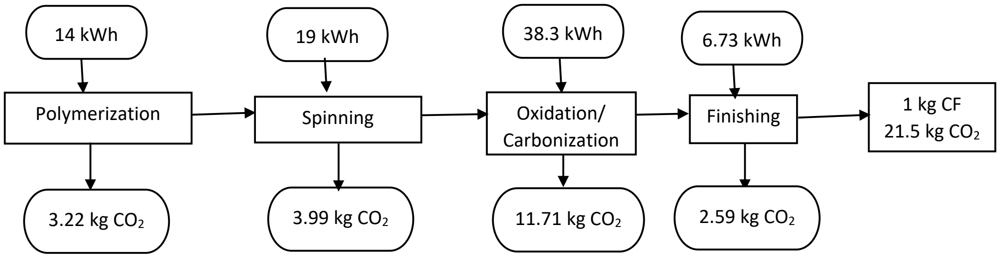

Figure 11 Carbon fiber production

Carbon Fiber is mainly produced from polyacrylonitrile (PAN) (about 90 %) and rayon or petroleum pitch (about 10 %). Propylene, ammonia, and air are collected during the first step of synthesis, which also uses air as the primary oxidant. The manufacturing process has the following steps:

1. Stabilization: First, the fibers are heated in air to undergo chemical changes to transform the linear atomic bonding into a more stable ladder bonding. At 200–300 °C, gas-phase stabilization normally takes ten minutes.
2. Carbonization: The stabilized fibers are then heated to the temperatures ranging between 1200 and 1600 °C for several minutes in a furnace with a gas mixture without oxygen content preventing them from burning. They start losing their non-carbon atoms after heating and form crystals of carbon which are firmly bounded.
3. Surface Treatment: In order to have a better bonding surface, the fibers are then slightly oxidized.

4. Sizing: The carbon fibers are coated to shield them from damage during winding or weaving once they have undergone the required surface treatment. Epoxy, nylon, urethane, polyester, and other compounds are often used as coating materials. The coated fibers are wound onto bobbins, which are then fed into spinning machinery where they are twisted into yarns of various diameters.

Figure 11 shows a detailed flow diagram of carbon fiber production. Table 5 summarizes the energy utilization for CFRC production which is adapted from [55]. CFRC gives total emission of 14.2 $kg_{CO2}/kg_{CFRC\ sheet}$ with the major contributors being oxidation of carbon fiber followed by resin production. As with GFRC, carbon fiber is combined with a polymeric material to make a robust composite. In this study, epoxy resin is considered as a composite and the ratio of fiber to resin is 35:65.

Table 5 Energy requirement for 1 kg CFRC production

Process	Energy (kWh/kg)	Natural gas (%)	Electric (%)
Polymerization	4.90	84.70	15.30
Spinning	6.66	95.70	4.30
Oxidation/Carbonization	13.41	43.40	56.60
Finishing	2.35	0.00	100
Resin production	27.31	91.90	8.10
Fabrication (SMC)	0.97	0.00	100
Total	42.01		

It is evident from Table 4 and Table 5 GFRC and CFRC requires high amount of energy, 14.15 kWh/kg_{GFRC} and 42.01 kWh/kg_{CFRC} respectively. A study on reduction of energy utilization in glass fiber, carbon fiber and resin production were conducted by U.S. DOE. This study shows that the total energy consumption for GFRC can be reduced to 4.69 kWh/kg_{GFRC}[56] and for CFRC energy utilization is 25.12 kWh/kg_{CFRC}[55]. The technologies used to attain lower energy consumption are explained in detail in [55,56]. These are still state-of-art technologies but are considered as a decarbonized pathway for production of fiber composites. The source of electricity assumed is renewable electricity and natural gas is used as source of energy for process heat. Table 6 and Table 7 gives the breakdown of energy utilization and GWP from GFRC and CFRC production. The final CO_2 emission from these processes is 3.65 kg CO_2/kg CFRC and 0.81 kg CO_2/kg GFRC.

Table 6 CO_2 emission from production of CFRC (State of Art)

CFRC production sub-Process	Energy(kWh/kg CFRC)	GWP (kg CO_2/kg CFRC)
Polymerization	4.42	0.78
Spinning	6.03	1.17
Oxidation/Carbonization	7.45	0.79
Finishing	1.90	0.06
Resin Production	4.36	0.82
Fabrication using SMC	0.97	0.03
Total	25.12	3.65

Table 7 CO_2 emission from production of GFRC (State of Art)

GFRC production sub-Process	Energy(kWh/kg GFRC)	GWP (kg CO_2/kg GFRC)
Batching	0.03	0.00
Melting	0.21	0.04
Direct emission		0.09
Fiberization	0.06	0.01
Finishing	0.07	0.01
Resin production	3.35	0.63
Fabrication using SMC	0.97	0.03
Total	4.69	0.81

d. Cost analysis:

The production cost per tonne of the above-mentioned materials and processes was calculated by cost analysis. The quantity of material and energy inputs to the process are often estimated using process modeling or literature searches to establish the cost. The efforts to estimate the global warming potential are consistent with these inputs. As it is reflective of manufacturing expenses in the years before to the global COVID-19 outbreak, the year 2019 was chosen as the analysis' starting point. It was contended that the 2019 prices given in this study are indicative of long-term, stable prices, even if labor, feedstock, and energy prices fluctuate constantly. Table 8 displays the cost of major sources of energy used for this study.

The manufacturing cost of fiber composites is unclear in literature. Assumptions were made about labor cost, capital cost and other costs due to obscure data. The calculated manufacturing cost is theoretical cost, the market cost of these products is observed to be much more that the calculated ones. But for the sake of this study these costs are treated as base minimum costs of fiber composites.

The disparity between market prices and the calculated costs can be seen due to inclusion of carbon tax. A carbon tax of \$80/t CO_2 is included in the total expenses. In order to calculate the total cost, the net CO_2 emissions in tonnes per tonne of material produced are multiplied by \$80 and added to the production cost. The assumptions used to estimate capital costs and labor costs per ton come from the literature. The appendix contains information on each cost model.

Table 8 Cost of used energy sources (2019)

Energy Sources	Cost ($ /kWh)	Reference
Traditional electricity	0.034	[57]
Renewable Electricity	0.056	[57]
Natural gas	0.011	[58]

Carbon Capture Cost:

The economics of carbon capture, storage, and transport were investigated in relation to steel and aluminum plants. Due to different CO_2 concentrations in the flue gases from the steel and aluminum facilities, there is a cost differential. In general, the relationship between Capex and CO_2 content in flue gas is inverse. It was chosen to utilize different costs for various businesses since, in addition to the concentration differential, there are other factors that impact the cost of carbon capture. The cost of carrying CO_2 varies according to the form of transportation (for example, pipelines vs. ships), the volume of CO_2 moved, the distance to the CO_2 storage facility, the monitoring and regulatory requirements, including any legislative obstacles and incentives, the cost structures connected to financing, capital, and labor, the CO_2 source, and whether or to what degree it is compressed or filtered before transferring. Because of geographical variances, each of these characteristics varies by location. There are three main sources of variance that affect the cost of CO_2 storage: Geological characteristics, size (amount of CO_2 stored), monitoring, financial, and other factors.

The costs for carbon collection, transport, and storage are summarized in Table 9, along with the underlying assumptions. For the purposes of this analysis, it was anticipated that the average cost of CO_2 capture for steel operations would be \$90/t CO and for aluminum processes would be \$127/t CO_2. For onshore storage, it was assumed that 3.2 Mtpa CO_2 is transferred more than 100 kilometers. The price of compression, transportation, and storage is estimated to be \$10/t CO. As a result, the overall cost for steel carbon capture and storage is estimated to be \$100/t CO_2 for steel and \$137/t CO_2 for aluminum.

Table 9 Carbon capture and storage cost for steel and aluminum plants

Scenario	Cost (\$/t CO_2)	Published year/ Forecast year	Assumptions	References
Carbon capture for steel	68.7	2013	Post-combustion capture	[59,60]

Carbon capture for steel	65.1-119.2	2013	Post-combustion capture	[61]
Carbon capture for steel	78.5	2011	Post combustion capture with MEA of blast furnace flue gas	[62]
Carbon capture for steel	104.21	N/A	N/A	[63]
Carbon capture for aluminum (4%)	123.51	2013	MEA based carbon capture, concentration of CO2 in flue gas is 4%	[64]
Carbon capture for aluminum (7%)	115.84	2013	MEA based carbon capture, concentration of CO2 in flue gas is 7%	[64]
Carbon capture for aluminum (10%)	110.52	2013	MEA based carbon capture, concentration of CO2 in flue gas is 10%	[64]
Storage and transport (Low)	12.38	2019	Mean value for transporting 3.2 Mtpa CO2 over 100 miles for storage without extra monitoring	[65]
Storage and transport (Medium)	28.51	2019		[65]
Storage and transport (High)	39.46	2019	Cost to transport CO_2 via ship for offshore storage based on	[65]

	estimates from the Northern Lights Project.

e. Normalization using material properties:

Automotive sheet was selected as the standard product for comparison in this study. The automotive industry's recent breakthroughs are promoting the use of lighter materials like aluminum, glass fiber reinforced composites, and carbon fiber composites in order to build cars with better fuel efficiency or battery range. Automobile companies are working to make vehicles lighter in order to appeal to customers more and to comply with legal regulations. With a density around one-third that of steel and high strength alloys that meet the torsion and stiffness specifications for automobile components, aluminum offers a potential technical solution in this area. Polymer composites frequently combine high-strength, high-stiffness fibers with low-density matrix materials to create strong, stiff, and lightweight materials. These qualities provide reinforced composites with an advantage over steel in the automotive industry, along with increased moldability, a good strength to weight ratio, and corrosion resistance. Weight reduction is calculated using the bending stiffness of sheets made of different materials.

For example, to compare steel and epoxy-based glass fiber reinforced composites (GFRC), the following method is used. This method of comparing bending stiffness is adapted from [66].

$$K \propto E \cdot t^3 \tag{13}$$

In equation 13, K = stiffness (N/m)

E = elastic modulus (GPa)

t = sheet thickness (cm)

The valued used for elastic modulus and other mechanical properties are as follows:

E_{GFRC} = 42 GPa; E_{Steel} = 207 GPa; ρ_{GFRC} = 1.9 g/cm^3; ρ_{Steel} = 7.8 g/cm^3

To achieve the same stiffness,

$K_{\text{steel}} = K_{\text{GFRC}}$

From equation 13,

$$\frac{t_{GFRC}}{t_{steel}} = \left[\frac{E_{steel}}{E_{GFRC}}\right]^{\frac{1}{3}} \tag{14}$$

$$\frac{E_{steel}}{E_{GFRC}} = 4.5 \tag{15}$$

$$\frac{t_{GFRC}}{t_{steel}} 1.65 \tag{16}$$

Equation 17 is used to calculate the weight savings,

$$weight\ savings\ = 1 - \left[\frac{(\rho_{GFRC} * 1.65)}{\rho_{steel}}\right] * 100 = 60\% \tag{17}$$

Similarly, weight reduction for aluminum and carbon fiber reinforced composites were calculated.

The results are given

Table 10.

Material	E: Elastic modulus (GPa)	Density (g/cc)	Equivalent Factor (kg $_{material}$ /kg $_{steel}$)	Weight Savings(%)
Steel	207	7.8	1	NA
Aluminum	71	2.8	0.5	50
Glass Fiber Reinforced Composite	41[67]	1.9[68]	0.4	60
Carbon Fiber Reinforced Composite	95.5[69]	1.4[69]	0.23	77

Table 10 Properties and results of material mass normalization.

4. RESULTS & DISCUSSION

The Global Warming Potential (GWP) and manufacturing costs of different materials, as well as the comparison with normalized factor, are detailed in Table 11 . In order to compare the weight reduction of other materials as compared to steel, it additionally contains a stiffness normalization factor. With the stiffness normalization factor taken into account, the materials are ordered according to their normalized GWP.

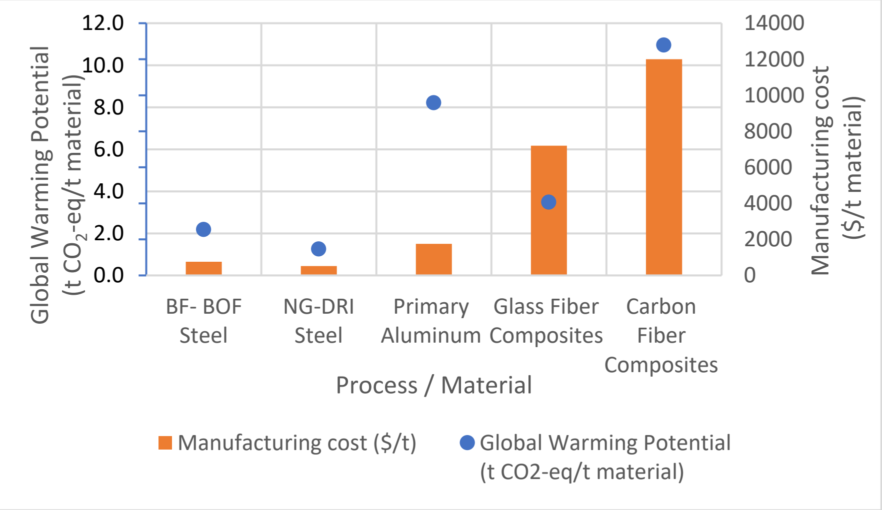

Figure 12 GWP and manufacturing cost of materials obtained through traditional pathways

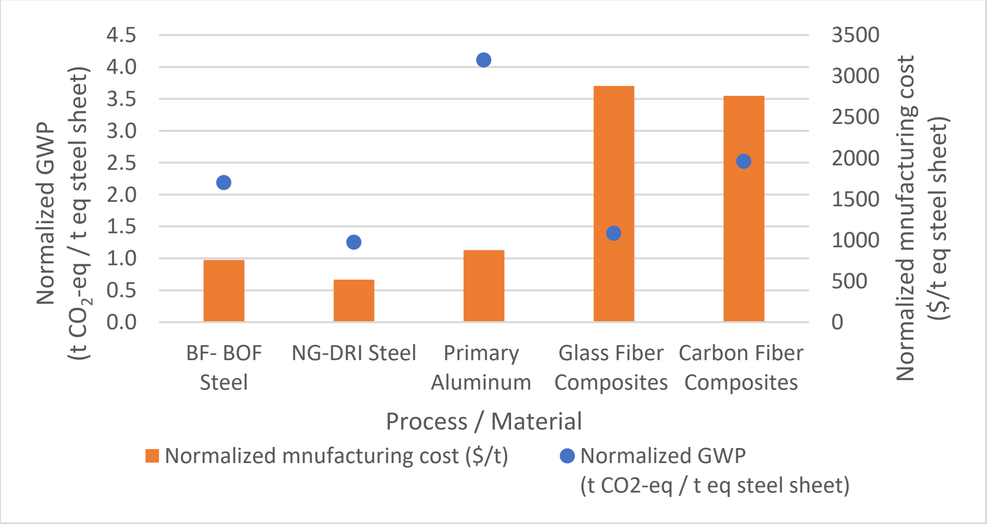

Figure 13 Normalized GWP and manufacturing cost of materials obtained through traditional pathways

Figure 12 & Figure 13 depicts the of GWP and manufacturing cost of different materials. The material with the lowest normalized GWP, 1.25 t CO_2-eq/t eq steel sheet, is NG-DRI steel. Also, it has a $518.55/t eq steel sheet production cost that is relatively cheap. When compared to typical blast furnace (BF)-basic oxygen furnace (BOF) steel manufacturing, this steel is produced utilizing natural gas in a direct reduced iron (DRI) method, which minimizes its environmental effect. When compared to carbon fiber composites and primary aluminum, glass fiber composites have a normalized GWP of 1.39 t CO_2-eq/t eq steel sheet, which is relatively low. However, with a material cost of $7,201.31 per tonne, or $2,880.53 per tonne equivalent of steel sheet, it has a very high production cost. The GWP of BF-BOF steel is greater than that of NG-DRI steel, with a normalized value of 2.19 t CO_2-eq/t eq steel sheet. As compared to composite materials, it has a cheaper production cost of $757.46/t eq steel sheet. Compared to the other materials obtained through the traditional pathway, carbon fiber composite has the highest GWP, 10.96 t CO_2-eq/t material, i.e., 2.52 t CO_2-eq/t eq steel sheet. Due to the normalizing factor carbon fiber composites are more favorable than primary aluminum. Moreover, it has a quite high production cost of $12,065 per tonne of material, which equates to a normalized manufacturing cost of $2,760.15 per tonne of eq steel sheet. Primary Aluminum has global warming potential (GWP) of 8.22 t CO_2-eq/t. It has the highest GWP(4.11 t CO_2-eq/t eq steel sheet) when normalization factor is considered. Additionally, it has a comparatively high production cost of $1,757.59 per tonne of material, which equates to a normalized manufacturing cost of $878.79 per tonne of equivalent steel sheet.

Table 11 Summarization of GWP and manufacturing cost of materials through traditional pathways

Process / Material	Global Warming Potential (t CO_2-eq/t material)	Stiffness Normalization Factor (t material / t steel)	Normalized GWP (t CO_2-eq / t eq steel sheet)	Manufacturing cost ($/t material)	Normalized manufacturing cost ($/t eq steel sheet)

BF- BOF Steel	2.19	1.00	2.19	757.46	757.46
NG- DRI Steel	1.25	1.00	1.25	518.55	518.55
Primary Aluminum	8.22	0.50	4.11	1757.59	878.79
Glass Fiber Composites	3.48	0.40	1.39	7201.31	2880.53
Carbon Fiber Composites	10.96	0.23	2.52	12000.65	2760.15

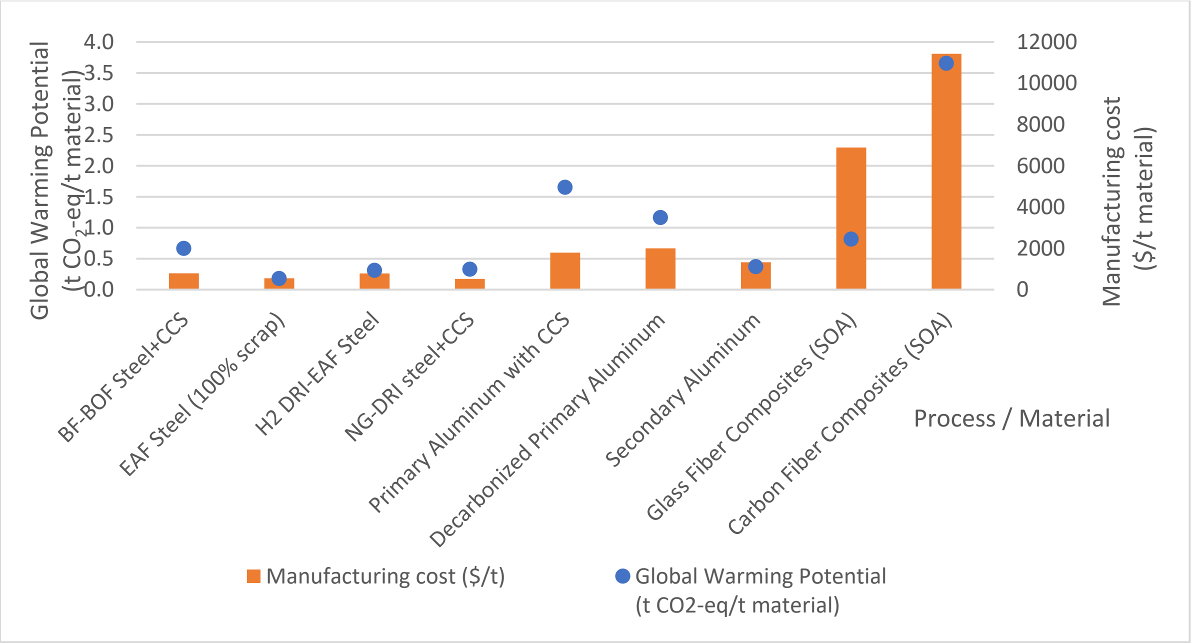

Figure 14 GWP and manufacturing cost of materials obtained through decarbonized pathways

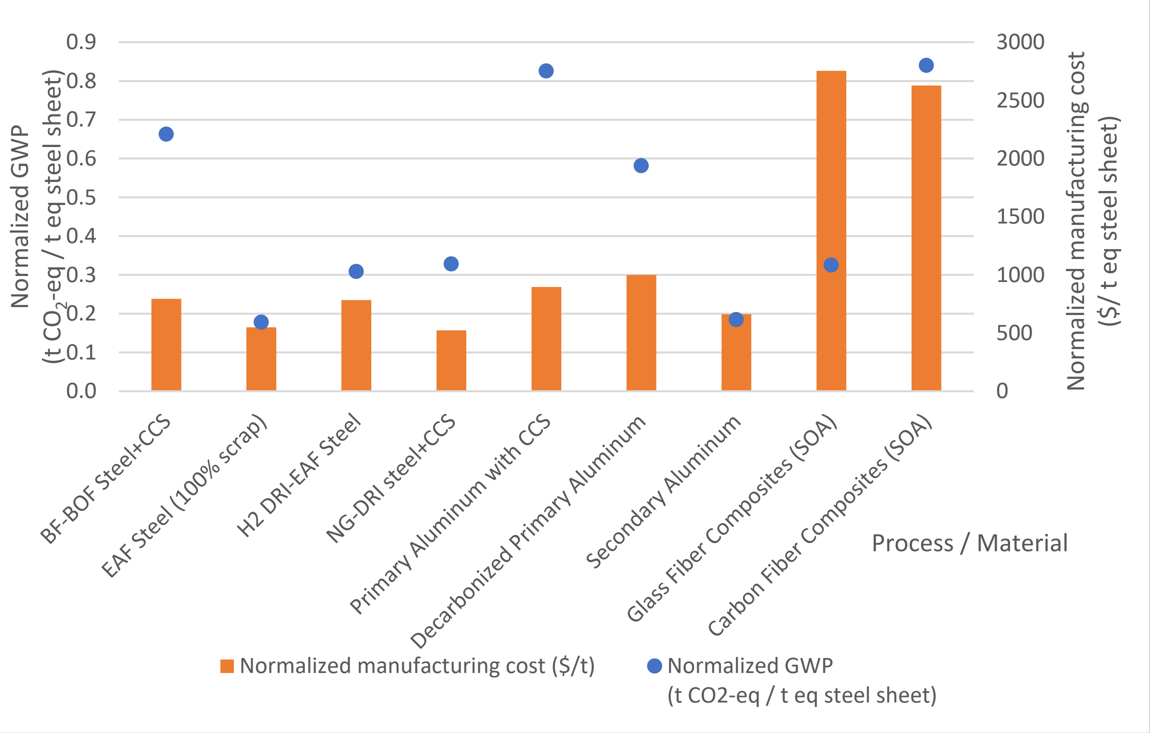

Figure 15 Normalized GWP and manufacturing cost of materials obtained through decarbonized pathways

The figures above (Figure 14 & Figure 15) provides information on different decarbonized pathways to produce steel, aluminum and fiber composites. It also displays their environmental impact in terms of Global Warming Potential (GWP), manufacturing cost, and their carbon capture and storage (CCS) potential. They include a stiffness normalization factor, which is used to compare the weight reduction potential of different materials with that of steel. Based on their normalized GWP, which incorporates the stiffness normalization factor, the materials are ranked. The lower the normalized GWP of a substance, the better its environmental performance.

- EAF Steel: With a normalized GWP of 0.18 t CO_2-eq/t eq steel sheet, this material has the lowest GWP out of all the other materials studied. This is due to the fact that it is manufactured entirely from scrap and doesn't call for any virgin metal. Moreover, it has a $549.36/t eq steel sheet comparatively low production cost.

- Hydrogen DRI-EAF Steel: The normalized GWP of this material is 0.31 t CO2-eq/t eq steel sheet. However, with a production price of $783.16/t eq steel sheet, it is rather expensive. The majority of this cost is influenced by the cost of hydrogen, which is assumed to be $4.5/kg.

- NG-DRI Steel with CCS: The normalized GWP from this pathway is 0.33 t CO_2-eq/t eq steel sheet, which is much lower than that of BF-BOF steel and primary aluminum. Also, it has a $523.03/t eq steel sheet production cost that is relatively cheap. As compared to standard NG-DRI steel manufacturing, this process's carbon capture and storage capability minimizes its CO_2 emissions.

- BF-BOF Steel with CCS: The normalized GWP of this material is 0.66 t CO_2-eq/t eq steel sheet, which is much lower than BF-BOF steel without CCS. It also has a low production cost of $794.50 per t eq steel sheet. In comparison to NG-DRI steel with CCS and EAF steel, it still has a larger environmental impact.

- Secondary Aluminum: This route has a normalized GWP that is equivalent to EAF steel at 0.18 t CO_2-eq/t eq steel sheet, which is a comparatively low value. It does, however, have a higher production cost of $662.88/t eq steel sheet.

- Decarbonized Primary Aluminum: This method has a lower normalized GWP of 0.58 t CO_2-eq/t eq steel sheet than primary aluminum with CCS. Nonetheless, the production cost is rather expensive at $999.41/t eq steel sheet.

- Glass Fiber Composites: This material has a normalized GWP of 0.33 t CO_2-eq/t eq steel sheet, which is low when compared to carbon fiber composites. However, it has a very high production cost of $6,884.40/t material, which corresponds to a normalized manufacturing cost of $2,753.76/t equivalent steel sheet. Besides that, the price of fiber composites depends on a number of variables, including the scale of production, capital costs, labor costs, the kind of resin used, the fabrication process, and others.

- Carbon Fiber Composites: Compared to the other materials examined, this material has the greatest GWP, which is 0.84 t CO_2-eq/t eq steel sheet. In addition, it has a comparatively high production cost of $11,423.11 per tonne of material, which corresponds to a normalized manufacturing cost of $2,627.32 per tonne of equivalent steel sheet.

Table 12 Summarization of GWP and manufacturing cost of materials through decarbonized pathways

Process / Material	CCS – t CO_2 captured	Global Warming Potential (t CO_2-eq/t material)	Stiffness Normalization Factor (t material / t steel)	Normalized GWP (t CO2-eq / t eq steel sheet)	Manufacturing cost ($/t material)	Normalized manufacturing cost ($/t eq steel sheet)
BF-BOF Steel with CCS	1.52	0.66	1.00	0.66	794.50	794.50
EAF Steel (from 100% scrap)	0	0.18	1.00	0.18	549.36	549.36
Hydrogen DRI-EAF Steel	0	0.31	1.00	0.31	783.16	783.16

NG-DRI Steel with CCS	0.64	0.33	1.00	0.33	523.03	523.03
Primary Aluminum with CCS	2.32	1.65	0.50	0.83	1792.63	896.31
Decarbonized Primary Aluminum	0	1.16	0.50	0.58	1998.82	999.41
Secondary Aluminum	0	0.37	0.50	0.18	1325.77	662.88
Glass Fiber Composites	0	0.81	0.40	0.33	6884.40	2753.76
Carbon Fiber Composites	0	3.65	0.23	0.84	11423.11	2627.32

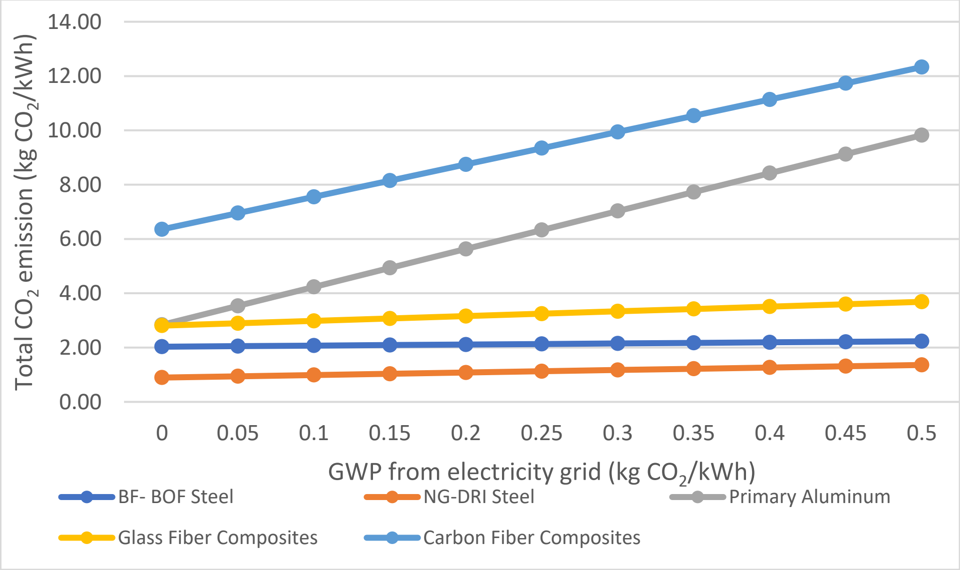

Figure 16 Dependence of GWP of electricity grid on total CO$_2$ emissions (Traditional pathways)

Figure 16 displays the dependence of GWP of electricity grid on total CO_2 emissions from materials obtained through traditional pathways. It can be observed that steel obtained through BF-BOF and NG-DRI both have negligible effect on total emission from electricity grid. Glass fiber composites have minimal effect. But the total carbon dioxide emission through primary aluminum and carbon fiber composite production is totally dependent on carbon intensity of electricity grid. If the traditional pathways are to be continued for primary aluminum and carbon fiber production, it is important to decarbonize electricity grid. But it should be noted that even when the GWP from electricity is 0 kg CO_2/kWh the emissions from production of carbon fiber composites are 6.36 kg CO_2/kg CFRC which comes from burning natural gas used in process heating. Therefore, to reduce CO_2 emission from CFRC the energy utilization should be reduced.

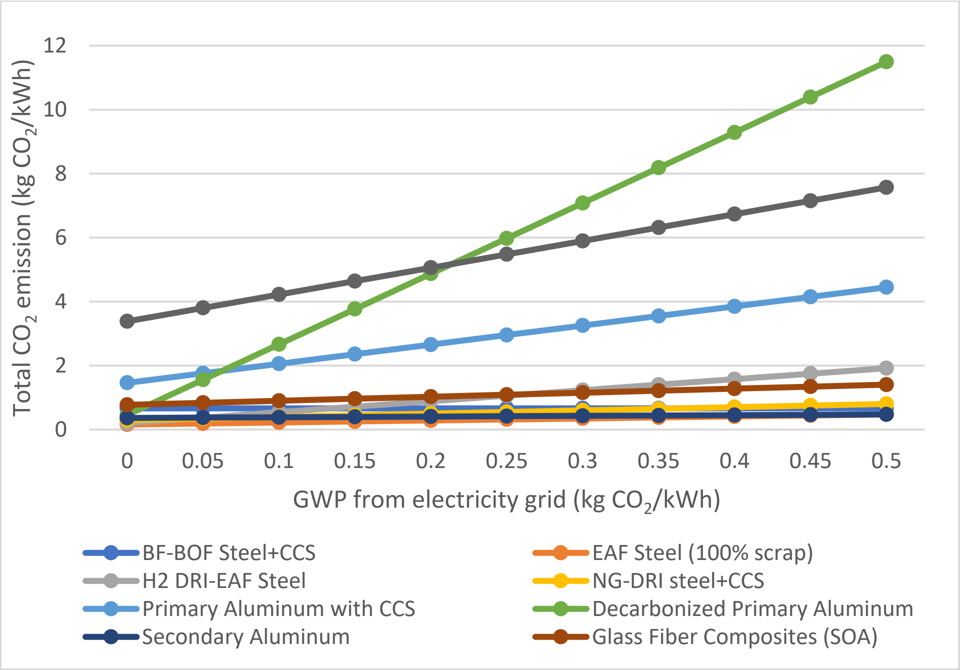

Figure 17 Dependence of GWP of electricity grid on total CO_2 emissions (Decarbonized pathways)

The dependence of GWP of electricity grid on total CO_2 emission from materials obtained through decarbonized pathway is shown in Figure 17. Even when the electricity grid is the cleanest, primary aluminum with CCS and CFRC emits a large amount of CO_2 compared to other pathways. This is due to the fact that both these processes utilize large amounts of thermal energy that comes from burning natural gas. Even GFRC is one such process that utilizes large amounts of energy that comes from burning natural gas.

As previously observed from Figure 16 carbon intensity of electricity grid has negligible effect on BF-BOF and NG-DRI steel making. As hydrogen making utilizes electric power, GWP of H_2-DRI steel making depends majorly on electricity grid. For H_2-DRI to be eco-friendly, the electricity grid utilized for hydrogen making should be clean. Other process emissions that show major dependence on carbon intensity from electricity are CFRC production, primary aluminum with CCS and decarbonized primary aluminum. To follow the decarbonized primary aluminum pathway, it is important to select the electricity grid with low GWP as this process is designed considering the clean energy factor.

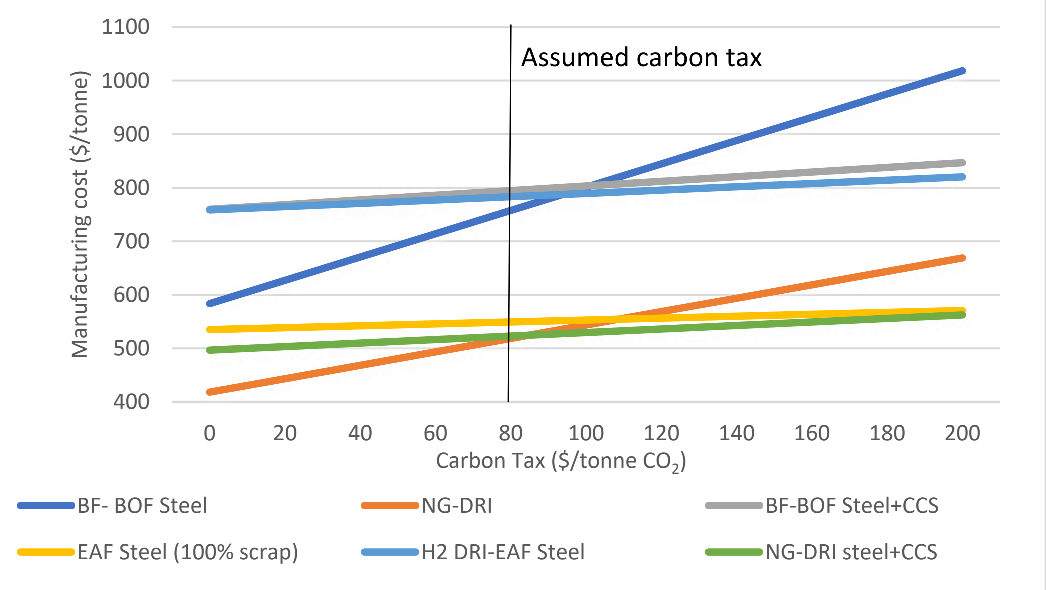

Figure 18 Variance of manufacturing cost with carbon tax for steel production through different pathways

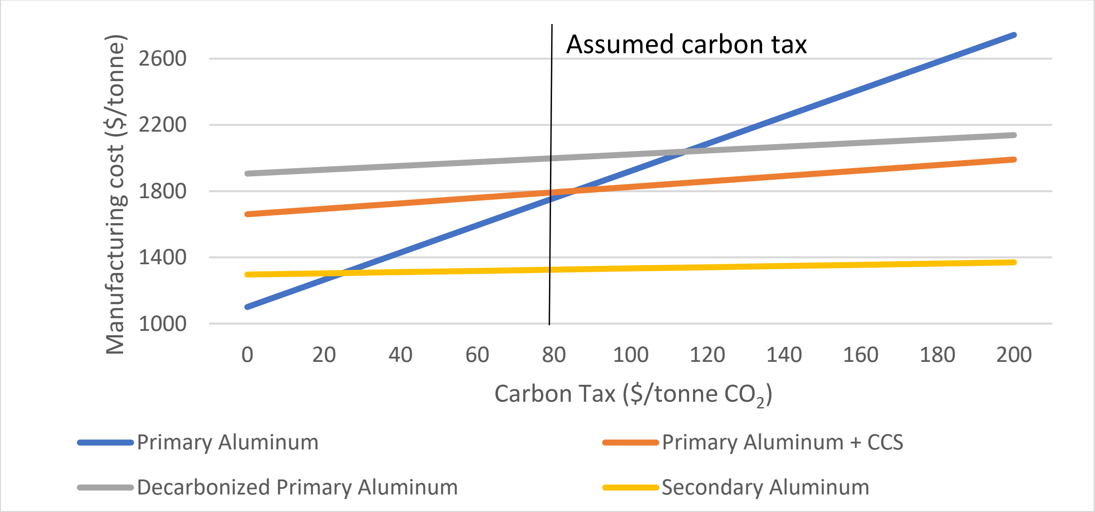

Figure 19 Variance of manufacturing cost with carbon tax for aluminum production through different pathway

Figure 18 and Figure 19 displays variance of manufacturing cost with carbon tax through different pathways for steel and aluminum production. It can be observed that the decarbonized pathways display negligible variation of production cost as carbon tax increases. For most of the processes in steel and aluminum production the breakeven price for applying new technologies and carbon tax lies between the range of \$80-\$100/ tonne of CO_2. When the carbon tax reaches \$200/ tonne CO_2 the production cost of steel may increase 90% and aluminum by 160%. But at any point manufacturing cost of steel is observed to be less than aluminum.

5. CONCLUSIONS

The conducted study analyzes traditional scenarios through current electricity grid and decarbonized scenarios through renewable electricity grid. Current electricity cost is assumed as \$0.034/kWh and renewable energy cost is considered as \$0.595/kWh [57]. The lowest emission of 0.18 t $CO_{2\text{-eq}}$ /t eq steel sheet is obtained through EAF and secondary aluminum making followed by 0.31 t $CO_{2\text{-eq}}$ /t eq steel sheet from H_2-DRI, if renewable electricity is energy source. Highest emission of 4.11 t $CO_{2\text{-eq}}$ /t eq steel sheet is through primary aluminum production, when natural gas is used for process heat and traditional electricity grid. Fiber composites are the most expensive to make and EAF steel is the cheapest.

It can be concluded that the cost of H_2-DRI depends on of cost of hydrogen. If the cost of hydrogen goes down to \$1/kg H_2 (\$4.5/kg H_2 assumed price), it can be the most economical and ecofriendly method for steel making. For aluminum making use of inert anode and use of renewable energy in the Bayer process can reduce CO_2 emission significantly but the final product can be costly. Secondary steel and aluminum are most economical and has least GWP, but it needs advanced scrap sorting technology to use as raw material in high end products.

Overall, it can be concluded that even with increasing carbon tax steel will always be the cheapest material followed by aluminum and fiber composites are most expensive. The GWP of above-mentioned material production substantially depends on the source of energy utilized. Therefore, it's important to use a cleaner grid to avoid carbon taxes.

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APPENDIX A

COST ESTIMATION TABLES FOR STEEL PRODUCTION PROCESSES

Blast Furnace / Basic Oxygen Furnace Steelmaking Costs

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Scrap Steel	0.148	t	283	$ 41.8	[70]	[71]
Iron Ore	1.509	t	107	$ 161.5	[70]	[72]
Coking + PCI Coal	0.86	t	145	$ 124.7	[70]	[73]
Industrial Gases	162	m^3	0.12	$ 19.4	[70]	[70]
Ferroalloys	0.009	t	1600	$ 14.4	[70]	[70]
Fluxes	0.46	t	50	$ 23.0	[70]	[70]
Refractories	0.004	t	1300	$ 5.2	[70]	[70]
Other Costs	1	count	20	$ 20.0	[70]	[70]
Natural Gas	0	kWh_{th}	0.011	$ -	[70]	[58]
Electricity - Reheat/Rolling	105	kWh	0	$ -	[74]	
Electricity - Steelmaking	295	kWh	0	$ -	[74]	
Labor	1	count	25	$ 25.0		[75]
Capital Charges	1	count	148.5	$ 148.5		[74]
Carbon Emission Surcharge	2.17	tCO_2	80	$ 173.9	-	-
Total (including carbon tax)				$ 757.5		

Natural Gas DRI + EAF

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Iron Ore	1.4	t	107	$ 149.8	[76]	[72]
Natural Gas	262	Sm^3	0.136	$ 35.6	[76]	[58]
Other Costs	1	count	10.44	$ 10.4		[77]
Electricity - EAF	600	kWh	0.034	$ 20.4	-	[57]
Electricity - Hot Rolling	105	kWh	0.034	$ 3.6	[74]	[57]
Labor	1	count	27	$ 27.0		[77]
Capital Charges	1	count	171.6	$ 171.6		[77]

Carbon Emission Surcharge	*1.25*	*tCO2*	*80*	$ 100.2	-	-
Total (including carbon tax)				$ 518.6		

Blast Furnace / Basic Oxygen Furnace Steelmaking w/ Carbon Capture Costs						
Item	Quantity	Unit	$/Unit	Total Cost ($/t)	Quantity Reference	Cost Reference
Scrap Steel	0.148	t	283	$ 41.8	[70]	[71]
Iron Ore	1.509	t	107	$ 161.5	[70]	[72]
Coal	0.86	t	145	$ 124.7	[70]	[73]
Industrial Gases	162	m^3	.12	$ 19.4	[70]	[70]
Ferroalloys	0.009	t	1600	$ 14.4	[70]	[70]
Fluxes	0.46	t	50	$ 23.0	[70]	[70]
Refractories	0.004	t	1300	$ .2	[70]	[70]
Other Costs	1	count	20	$ 20.0	[70]	[70]
Thermal Cost	0	kWhth	0.011	$ -	[70]	[58]
Electricity	468	kWh	0.0595	$ 27.9	[74]	
Electricity - Hot Rolling	105	kWh	0.0595	$ 6.2	[74]	
Labor	1	count	25.0	$ 25.0		[75]
Capital Charges	1	count	148.5	$ 148.5		[74]
CCS (all charges)	1.42	t	100	$ 142.1	-	-
Carbon Emission Surcharge	0.4	tCO2	80	$ 34.8	-	-
Total (BF-BOF + Carbon Capture)				$ 794.5		

Electric Arc Furnace Steelmaking Costs						
Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Scrap Steel	1.1	t	283	$ 310.9	[70]	[71]

Ferroalloys	0.021	t	1600	$ 33.6	[70]	[70]
Electrodes	2	kg	4	$ 8.0	[70]	[73]
Other Costs	1	count	31	$ 31.0	[70]	[70]
Electricity - EAF	421	kWh	0.034	$ 14.3	-	[57]
Electricity - Hot Rolling	105	kWh	0.034	$ 3.6	[74]	[57]
Labor	1	count	15	$ 15.0		[70]
Capital Charges	1	count	105	$ 105		[74]
Carbon Emission Surcharge	*0.4*	*tCO_2*	*80*	$ 32.0		
Total (including carbon tax)				$ 553.7		

Natural Gas DRI + EAF + CCUS						
Item	Quantity	Unit	$/Unit	Total Cost ($/t)	Quantity Reference	Cost Reference
Iron Ore	1.4	t	107	$ 149.8	[76]	[72]
Natural Gas	262	m^3	0.136	$ 35.6	[76]	[58]
Other Costs	1	count	10.44	$ 10.4		[77]
Electricity	1000	kWh	0.0595	$ 59.5	-	[57]
Electricity - Hot Rolling	105	kWh	0.0595	$ 6.2	[74]	[57]
Capital Charges	1	count	171.6	$ 171.6		[77]
CCS (all charges)	0.64	count	100	$ 63.6	-	-
Carbon Emission Surcharge	*0.33*	*tCO_2*	*80*	$ 26.3	-	-
Total (including carbon tax)				$ 523.0		

Hydrogen DRI+EAF						
Item	Quantity	Unit	$/Unit	Total Cost ($/t)	Quantity Reference	Cost Reference

Iron Ore	1.4	t	107	$ 149.8	[76]	[72]
Natural Gas	50	Sm^3	0.136	$ 6.8	[76]	[58]
Hydrogen	79.4	kg	4.5	$ 357.2	[76]	-
Other Costs	1	count	10.44	$ 10.4		[77]
Electricity - EAF	494	kWh	0.0595	$ 29.4	-	[57]
Electricity - Hot Rolling	105	kWh	0.0595	$ 6.2	[74]	[57]
Labor	1	count	27	$ 27.0		[77]
Capital Charges	1	count	171.6	$ 171.6		[77]
Carbon Emission Surcharge	*0.31*	*tCO2*	*80*	$ 24.7	-	-
Total (including carbon tax)				$ 783.2		

COST ESTIMATION TABLES FOR ALUMINUM PRODUCTION PROCESSES

Primary Aluminum Costs						
Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Bauxite	5.1	t	52	$ 265.2	[78]	[79]
Limestone	0.06	t	35	$ 2.1	[78]	[80]
Caustic Soda	0.09	t	495	$ 44.6	[78]	[81]
Thermal energy	5450	kWh	0.011	$ 59.4	-	[58]
Carbon Anode	0.45	t	110	$ 49.5	[78]	[82]
Electricity	13394	kWh	0.034	$ 455.4	-	[57]
Labor	1	count	107.1	$ 107.1		[83]
Natural Gas - Sheet Prod.	524	kWh$_{th}$	0.011	$ 5.7	-	[58]
Electricity - Sheet Prod.	518	kWh	0.034	$ 17.6	-	[57]
Capital Charges	1	count	93.78	$ 93.8		[83]
Carbon Emission Surcharge	8.22	tCO2	80	$ 657.3	-	-

Total (including carbon tax)	$ 1,757.6

Secondary Aluminum Production Costs

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Scrap	1.2	MT	860	$ 1031.9	[84]	[85]
Natural Gas	1265	kWh$_{th}$	0.011	$ 13.8	-	
Electricity	222	kWh	0.0595	$ 13.2	-	[58]
Labor	1	count	107.1	$ 107.1		[83]
Natural Gas - Sheet Prod.	524	kWh$_{th}$	0.011	$ 5.7	-	[58]
Electricity - Sheet Prod.	518	kWh	0.0595	$ 30.8	-	[57]
Capital Charges	1	count	93.78	$ 93.8		[83]
Carbon Emission Surcharge	0.4	tCO2	80	$ 29.5	-	-
Total (including carbon tax)				$ 1,325.8		

Primary Aluminum making Costs, Decarbonized path

Item	Sizing Value	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Bauxite	5.1	t	52	$ 265.2	[78]	[79]
Limestone	0.06	t	35	$ 2.1	[78]	[80]
Caustic Soda	0.09	t	495	$ 44.6	[78]	[81]
Electricity - Thermal	5560	kWh	0.0595	$ 330.8	-	
Inert anodes	0.01	t	7374	$ 73.7	-	-
Electricity - Electrolysis	16000	kWh	0.0595	$ 952.0	[78]	

Labor	1	count	107.1	$ 107.1		[83]
Natural Gas - Sheet Prod.	524	kWh$_{th}$	0.011	$ 5.7	-	[58]
Electricity - Sheet Prod.	518	kWh	0.0595	$ 30.8	-	[57]
Capital Charges	1	count	93.78	$ 93.8		[83]
Carbon Emission Surcharge	1.16	tCO2	80	$ 93.0	-	-
Total (including carbon tax)				$ 1,998.8		

Inert Anode Cost

Item	Sizing Value	Unit	$/Unit	Total Cost ($/t)	Quantity Reference	Cost Reference
Fe_2O_3	0.483	t	$ 700	$ 338.1	[86]	[87]
NiO	0.517	t	$13,610	$ 7,036.4	[86]	[88]
Total				$ 7,374.5		

Primary Aluminum with CCU Making Costs

Item	Quantity	Unit	$/Unit	Total Cost ($/t)	Quantity Reference	Cost Reference
Bauxite	5.1	t	52	$ 265.2	[78]	[79]
Limestone	0.06	t	35	$ 2.1	[78]	[80]
Caustic Soda	0.09	t	495	$ 44.6	[78]	[81]
Thermal energy	5450	kWh	0.011	$ 59.4	-	
Carbon Anode	0.45	t	110	$ 49.5	-	-
Electricity	13394	kWh	0.0595	$ 796.9	[78]	
Labor	1	count	107.1	$ 107.1		[83]
Capital Charges	1	count	93.78	$ 93.8	-	[83]
Natural Gas - Sheet Prod.	524	kWh$_{th}$	0.011	$ 5.7	-	[58]
Electricity - Sheet Prod.	518	kWh	0.0595	$ 30.8		[57]
CCS (all charges)	1.5	count	137	$ 205.5	-	-
Carbon Emission Surcharge	1.7	tCO2	80	$ 132.1	-	-

Total (Aluminum Production + CCS)	$1,792.6

COST ESTIMATION TABLES FOR GLASS FIBER REINFORCED COMPOSITES

Glass Fiber Reinforced Composite

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Sand	0.178	MT	203	$36.13	[53]	[89]
Limestone	0.179	MT	35	$6.27	[53]	[80]
Kaolin	0.1485	MT	178.6	$26.52	[53]	[90]
Refined B_2O_3	0.028	MT	198.4	$5.56	[53]	[91]
Electricity	1760	kwh	0.034	$59.84	-	[57]
Natural gas	12390	kwh	0.011	$134.93	-	[58]
Epoxy resin	0.5	MT	3306.8	$1,653.40	[54]	[92]
Labor	1	count	2000	$2,000.00	-	-
Capital Charges	1	count	3000	$3,000.00	-	-
Carbon Emission Surcharge	*3.5*	MT_{CO_2}	*80*	$278.67	-	-
Total (including carbon tax)				$7201		

Glass Fiber Reinforced Composite, SOA

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Sand	0.178	MT	203	$36.13	[53]	[89]
Limestone	0.179	MT	35	$6.27	[53]	[80]
Kaolin	0.1485	MT	178.6	$26.52	[53]	[90]
Refined B_2O_3	0.028	MT	198.4	$5.56	[53]	[91]
Electricity	1018	kwh	0.0595	$60.57	[56]	[57]
Natural gas	2861	kwh	0.011	$134.93	[56]	[58]
Epoxy resin	0.5	MT	3306.8	$1,653.40	[54]	[92]
Labor	1	count	2000	$2,000.00	-	-

Capital Charges	1	count	3000	$ 3,000.00	-	-
Carbon Emission Surcharge	*3.5*	*MTCO2*	*80*	$ 278.67	-	-
Total (including carbon tax)				$ 6884		

COST ESTIMATION TABLES FOR CARBON FIBER REINFORCED COMPOSITES

Carbon Fiber Reinforced Composite

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Precursor (PAN)	0.735	MT	3348	$ 2,460.78	[93]	[93]
Electricity	10980.55	kwh	0.034	$ 373.34	-	[57]
Natural gas	16340.1	kwh	0.011	$ 177.94	-	[58]
Epoxy resin	0.65	MT	3306.8	$ 2,149.42	[69]	[92]
Labor	1	count	1173.7	$ 1,173.70		[94]
Shipping	1	count	93.9	$ 93.90		[94]
Capital Charges	1	count	4695	$ 4,695.00		[94]
Carbon Emission Surcharge	*11.0*	*MTCO2*	*80*	$ 876.57		
Total (including carbon tax)				$ 12,000.65		

Carbon Fiber Reinforced Composite, SOA

Item	Quantity	Unit	$/Unit	Total Cost ($/MT)	Quantity Reference	Cost Reference
Precursor (PAN)	0.735	MT	3348	$2,460.78	[93]	[93]
Electricity	7050	kwh	0.0595	$419.48	[55]	[57]
Natural gas	12749	kwh	0.011	$138.84	[55]	[58]
Epoxy resin	0.65	MT	3306.8	$2,149.42	[69]	[92]

Labor	1	count	1173.7	$1,173.70	[94]
Shipping	1	count	93.9	$93.90	[94]
Capital Charges	1	count	4695	$4,695.00	[94]
Carbon Emission Surcharge	*3.7*	MT_{CO_2}	*80*	$292.00	
Total (including carbon tax)				$11,423.11	

Note: ‘-‘ represents assumed values or extracted values from GWP calculations shown in appendix B.

APPENDIX B

CALCULATION OF GLOBAL WARMING POTENTIAL FOR DIFFERENT PATHWAYS

BF-BOF			
CO_2 Emissions Breakdown	Reference Steel Mill without CO_2 Capture, Traditional Electricity-Emissions (kg/kg steel sheet)	Steel Mill with Post-Combustion Capture, Traditional Electricity-Emissions (kg/kg steel sheet)	References
Mining	0.01	0.01	[95]
Flue Gas — Coke Oven	0.191	0.019	
Flare — Coke Oven	0.003	0.003	
Flue Gas — Sinter Plant (incl. CO emissions as CO_2)	0.289	0.029	[44]
Flue Gas — Hot Stoves	0.415	0.042	
Diffuse Emissions - HM Desulphrisation & Ancillaries	0.008	0.008	
Flare — Blast Furnace	0.020	0.020	
Flare (incl. losses) - BOF, Diffuse Emissions from SM	0.051	0.051	
Diffuse Enlissions — Continuous Casting	0.001	0.001	
Flue Gas — Reheating Furnaces	0.058	0.058	
Diffse Emissions — Hot Rolling Mills	0.080	0.080	
Flue Gas — Lime Plant	0.072	0.007	
Flue Gas — Power Plant	0.982	0.227	
Flue Gas — Steam Generation Plant	N/A	0.103	
Ancillaries transport fuel emissions (trucks and rails)	0.004	0.004	
Total Emissions	2.186	0.663	
Electricity used (kWh/ kg steel sheet)	0.400	0.573	
Renewable electricity	2.045	0.460	

EAF			
Processes	Traditional electricity (kg CO_2/ kg steel sheet)	Renewable electricity (kg CO_2/ kg steel sheet)	References
Scrap processing	0.04	0.04	[96]
Transportation	0.02	0.02	[96]
Direct emission	0.04	0.04	[18]
Emission from electricity (indirect emission)	0.16	0.01	[97]
Reheating Furnace	0.06	0.06	[44]
Sheet Rolling	0.08	0.01	[96]
Total	0.40	0.18	

NG-DRI					
Processes	Energy input (kWh/kg steel sheet)	Direct emissions (kg CO2 / kg steel sheet)	Traditional electricity grid (kg CO_2/ kg steel sheet)	Renewable electricity grid (kg CO_2/ kg steel sheet)	Reference
Mining			0.01	0.01	[95]
Transportation			0.02	0.02	[96]
Pelletizing	0.02		0.06	0.06	[98]
MIDREX	0.12	0.71	0.75	0.71	[22]
EAF			0.27	0.06	
Reheating furnace			0.06	0.06	[44]
Hot rolling			0.08	0.01	[96]
Total			1.25	0.92	

NG-DRI +CC					
Processes	Energy input (kWh/kg steel sheet)	Direct emissions (kg CO2 / kg steel sheet)	Traditional electricity grid (kg CO_2/ kg steel sheet)	Renewable electricity grid (kg CO_2/ kg steel sheet)	Reference
Mining			0.01	0.01	[95]
Transportation			0.02	0.02	[96]
Pelletizing	0.02		0.06	0.06	[98]
MIDREX	0.12	0.71	0.75	0.71	[22]
EAF			0.27	0.06	
Reheating furnace			0.06	0.06	[44]
Hot-rolling			0.08	0.01	[96]
CO_2 captured		0.64			
CO_2 from carbon capture unit			0.07	0.04	
Total			0.68	0.33	

H_2-DRI				
Processes	Energy input (kWh/kg steel sheet)	Traditional electricity grid (kg CO_2/ kg steel sheet)	Renewable electricity grid (kg CO_2/ kg steel sheet)	Reference
Mining		0.01	0.01	[95]
Transportation		0.02	0.02	[96]
Pelletizing		0.06	0.06	[98]
Hydrogen production	2.63	1.01	0.08	[77]
Shaft reactor	0.32	0.12	0.01	
EAF		0.27	0.06	

Reheating furnace		0.06	0.06	[44]
Hot rolling		0.08	0.01	[96]
Total	2.96	1.64	0.31	

Primary Aluminum Production				
Processes	Energy input (kWh/kg Al sheet)	Traditional electricity grid-USA (kg CO_2/ kg Al sheet)	Renewable electricity grid-USA (kg CO_2/ kg Al sheet)	Reference
Bauxite mining	0.32	0.10	0.10	[46]
Bayer process (heat)	5.17	1.04	1.04	[47]
Bayer process (electricity)	0.39	0.15	0.01	[47]
Anode production (heat)	0.28	0.06	0.06	[47]
Anode production (electricity)	0.06	0.02	0.002	[47]
Electrolysis (Direct Emission)		1.53	1.53	[32]
Electricity for electrolysis	13.00	5.01	0.42	[47]
Sheet production (heat)	0.524	0.11	0.11	[48]
Sheet production (electricity)	0.518	0.20	0.02	[48]
Total	20.27	8.22	3.28	

Primary Aluminum + Carbon Capture				
Processes	Energy input (kWh/kg Al sheet)	Traditional electricity grid (kg CO_2/ kg Al sheet)	Renewable electricity grid (kg CO_2/ kg Al sheet)	Reference
Bauxite mining	0.32	0.10	0.10	[46]
Bayer process (heat)	5.17	1.04	1.04	[47]
Bayer process (electricity)	0.39	0.15	0.01	[47]
Anode production (heat)	0.28	0.06	0.06	[47]
Anode production (electricity)	0.06	0.02	0.002	[47]
Electrolysis (Direct Emission)		1.53	1.53	[32]
Electricity for electrolysis	13.00	5.01	0.16	[47]
Sheet production (heat)	0.524	0.11	0.11	[48]
Sheet production (electricity)	0.518	0.20	0.02	[48]
CO_2 avoided		2.32	2.32	
CO_2 from carbon capture unit	0.417	0.25	0.14	
Total	20.263	6.84	1.65	

Decarbonized Aluminum (Primary)				
Processes	Energy input (kWh/kg Al sheet)	Traditional electricity grid (kg CO_2/ kg Al sheet)	Renewable electricity grid (kg CO_2/ kg Al sheet)	Reference

Bauxite mining	0.32	0.10	0.10	[46]
Bayer process (heat)	5.17	1.99	0.17	[47]
Bayer process (electricity)	0.39	0.15	0.01	[47]
Anode production		0.25	0.25	[99]
Electrolysis (Direct Emission)		0.00	0.000	
Electricity for electrolysis	16.00	6.16	0.51	[51]
Sheet production (heat)	0.52	0.11	0.11	[48]
Sheet production (electricity)	0.518	0.20	0.02	[48]
Total	22.923	8.96	1.16	

Secondary Aluminum Production					
Processes	Energy input (kWh/kg Al sheet)	Source of energy	Traditional electricity grid- USA (kg CO_2/ kg Al sheet)	Renewable electricity grid- USA (kg CO_2/ kg Al sheet)	References
Scrap preparation	0.24	Natural gas	0.05	0.05	[48]
	0.11	Electricity	0.04	0.00	
Ingot Casting	1.02	Natural gas	0.21	0.21	
	0.11	Electricity	0.04	0.00	
Sheet production	0.524	Natural gas	0.11	0.11	
	0.518	Electricity	0.20	0.02	
Total	2.53		0.45	0.37	

Glass Fiber Production, Traditional electricity				
Processes	Energy (kWh/kg GF)	Source	kg CO_2 / kg	Reference
Batch preparation	0.36	Electricity	0.14	[53]
Melting and Refining	2.60	Natural gas	0.53	
		Direct emission	0.17	
Forming	1.21	Electricity	0.47	
Post forming	1.07	Natural gas	0.22	
Total	5.23		1.52	
Resin Production	21.11	Natural gas	4.70	[54]
Glass Fiber reinforced composite		GF: resin=50:50		
Fabrication using SMC	0.97	Electricity	0.37	[56]
Materials used	13.17		3.11	
Total	14.15		3.48	

Glass Fiber Production State of Art, Renewable Electricity							
	Energy(kWh/kg GF)	Natural Gas %	Electric%	CO_2 through NG (kg CO_2/ kg)	CO_2 through electricity (kg CO_2/ kg)	Total CO_2 (kg CO_2 / kg)	Reference
Batching	0.05	0.00	100.00	0.00	0.00	0.00	[56]
Melting	0.43	100.00	0.00	0.09	0.00	0.09	
Direct emissiom				0.00	0.00	0.17	
Fiberization	0.13	74.00	26.00	0.02	0.00	0.02	
Finishing	0.14	95.00	5.00	0.03	0.00	0.03	
Total	0.75					0.30	
Resin production	6.70	91.90	8.10	1.24	0.02	1.26	
Glass Fiber reinforced composite							
Fabrication using SMC	0.97					0.03	
Materials used						0.78	
Total	4.69					0.81	

Carbon fiber production, Traditional electricity							
Carbon fiber production sub-Process	Energy(kWh/kg CF)	Natural Gas %	Electric%	CO_2 through NG (kg CO_2/ kg)	CO_2 through electricity (kg CO_2/ kg)	Total CO_2(kg CO2/kg)	Reference
Polymerization	14.00	84.70	15.30	2.39	0.82	3.22	[55]
Spinning	19.02	95.70	4.30	3.68	0.31	3.99	
Oxidation/Carbonization	38.31	43.40	56.60	3.36	8.35	11.71	
Finishing	6.73	0.00	100.00	0.00	2.59	2.59	
Total	78.05			9.43	12.08	21.51	

Resin	21.11		4.7	[54]
Carbon Fiber reinforced composite		resin:reinforcement= 65:35		
Fabrication using SMC	0.97		0.37	[55]
Materials used			10.58	
Total	42.01		10.96	

Carbon fiber production, State of art, Renewable electricity							
Carbon fiber production sub-Process	Energy(kWh/kg CF)	Natural Gas %	Electric%	CO_2 through NG (kg CO_2/ kg)	CO_2 through electricity (kg CO_2/ kg)	Total CO_2	Reference
Polymerization	12.64	84.70	15.30	2.16	0.06	2.22	[55]
Spinning	17.22	95.70	4.30	3.33	0.02	3.35	
Oxidation/Carbonization	21.29	43.40	56.60	1.87	0.39	2.25	
Finishing	5.42	0.00	100.00	0.00	0.17	0.17	
Total	56.57			7.36	0.64	8.00	
Resin production	6.70	91.90	8.10	1.24	0.02	1.26	
Carbon Fiber reinforced composite		resin:reinforcement= 65:35					
Fabrication using SMC	0.97					0.03	
Materials used	24.15					3.62	
Total	25.12					3.65	