Competition for forest resources: The role of biomass and biofuels in decarbonizing the Swedish industry sector

Ritesh Pawar
Percy Braganza

DEPARTMENT OF SPACE, EARTH, AND ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
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www.chalmers.se

Abstract

This report explores different pathways of technological developments in the steel and cement industries and on how the integration of biofuel and biomass can contribute to decarbonizing the Swedish industrial sector. The study employs a combination of qualitative review and quantitative analytical techniques, including scenarios and stylized models. The results demonstrate how different strategic decisions with regards to production processes, choice of energy carriers and possible implementation of carbon capture, may have significant long-term effects on energy usage and CO_2 emissions. Based on the findings, it can be concluded that the available biomass in Sweden is sufficient to meet the needs of the cement and steel industries if alternative paths are chosen but the technical shift will likely result in a significant increase overall electricity demand.

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List of acronyms and abbreviations

TGR	Top gas recycling
TGR-BF	Top gas recycling blast furnace
DRI	Direct Reduced Iron
ISI	Iron and Steel Industry
BOF	Basic Oxygen Furnace
BF	Blast Furnace
CCS	Carbon capture and storage
HDRI	Hydrogen Direct Reduced Iron
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
I-EAF	Biomass based electric arc furnace
EAF	Electric Arc Furnace
CCU	Carbon capture and utilization
CO_2	Carbon dioxide
GHG	Greenhouse gas
SNG	Synthetic Natural Gas
H_2	Hydrogen
IEA	International Energy Agency
IPCC	International Panel on Climate Change
kW	Kilowatt
Mt	Megaton
Mt/yr	Megaton per year
TW	Terawatt
TWh	Terawatt hour
CAPEX	Capital Expense
$MtCO_2e$/year	Megaton Carbon dioxide per year
ASU	Air separation unit
CPU	Carbon dioxide purification unit

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1. INTRODUCTION

1.1.Background

The 2015 Paris climate agreement aims to put the world on a pathway that restricts global warming to well below 2°C above pre-industrial levels. The Paris Agreement is the universal, legally binding international treaty on climate change, and till date a total of 196 countries have agreed to combat climate change and take the necessary actions for creating a sustainable low carbon future. Additionally, the goal is also to build resilience among communities and businesses so that there will be more investments in more clean energy if the ambitious goal is to be achieved. The global community is now acting in unison and agreeing to do so for decades to come, various industries have collaborated to tackle climate change. (Wei, et al., 2016)

In June 2017, the Swedish Parliament adopted a proposal on a national climate policy framework for Sweden. The climate policy framework is the most important climate reform in Sweden's history which focuses on setting long-term conditions for the business sector and society. The climate act is a key component of Sweden's efforts to live up to the Paris Agreement i.e., by 2045, Sweden is to have zero net emissions of greenhouse gases (GHGs). into the atmosphere. (Government offices of Sweden, 2021). In 2017, industries accounted for approximately 27 percent of total GHG emissions in Sweden this is the equivalent of 17.2 Mt CO_2. The Iron and steel, cement, refineries, and chemicals are the four industrial sectors in Sweden that emit the most GHGs and each of these industries have numerous options for being climate neutral. While significant advancements have been made with adoption of transformative changes in the process of production and the use of different raw material. (Klugman, 2019) considerable efforts still remain for industry to align with national climate targets. This report focuses on steel and cement production as these industries account for 54 % of the total industrial GHG emissions in Sweden. Each sectors have several possible pathways to become climate neutral which are described and discussed in the report.

The cement industry accounts for 18 % of the industrial GHG emissions in Sweden. Replacing fossil fuels in the cement production has the potential to reduce the CO_2 emissions by approximately 30 %. Fossil fuels could be replaced by either biofuels or electricity. However, the process related GHG emissions which account for 70 % are not removed by this measure. The process related emissions mainly originate from clinker production and could be reduced by substituting clinker with other materials. However, even with a combination of clinker substitution and fuel switch, 30-60 % of the CO_2 emissions remain. Therefore, CCS is inevitable in order to produce a climate neutral cement. (Toktarova, 25 May 2020)

1.2.Aim

Sweden has committed in reducing GHG emissions to net-zero by 2045 and majority of the studies suggest that there is significant amount of potential for further reduction in the CO_2 emissions from the heavy industries without major substantial changes in the conventional manufacturing processes (Klugman et al, 2019;Toktarova et al , 2020).

The aim of this thesis is to assess how biomass and biofuels in combination with other technological options can contribute towards decarbonizing the Swedish industrial sector. The focus will be on heavy industries like iron and steel and cement industries. Primarily the focus will be on reviewing the available technologies and assessing their potential in reducing the CO_2 emissions using suitable pathways.

The thesis explores how a switch from fossil fuels to biogas/biofuels affects these industries and how much biomass/biofuels can be implemented in these industries. This was carried out through a detailed study of the current steel and cement production with describing the technologies used, raw materials and energy use in detail. Furthermore, alternative pathways aimed at reducing CO_2 emissions were analysed including scenarios with increased biomass/biofuel use and alternative technological developments such as Carbon Capture and Storage (CCS). In a carbon constrained world as all sectors of the economy seek to lower emission – competition for energy carriers with a low climate impact (biomass/biofuels, green electricity, and hydrogen) will grow – thus how the use of, in this case biomass and biofuels, are managed and how interlinkages and interactions across sectors are handled will be key to the overall outcome.

1.3 Technological overview

This section presents the theoretical background regarding the different technological options available in the steel and cement industry. This section also describes the different pathways used for analysis of the potential CO_2 emission reduction and biomass implementation.

1.3.1 Iron and Steel Industry

The iron and steel industry plays a major role and is a centre pillar for the global growth and the economy. According to IEA Energy perspective (IEA, 2020), the iron and steel industry accounted for 22% of industrial energy use and 8% of total final energy use in 2019 with energy typically making up 10- 25% of total production costs. The global steel production has increased sharply in recent years, with an average growth rate per annum of 3% for the year 2015-2020 for million tonnes of crude steel production with coal being the main source of that energy along with electricity and natural gas (World Steel Association, 2021). Steel manufacturing is one of the largest carbon-consuming and carbon emitting sectors. Steel production has a high CO_2 intensity, with each ton of crude steel resulting in approximately 1.4 t of direct CO_2 emissions on average, or 2.0 t when indirect emissions from imported electricity and heat generation are included (Perspectives, 2020)

Swedish steel industry has an annual steel production of 4.4 million tons for the year 2020 with special steels that represent a high share of the total production volume. Most of the steel products are exported with a value of 53 billion SEK (Swedish Krona). There are three integrated iron ore production plants, two integrated steel plants via the BF-BOF route, one sponge iron plant and thirteen scrap-based steel plants via electric arc furnace (EAF) route and 15 finishing plants (Jernkontoret, n.d.).The total fossil energy demand for ISI plants collectively is 20.6 TWh – fuel oils (3%), gas (13%), coal (84%). Globally, the most common primary production pathway is the blast furnace-basic oxygen furnace (BF-BOF) route, which accounts for around 70% of global steel production and around 90% of primary production. (Perspectives, 2020)

The principal inputs to steelmaking today are iron ore, energy (mainly coal, natural gas, and electricity), lime fluxes and steel scrap. The iron and steelmaking process can be classified as "primary" and "secondary" steel production. The "primary" steelmaking refers to production with iron ore as the main source of metallic input, whereas "secondary" production is purely based on scrap. The main difference between primary and secondary is that primary uses both metallic inputs, but the secondary is mainly based on scrap. Once the scrap has been collected and sorted, the secondary production route primarily requires electricity to melt the steel in an electric furnace, often in combination with a small amount of natural gas or coal to form a protective slag foam. The primary production pathway is more complex than the secondary route, involving multiple different process arrangements (Perspectives, 2020).

The steelmaking process can be generally divided into different routes blast furnace/basic oxygen furnace, direct reduction/electric arc furnace using smelting reduction/basic oxygen fitness and melting of scrap using electric arc furnace. The Figure 1 shows the different steel production routes from raw materials to crude steel production. The BF/BOF route is considered the most important route as 70% of the world's steel production is produced using this route and the rest using EAF route. Due to the recent technological advancements research is being done on using hydrogen as a reducing agent for production of steel. As the aim of the thesis is implementing biomass in the steel production the different production methods are described in detail below.

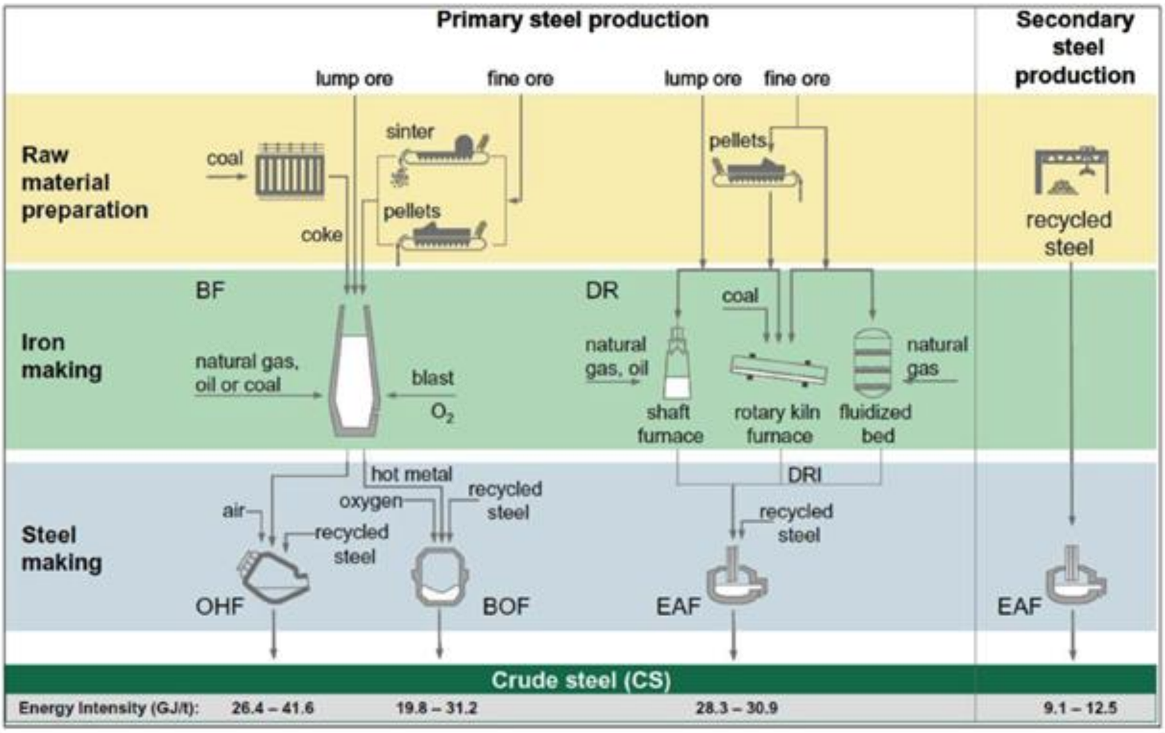

Figure 1- Steel production routes *(Mousa E., (2016))*

1. Blast Furnace (BF)/Basic Oxygen Furnace (BOF)

For primary steel production high quality iron ore is required, which is extracted from the earth's crust which is mined and then shipped around the world to steelworks works. The iron ore is then blended with a favourable mix which is later combined with coke and heated to produce the iron rich material called sintering. Carbon is required for the blast furnace and is supplied in the form of coke. To make coke coal is heated in an oven and the volatile by products are removed which leaves carbon. Gas produced in this process is used as a fuel whilst other by-products such as tar and sulphur are extracted and refined. These raw material iron ore and coke meet each other at the blast furnace where they are fed into the top of the furnace along with some limestone. Then hot air blast is injected through nozzles called tuveyrs in the base of the furnace, this blast raises the temperature in the furnace to white hot intensity around 2200 degrees centigrade. This very high temperature is needed for the chemical reduction and melting of the iron ore to form a pool of molten iron in the lower part of the furnace. Just above the molten pool in the furnace the limestone combines with the impurities to form a liquid which floats on top of the molten iron this is known as slag. The molten iron is tapped from the furnace and the slag is skimmed off and taken away for use in other industries such as road building or cement manufacturing. The molten iron we get from a blast furnace or hot metal isn't pure iron and contains the elements carbon, sulphur, phosphorus, manganese, and silicon to make steel these elements must be removed or reduced, and other elements are added depending on the type of steel being made. One of most important alloying element in steel is the carbon content and it can be present up to 2% (although most welded steels have less than 0.5%). Increasing carbon content increases hardness and strength and improves hardenability. But carbon also increases brittleness and reduces weldability because of its tendency to form martensite (Capudean, n.d.) With a carbon content of about 4% steel very brittle and unsuitable for rolling or forging. In the next step first the scrap steel is put into the vessel and then the hot metal is added which may have been pre-treated to remove elements such as sulphur alarms then close high purity oxygen onto the hot metal this combines with impurities and this oxidation produces heat, the temperature is controlled by the quantity of scrap steel and also by the addition of iron ore as a coolant this creates carbon monoxide gas which can be collected cleaned and used as a fuel. (Rainer Remus, 2010)

2. Electrical Arc Furnace (EAF)

The other main method of making steel is by means of the electric arc furnace or EAF, this process uses mainly cold steel scrap as raw material. The furnace is filled with recycled steel scrap. The roof is then swung into place and three graphite electrodes are loaded into the furnace. A powerful electric current is then passed through the furnace due to this an arc is created and the heat generated melts the steel scrap. Oxygen is blown into the melt as a result impurity in the metal combines to form a slag. The steel is sampled and analysed and once it reaches its correct temperature and composition it is topped off. At this stage final adjustments are made to meet the customer specifications. This can be made by adding alloying elements. These furnaces give very precise control over composition due to this there is increase in production by this route. Steel producing plants operating with the EAF's are closely linked to casting and rolling facilities are often referred to as mini mills. After EAF steelmaking process, the steel is further refined and designed to improve the composition and of ensure that the steel meets exact customer specifications. (Madias, 2013)

3. Hydrogen direct reduced iron (HDRI)

Traditionally the steel has been made by blast furnaces for the past thousands of years, the blast furnace process uses coal and coke which main carbon dioxide emitter. So, research and development are being made to employ a method known as Hydrogen direct reduction. This involves the use of iron ore pellets manufactured without fossil fuel and green hydrogen (produced through electrolysis with electricity from renewable sources) for fossil free steelmaking. This process emits ordinary water instead of CO_2. The basic idea is that in electrolyser which powered by renewables replaces the coke that would normally be added to the iron oxide to reduce it. The hydrogen reacts with iron oxide at the relatively low temperature of about 800 degrees Celsius to make what is known as sponge iron. Hydrogen direct reduction is no longer carbon dioxide intensive as its by-product is simply water. The sponge iron now does not need to go through a blast furnace but can be charged straight into an electric arc furnace along with recycled scrap iron along with some carbon to make the iron into steel. (SSAB, 2016)

4. Top gas recycling blast furnace (TGRF)

The top gas recycling blast furnace (TGR-BF) replaces a conventional blast furnace to reduce CO_2 emissions from the steelmaking process. The main concept of this technology is based on reducing the usage of fossils fuels with reusing the reducing agents CO and H_2, after removing the CO_2 from the top gas. TGR-BF process is a promising ironmaking process in future due to lower the energy requirements and high productivity, high PCI (pulverized coal injection) rate, low fuel rate, and low CO_2 emission (Steel 360, 2019). The basic principles of the steelmaking process with a top gas recycling blast furnace are the same as in the conventional BF-BOF route.

The blast furnace is modified in the TGR-BF configuration so that the coal is burned in the presence of pure oxygen rather than air or oxygen-enriched air. This results in a higher CO_2 content in the top gas and a lower nitrogen gas content. After the top gases (exhaust gases leaving the top of the BF) leaves the blast furnace, the CO_2 is removed (for use or storage), and the residual CO & H_2-rich gas (with less than 3% CO_2 content) is reinjected into the BF. Because the reinjected gas works as a reducing agent, less coke is required, resulting in lower energy consumption, cost, and emissions from coke ovens. The pig iron produced has the same properties as a traditional BF, and the steelmaking process is finished with a traditional BOF. This process also generates several energy-rich off-gases from the coke ovens and basic oxygen furnace, which may be utilized in the process or in on-site utilities. (Energy NL, 2020).

1.3.2 Cement industry

The Cement and concrete industry emit about 8% of worlds CO_2 emissions (Andrew, 2018) and this is why we need to try and reduce the CO_2missions as much as possible by integrating it with more and more clean energy and the best way to do it so far is to increase the use of Biomass in the cement making process and also integrate it with CCS technology. The most common cement used today is Portland Cement. Portland Cement is a finely ground powder which is manufactured by burning and grinding a mixture of limestone and clay or limestone and shale in a rotary kiln to form clinker which is then grinded. (Britannica, 2019)

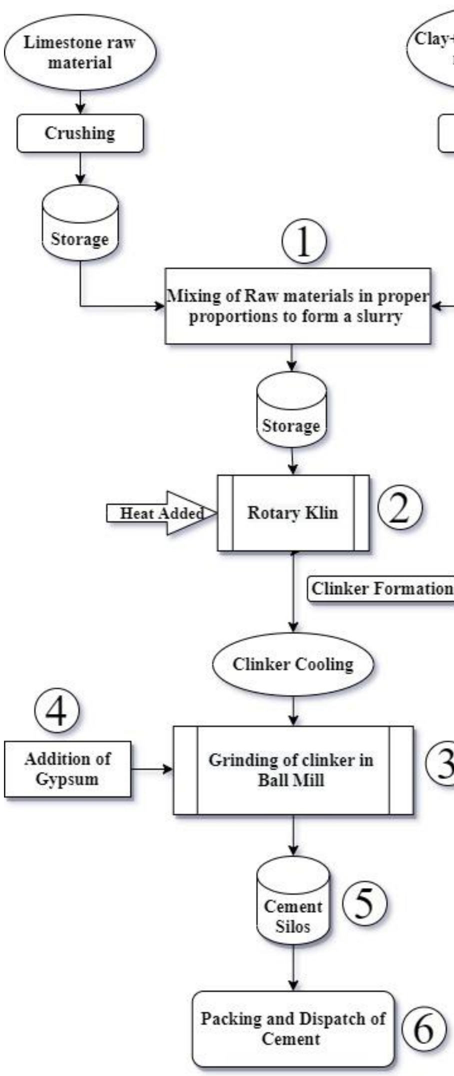

Figure 2- Overview of the cement manufacturing process

Figure 2 provides an overview of the cement making process thus to manufacture cement raw materials like limestone ($CaCO_3$), clay or shale is mixed (1) with raw materials containing quartz and iron oxides. This mixture is sent to the Rotary Kiln (2) where it is heated, at temperatures below 1300˚C limestone decomposes and we obtain lime (CaO) with release of

CO_2 and the clay mineral slowly starts decomposing too and lime, quartz and decomposed clay combine and results in Clinker's formation at around 1450 ˚C. After this the cement clinker is cooled and sent to a ball mill (3) where it is then crushed, grinded, dried, and then stored into cement silos (5) also a small amount of Gypsum (4) is added during the grinding process and thus finally from the silos the cement is packed and dispatched (6).

Cement factories can potentially use alternative fuels, including biomass and biomass residues, to heat their kilns. Thus, certain amount of fossil fuel can be substituted by biomass. Biomass along with alternate fossil fuels can substitute for approximately 70% of process heat requirements without the need for major capital investment. (Ida Karlsson, 2020)

1. Post Combustion capture technology

The post combustion technology and the oxy fuel combustion technology have the same function of capturing CO_2 emissions, except that the CO_2 is captured after it has been generated in the cement kiln in a post combustion technology. Post-combustion capture systems do not need major alterations to cement kilns and may be used in existing plants if appropriate physical space is available (Ida Karlsson, 2020).Without significantly altering the cement production process, a new cement factory may simply be retrofitted with post-combustion CO_2 collection technology. Only the energy management methods and the start-up and shut-down processes would be impacted. (Marta G. Plaza, 2020). Chemical absorption, CO_2 scrubbing in flue gases with solvents such as amine solutions, and CO_2 capture via a calcium looping cycle using lime-based sorbents are examples of the different technologies that can be used in a Post combustion process (Ida Karlsson, 2020).

2. Oxy-fuel Combustion

The difference between a conventional cement plant and an Oxy-fuel plant is that the entire cement manufacturing will remain the same except for some new components added and for the part where oxygen is used instead of air to make it easy for carbon capture and storage.

The oxyfuel process uses an oxidizer that mostly consists of oxygen combined with recycled CO_2 to generate a CO_2-rich flue gas that is relatively straightforward to purify with a CO_2 purification unit (CPU). The cement kiln process is altered when the oxyfuel process is integrated into a kiln system, as opposed to the MEA (Monoethanolamide) technology. The air separation unit (ASU) and a CPU require additional power, but an Organic Rankine Cycle (ORC) that generates electricity from waste heat can meet some of these requirements. (Stefania Osk Gardarsdottir, 2018)

The pulverized coal-fired boiler was the first to use oxygen-fuel combustion technology. However, the economics of an oxy-fuel pulverized-coal boiler was poor due to excessive power consumption while using oxygen-rich combustion. The circulating fluid bed boiler became the focal point of oxy-fuel combustion technology. (Wang, 2018)

3. Electrification

In Electrification process the energy source which is conventional fuels is replaced by fossil-free electricity it can also help reduce emissions by using low-emissions electricity and by facilitating the capture of process CO_2 emissions (IEA, 2020) In the Rotary kilns heat transfers by use of plasma generators or electrical resistance elements. By this CO_2 from fuel usage is reduced and higher concentrations of CO2 in flue gas streams from the processes are obtained, which can be captured by CCS. (Somers, 2020). This technology will evaluate the products and optimize them with secondary cementitious materials (SCM) for end use applications (Markus Broström, 2020). The most feasible way of producing Cement by electrification and replacing fossil-fuels can be achieved if the electricity comes from a renewable energy source, such as solar, wind or hydro (Energy F. C., 2020).

1.4 Biomass and Biofuels – opportunities and challenges

Biomass is renewable organic material that comes from plants and animals. It is, if produced sustainably, a renewable source of energy that can be used to generate electricity or other sources of power. (ReEnergy, 2011) . Biomass has the potential to become one of the world's largest primary energy sources over the next century, and modernized bioenergy systems are seen as key contributors to future renewable energy systems (Berndes, 2003).

Biofuel is basically a fuel that is derived from biomass. And unlike fossil fuels a green energy source since such feedstock content can be easily replenished. Biofuel is cost-effective and environmentally friendly alternative to petroleum and other fossil fuels, especially considering increasing petroleum prices and concern about fossil fuels GHG emissions. (Lehman, 2020).

1.4.1 Opportunities

There are concerns about the use of woody biomass for renewable energy production, with some associating it with forest overexploitation, even permanent deforestation, and “tree burning,” but in fact, forest bioenergy is an integral part of the forest industry, which reacts to bioenergy demand by developing forest management approaches. and industrial processes to produce fuels, heat, and electricity (Bioenergy, Use of woody biomass for energy, 2021) along with a range of forest products such as construction wood, paper biomaterials, fuels and chemicals that can contribute to climate change mitigation by replacing GHG intensive products such as cement, steel, and petroleum-based plastics and chemicals, as well as fossil fuels (Bioenergy, The use of forest biomass for climate change mitigation: dispelling some misconceptions, 2021). Now a days Combustion is the most frequent means of converting woody biomass into energy, particularly in the form of heat and/or power. This can conjure the vision of “burning trees and forests” in the mind of the common reader and even scientists that are unfamiliar with on-the-ground forestry, however the reality is very different! It is now widely acknowledged that any harvesting of biomass whether for bioenergy, building material, paper, or other purposes must take place within sustainable boundaries and that wood production and use is part of the biogenic carbon cycle. This entails management and harvesting concepts that protect against overharvesting while also preserving ecological health and cultural and recreational values. Also, certain ecological forest management systems are used on hundreds of millions of hectares of woodland around the world, and they have specific criteria for preserving habitats and biodiversity. In their national or provincial forestry laws, several countries have followed common forest management concepts. Sustainable bioenergy allows for the rapid replacement of coal, natural gas, or petroleum fuels. As a result, it has the potential to play a critical role in assisting energy market transition to achieve carbon neutrality also when it is combined with carbon capture and storage of released CO_2, it can remove CO_2 from the environment. It can also support the expansion of seasonal or intermittent renewables such as solar or wind energy by providing balancing power and the wood used for bioenergy is not high-quality lumber, but typically comprises thinning's, low-quality wood, salvage wood, harvest logging residues, processing residues or wood waste that cannot be used in sawmills or pulp and paper production. And increased demand for bioenergy and other forest products, along with strong consumer conditions for sustainable forestry practices, will potentially incentivize reforestation and better forest management. It will also minimize the likelihood of carbon stock losses due to wildfires and disease/insect outbreaks, all of which are becoming more common because of climate change. (Bioenergy, Use of woody biomass for energy, 2021). Also, some bioenergy's environmental drawbacks can be addressed by having a more sustainable forest management and by careful selection of biomass we gather for fuel and how we harvest it, research and technological advancements, as well as policy development all these can assist in making future bioenergy investments more ecologically friendly. (EnergySage, 2019)

1.4.2 Challenges

The global demand for biomass is growing, but the climate change, environmental pressures, and large-scale extinction of animal and plant biodiversity are disrupting biomass supply. The aim is to learn more about whether woody biomass for energy can be grown, processed, and used in a safe and effective manner to maximize GHG emissions reductions while maintaining ecosystem services and all without causing deforestation, degradation of habitats or loss of biodiversity. (Camia A., 2021). But for decades, manufacturers of paper and wood products have provided electricity and heat as by-products from their process wastes. Thus, due to this additional harvesting of timber would not be required. However, in recent years, there has been a misplaced push to cut down whole trees or divert vast amounts of stem wood for bioenergy, releasing carbon that would otherwise remain bottled up in forests. As a result of this additional wood production, there is a significant rise in carbon emissions creating a "carbon debt" that grows over time as more trees are cut for continued bioenergy use. Regrowing of trees and displacement of fossil fuels may eventually pay off this carbon debt, but regrowth takes time. (Von der Leyen, 2021).

European Academics Science Advisory Council (EASAC) scientists have been researching the answer to the fundamental, question "whether and, if so when, can woody biomass from forests contribute to climate change mitigation". They classify different sources of bioenergy feedstock according to the length of time before they "are likely to achieve carbon emission savings compared to fossil fuels". The only scenario that has short-term carbon impacts is burning fine woody debris from coniferous forests. Also, the EASAC's Environment Steering Panel stated that the current biomass policy had led to "…an expensive policy which is increasing atmospheric levels of CO_2 and worsening rather than mitigating climate change.

Also, they show how the billions in public subsidy for biomass conversions are worsening carbon emissions for many decades. (Council, 2021). We also know that large-scale energy generation from forest wood poses a danger to biodiversity and climate resilience. Thus, logging may be entrenched, intensified, and expanded if forest biomass is used for electricity. This affects the forest's ability to provide important ecosystem services like clean drinking water, flood protection, and clean air by degrading forest ecosystems, depleting biodiversity, and depleting soils. And then we come to one of our main points which is protecting and restoring the world's forests is a climate change solution, burning them is not. (Richter, 2018) And finally, if you are being provided with "green" electricity from biomass energy facilities, keep in mind that it's not always as clean as other renewable energy sources. (EnergySage, 2019)

1.5 Technologies for conversion of biomass to biofuel

In order to substitute the raw biomass as an alternative to fossil fuel the properties need to be improved which is done by different technologies that are described in this section. The main reason for such conversion is to improve the physical and chemical properties of raw biomass and to provide a better fuel quality for combustion and gasification applications.

a) Pyrolysis:

Pyrolysis is the chemical decomposition of organic compounds in the absence of oxygen at high temperatures. The reaction takes place at temperatures between 300°C -650°C and under pressure. It is an irreversible process that involves a change in physical phase and chemical composition at the same time. Biochar, bio-oil, and gases such as methane, hydrogen, carbon monoxide, and carbon dioxide are among the by-products of biomass pyrolysis.

Pyrolysis will produce mostly biochar at low temperatures (less than 450°C) when the heating rate is slow, and mostly gases at high temperatures (more than 800°C) when the heating rate is high. And with the help of pyrolysis, we obtain biochar which has a lot of benefits over normal coal.

b) Torrefaction

Torrefaction is a mild pyrolysis process that includes heating the feedstock at modest temperatures in an inert environment. The torrefaction process is made up of three steps: drying, torrefaction, and cooling. Initially the moisture in the biomass is released by drying it. And when the temperature of biomass ranges between 200℃ to 300℃ the torrefaction decomposition reactions occur (Luo, 2011).

c) Gasification: -

Biomass gasification is the process of converting biomass into a combustible gas that contains carbon monoxide, carbon dioxide, hydrogen, methane, water, and nitrogen, as well as impurities such as tiny char particles, ash, and tars. The gas is cleaned so that it may be used to generate heat and electricity in boilers, engines, and turbines. (Zafar, 2021).

Gasification is a process that transforms organic or fossil-based carbonaceous materials into carbon monoxide, hydrogen, and carbon dioxide at high temperatures (>700°C) without combustion and with a regulated quantity of oxygen and/or steam. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction. Hydrogen may be separated from this gas stream using adsorbers or specific membranes. Gasification is also known as synthesis gas. (Energy E. E., u.d.)

2. METHODOLOGY

2.1 Overview

For this study both quantitative and qualitative methods was used to further investigate the effects of biomass utilization in the iron and steel and cement industry. Both primary and secondary data sources were used to investigate the biomass potential. The work builds on previous studies conducted by Toktarova et al. (2020) and Karlsson et al. (2020). However, their research primarily focused on the pathways for decarbonizing the sector but as the primary goal of this thesis is to incorporate and analyse the utilization potential of biomass/ biofuel, and CCS in these industries further work was done with the aim of finding the overall biomass use in ISI (Iron and steel industry) and cement industry. The figure 1 shows the structure of the methodology adopted for the thesis.

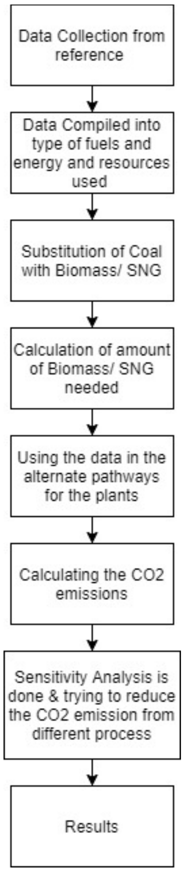

Figure 3-Methodology

Literature study

Literature study is considered as the first step in increasing understanding of the problem using the existing knowledge. Prior to analysing the data, extensive literature study was conducted towards understanding the manufacturing process to produce steel and cement. This included studying the different existing and new manufacturing technologies along with the development efforts made to reduce the CO_2 emissions. This approach allowed for a deeper understanding of the overall manufacturing process and identifying the potential areas for biomass substitution. Further study was done on how and in which process and phase of manufacturing biomass/ biofuels and CCS can be implemented.

Data collection

In the next step to further investigate the quantitative data was used from Toktarova et al. (2020) and Karlsson et al. (2020) from their research in the carbon exit roadmaps. Their research primarily focused on alternate pathways and processes to manufacture steel and cement and ways to lower the CO_2 emissions. Since the primary focus of this thesis is analysing the amount of biomass that can be implemented in the individual industries, further literature research was conducted to find the substitution potential.

Data analysis

After analysing the collected data, the missing data was identified and merged to formulate the type and quantity of fuel and energy required according to current production. Then substitution potential described in different literature sources were substituted in each production step. The corresponding results where the amount biomass/biofuel required in the future when fossil fuels are planned to be phased out. This process also assisted in determining ways to reduce overall total CO_2 emissions. The final phase of the study involved performing sensitivity analysis on various parameters such as changing the production volume and analysing how it affects the result, which were then plotted against the different parameters to describe the future biomass need.

2.2 Limitations

The collection of primary data was difficult to come by thus secondary data was used and particularly when it came to information on biomass, such as the percentage of biomass used in the steel and cement industries for various processes. Also, wherever data was missing necessary assumptions have been made. Another limiting factor that could be considered was due to Covid-19 we were unable to conduct interviews with some companies.

2.3 Scenario analysis

This section describes the different pathways and the substitution potential of biomass/biofuels in iron steel and cement industry. The focus is on utilization of biomass/biofuels in the different pathways in order to reduce the CO_2 impact.

2.3.1 Steel industry

As described in the introduction chapter the main steel production routes in iron and steel industry is Blast furnace and Electric Arc furnace. This section presents the different alternative pathways implemented in order to reduce the CO_2 emissions. This section also presents the three pathways and the substitution potential of biomass in the form of charcoal and SNG in each production step of the iron and steel industry. The methodology adopted has been described in the Figure 3.

2.3.1.1 Pathway 0 – Blast furnace + Electric Arc Furnace (Conventional route)

This pathway is the conventional pathway of steel manufacturing as described in section 1. As we can see in the Figure 4 the steel making is divided into primary and secondary steelmaking using BF/BOF and Electric arc Furnace. As this pathway is the most CO_2 emitter and fossil fuel intensive this is used as a comparison to the other pathways. This is done by finding the data for different fuel consumption such as hard coal, coke, natural gas, and electricity and then calculating the CO_2 emission intensity for the steel production volume i.e., 4.8 million ton. The assumed steel production volume for the year 2020-2045 is described in the table (1)

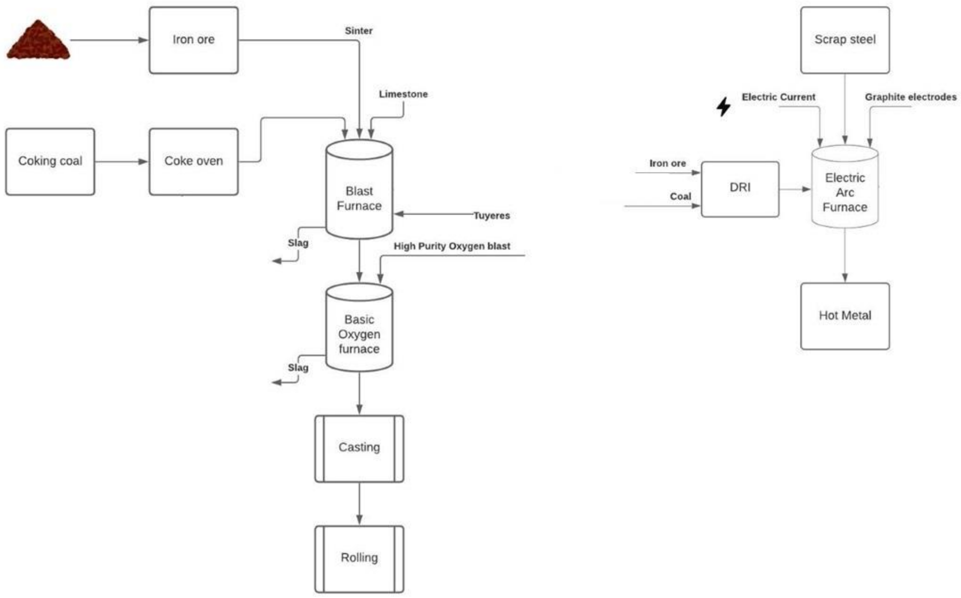

Figure 4- Pathway 0- BF/BOF+EAF

Year	BOF/BF (Mton)	EAF (Mton)
2020	3.2	1.60
2025	3.2	1.60
2030	3.2	1.60
2035	3.2	1.60
2040	3.2	1.60
2045	3.2	1.60

Table 1- Pathway 0 - Steel production 2020-2045

2.3.1.2 Pathway 1- Top gas recycling blast furnace + Carbon Capture and storage + Biomass

In this pathway is TGR-BF is quite similar to the conventional steel manufacturing method but with Carbon capture and storage and using biomass as a fossil free alternative. Charcoal is substituted in place of hard coal and biomass is substituted in place of coke. The assumed steel production volume for the year 2020-2045 is described in the table below.

Year	BOF/BF (Mton)	EAF (Mton)	I-EAF (Mton)	TGRF+CCs+ Charcoal (Mton)
2020	3.20	1.60	0	0
2025	2.07	1.60	1.13	0
2030	0.00	1.13	1.60	2.07
2035	0	0.00	2.73	2.07
2040	0	0	2.73	2.07
2045	0	0	2.73	2.07

Table 2- Pathway 1- Steel production 2020-2045

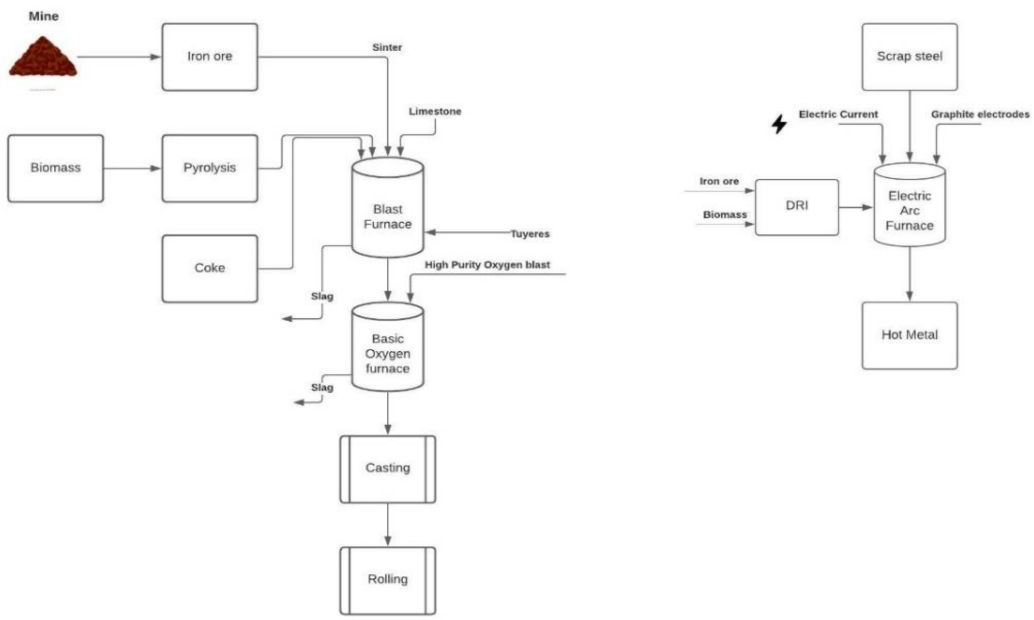

Figure 5- Pathway 1- TGR-BF+CCS+Biomass

2.3.1.3 Pathway 2- Direct reduced iron + Electric arc furnace+ Synthetic natural Gas

In this pathway Synthetic natural gas is substituted as an alternative to natural gas. In this scenario EAF with biomass is considered as the primary and secondary manufacturing method. This method incorporates pellet production method with SNG as a fossil free alternative. The assumed steel production volume for the year 2020-2045 is described in the table below.

Year	BOF/BF (Mton)	EAF (Mton)	I-EAF (Mton)	DRI/EAF (Mton)
2020	3.2	1.60	0	0
2025	2.07	1.60	1.13	0
2030	0.00	1.13	1.60	2.06
2035	0.00	0.00	2.07	2.73
2040	0	0	2.07	2.73
2045	0	0	2.07	2.73

Table 3 - Pathway 2 -Steel production 2020-2045

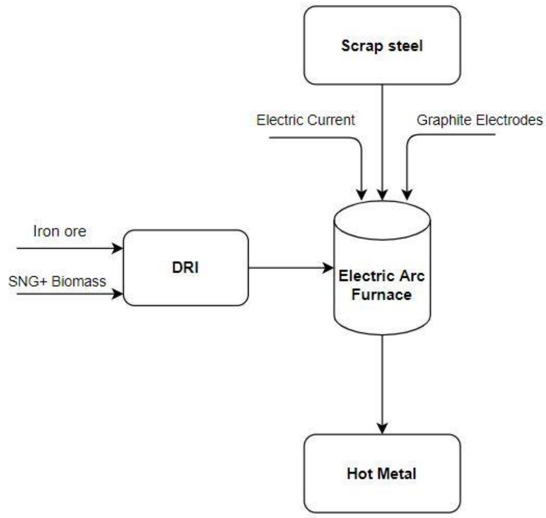

Figure 6- Pathway 2- DRI

2.3.1.4 Pathway 3-Hydrogen Direct Reduction + Electric Arc Furnace

In this pathway hydrogen direct reduction is considered as the steel manufacturing method. This is based on the HYBRIT technology which uses renewables and hydrogen electrolyzer to reduce the iron ore into sponge iron. Which is then converted into liquid steel using EAF technology. This method is considered as the green alternative to the steel manufacturing as it is powered by renewables and is fossil free. The assumed steel production volume for the year 2020-2045 is described in the table below.

Year	BOF/BF (Mton)	EAF (Mton)	I-EAF (Mton)	H-DRI/EAF (Mton)
2020	3.20	1.60	0	0
2025	2.07	1.60	1.13	0
2030	0.00	1.13	1.60	2.07
2035	0	0.00	2.07	2.73
2040	0	0	1.60	3.20
2045	0	0	1.60	3.20

Table 4- Pathway 3 - Steel production and export 2020-2045

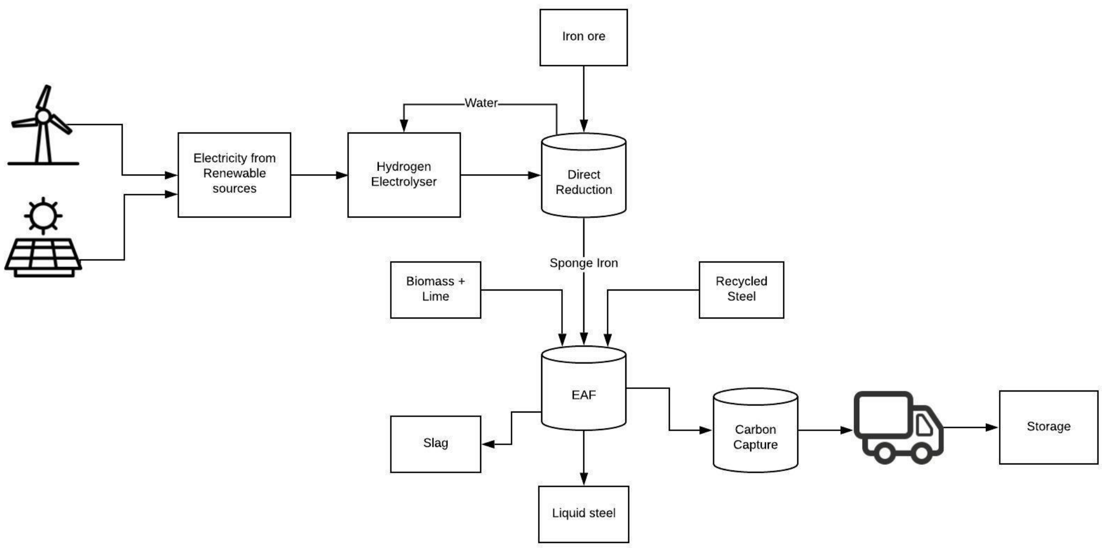

Figure 7: HDRI

2.3.2 Cement Industry

The different cement manufacturing routes in the cement industry are explained in the introductory chapter. This section describes three different pathway routes and about biomass substitution potential in each of them and also about CO_2 emission reduction. The methodology adopted has been described in the figure shown below.

2.3.2.1 Pathway 0: - Conventional Route

This pathway follows the conventional route of cement manufacturing as described in the section 1.3.2 also this pathway is used as a contrast to the others since it emits the most CO_2 and uses the most amount of fossil fuels.

2.3.2.2 Pathway 1: - Post Combustion capture technology

In this pathway the post combustion technology has the same work of capturing CO_2emissions as the oxy fuel technology, but the carbon capture will be done on the flue gases after being generated in the cement kiln. And with this technology most of the CO_2 can be captured and can be considered more effective than oxy-fuel technology for carbon capture.

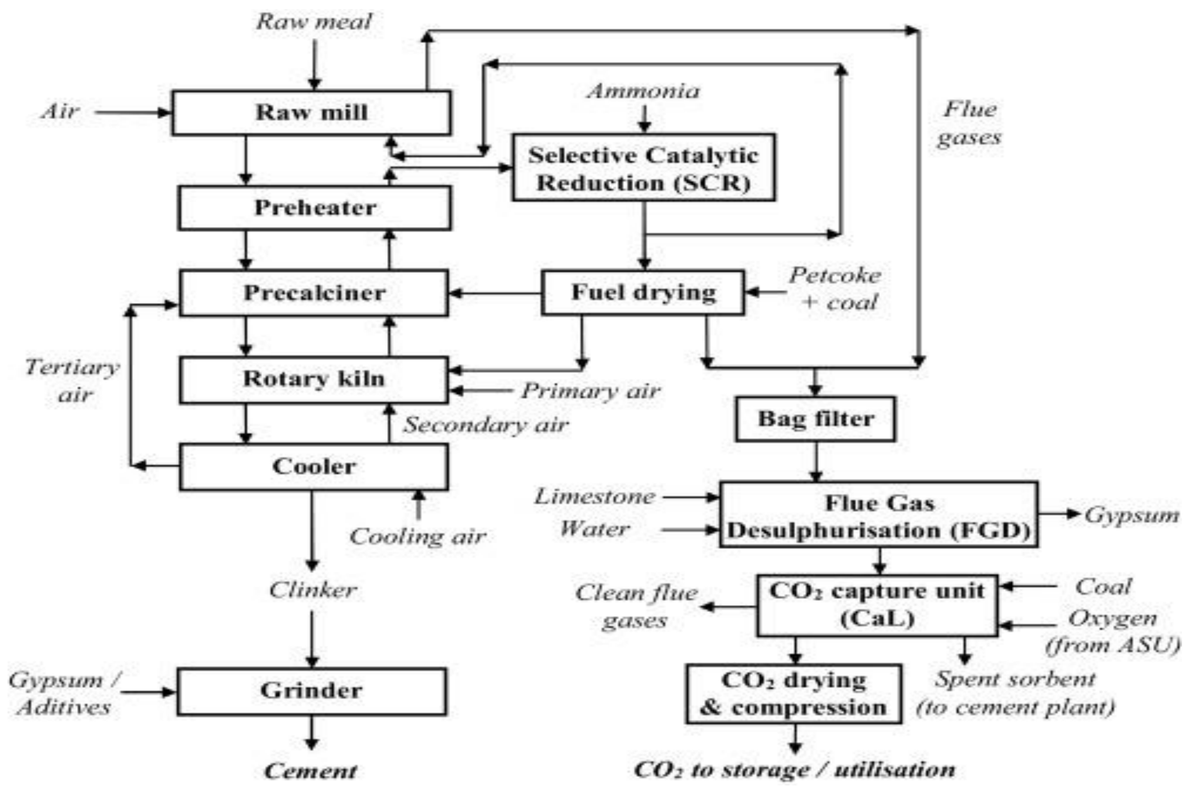

Figure 8- Pathway 1- Post-combustion capture technology *(Ana-Maria Cormos, 2017)*

2.3.2.3 Pathway 2: - Oxy-fuel CCS

In this pathway the Oxy Fuel combustion and CCS capture takes place before the cement mixture enters the Rotary Kiln thus it will not be able to eliminate 100% of CO_2 by CCS capture from the whole system but will be able to drastically reduce the CO_2 emissions.

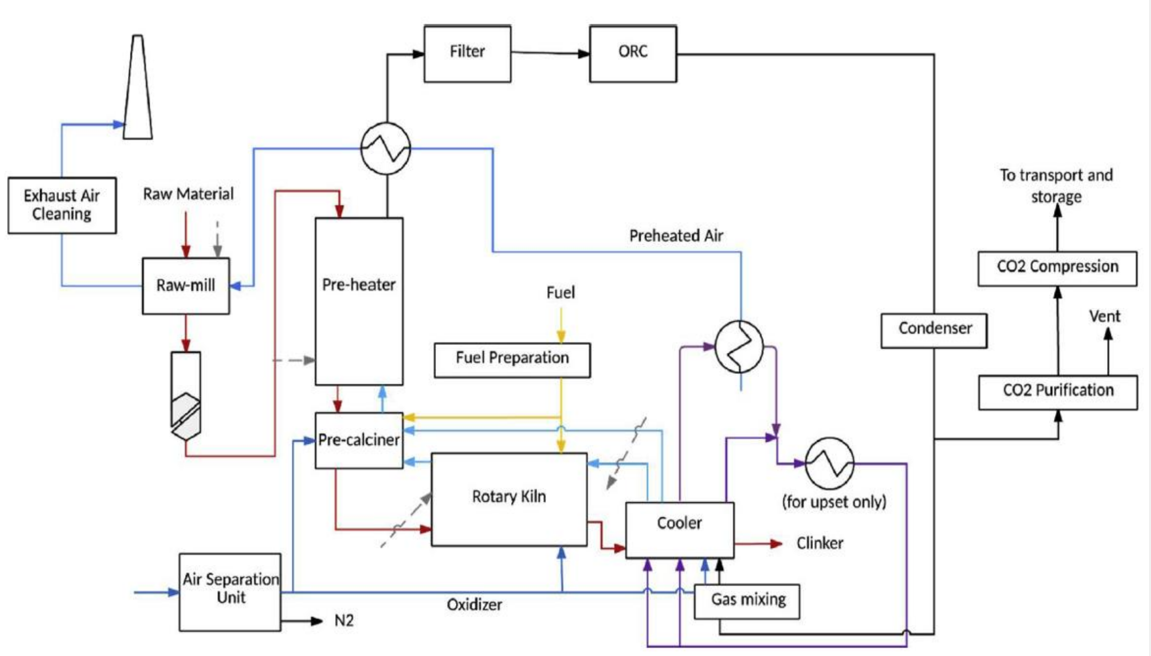

Figure 9- Pathway 2- Oxy-fuel CCs *(Mario Ditaranto, 2019)*

2.3.2.4 Pathway 3: - Electrification

In this pathway as mentioned earlier the main fuel for heating the cement to form cement clinkers in the rotary kiln will be replaced by fossil free electricity. No doubt by doing this the overall cost of cement and the electricity required will increase but this pathway will drastically reduce the CO_2 emission, but CCS will still be required to capture the post combustion emissions. Thus, moving forward this will be one of the important pathways towards a greener cement manufacturing.

3. RESULTS

This chapter will focus on describing the detailed description of energy consumption in each process of manufacturing process, the results of CO_2 emissions from different pathways, and the corresponding results from the biomass substitution in steel and cement industry. The methodological chapter describes the method adopted for the results below.

3.1 Steel industry

This section presents the results from the three pathways and substitution potential of biomass in the form of charcoal and L-SNG in each production step of the iron and steel industry. As the main aim of the thesis is to identify the CO_2 impact and the biomass demand this will also be presented in this section. The energy consumption and biomass substitution rate for each production step is described in

Table *12* in the appendix section.

3.1.1 Total Fuel demand for Annual steel production

After substituting the biomass values, the results were calculated for an assumed increased annual production volume of 4.8 million tons (Jernkontoret, n.d.). The table below compares the amount of biomass, SNG, Electricity and Hydrogen required for the production volume.

Results per ton

Pathway	Biomass Charcoal (kg/t)	Biogas (SNG) (kWh/t)	Electricity (kWh/t)	Hydrogen (kg/t)
Pathway 0	477.5	77.7	688.7	0
Pathway 1	407.3	82.3	672.3	0
Pathway 2	9.2	1387.8	866.	0
Pathway 3	9.2	21.3	4002.7	51

Table 5-Energy and fuel demand for the 1 ton of steel.

Results for million ton- 4.8

Pathway	Biomass - Charcoal (Mill ton)	Biogas (TWh/Mill ton)	Electricity (TWh/Mill Ton)	Hydrogen (Mill ton)
Pathway 0	2.3	0.3	3.2	0
Pathway 1	1.9	0.3	3.1	0
Pathway 2	0.04	6.5	4.0	0
Pathway 3	0.04	0.1	18.8	0.2

Table 6- Energy and fuel demand for the 4.8 ton of steel.

As shown in table 5 and 6 the different fuel consumption values are compared with respect to the different pathways. It is apparent that the biomass demand is higher in the BF/BOF and TGR-BF route as compared to the other pathways. The most surprising aspect of the data is in the correlation between the electricity demand in HDRI and other pathways.

3.1.2 Electricity Demand

The table 7 presents data of electricity demand for the different pathways and the electricity available for industrial use. The data for electricity consumption for Sweden is collected from IEA statistics database (IEA World Energy Balances, n.d.) this data includes the electricity consumption for the all-industrial sector for the year 2018.

Pathway	**Electricity demand (TWh/yr)**	**Actual Electricity use (TWh/yr)**
Pathway 0	3.3	50.7
Pathway 1	3.2	
Pathway 2	6.5	
Pathway 3	18.9	

Table 7- Comparison of steel industry electricity demand to the total industrial electricity demand in 2020-2045.

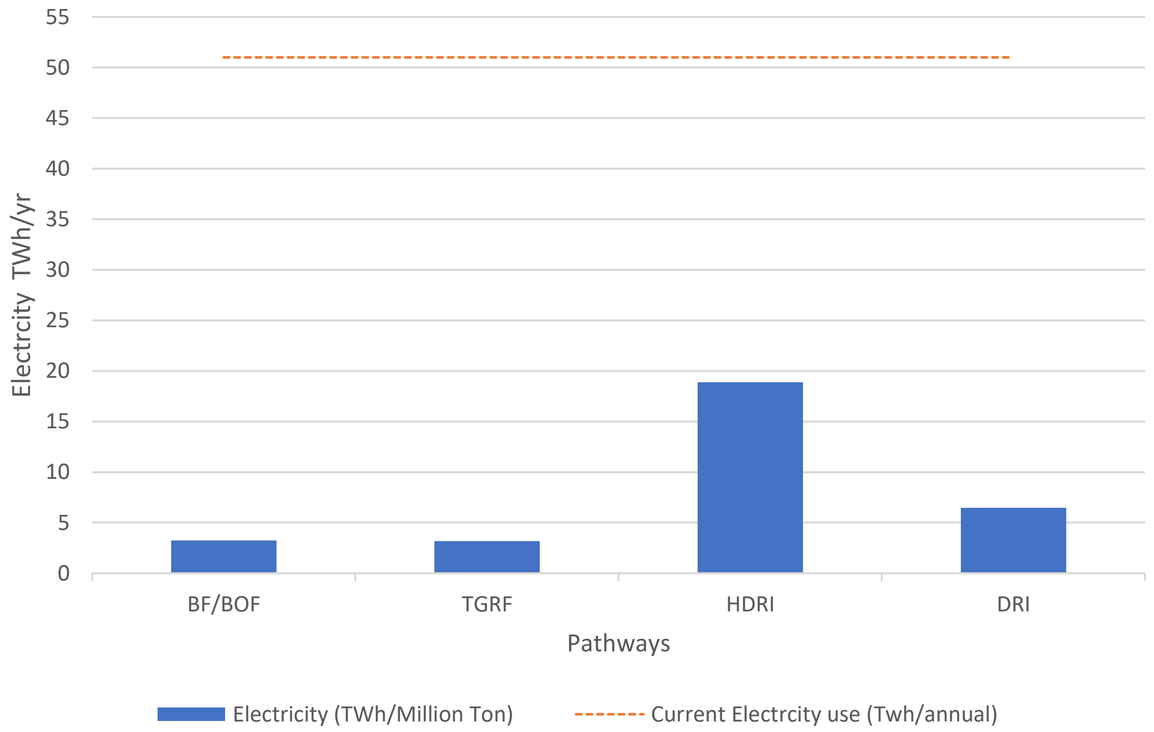

Figure 10- Comparison of steel industry electricity demand versus total industrial electricity demand in 2020-2045

From the figure above we can see the comparison between the electricity demand and the available electricity for industrial use in Sweden. It is apparent from the table that as there is much higher demand of electricity in HDRI as compared to the other pathways.

3.1.3 Charcoal demand

As charcoal is used as a substitute to coke and coking coal, it is important to assess the correlation between the demand and actual availability. The table below compares the charcoal demand with the availability of biomass that can be used as an alternative to fossil fuels.

Pathway	**Charcoal (TWh/yr)**	**Residues and stumps (TWh/yr)**
Pathway 0	20.03	52.6
Pathway 1	17.1	
Pathway 2	0.38	
Pathway 3	0.38	

Table 8- Comparison of biomass demand vs availability

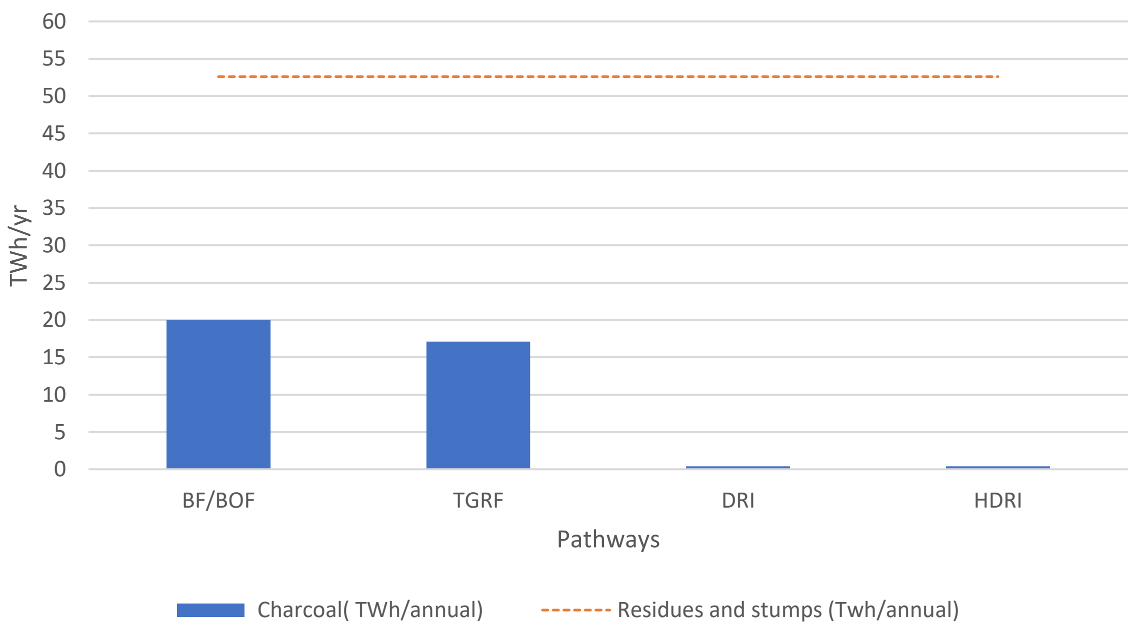

Figure 11- Comparison of charcoal demand and availability

The results obtained from Table 8 are compared in the graph above. The graph is quite revealing in several ways. First, what is interesting is the difference between the actual biomass available for use, this includes biomass in the form of sawlogs, pulpwood, waste wood, wood pellets, industrial by-products and harvesting residues and stumps. However, studies suggest that residues and stumps provide to be a better alternative as a biomass use in the industries. Comparing the results, it can be concluded that despite the use of other biomass the demand can be met with residues and stumps as biomass.

3.1.4 CO_2 Emissions for alternative pathways

This section presents the CO_2 emissions from the four pathways to the corresponding years. The results are calculated from the specific energy consumption per ton of steel, the production volume, and the CO_2 intensity factor. The production volume has been varied according to the TRL level of the technologies. For comparison BF/BOF is assumed to be the main pathway of steel production in the year 2020 with a production volume of 4.8 Mill ton. The Table 10 compares the CO_2 emissions from the different pathways.

	Hard coal	**Coke**	**Oil**	**Natural gas**	**Electricity**	**Bio-charcoal**	**Bio- Gas SNG**	**Total, [GJ/tHM]**
BF/BOF	4.97	10.21	0.57	1.47	0.39	0.00	0.00	17.61
TGRF+CCs	0.00	3.72	0.57	1.80	1.20	7.13	1.80	16.21
DRI	0.08			0.40	2.52	2.63	0.40	6.01
EAF	0.23			0.79	2.52			3.54
EAF-I	0.15				1.78	1.37		3.30
HDRI/EAF	0.00				12.56	3.03	0.50	16.09

Table 9- Specific Energy consumption per ton of steel

Year	**Pathway 0**	**Pathway 1**	**Pathway 2**	**Pathway 3**
2020	5.6	5.6	5.6	5.6
2025	5.6	3.6	3.7	3.7
2030	5.5	0.6	0.2	0.4
2035	5.5	0.5	0.08	0.1
2040	5.5	0.4	0.03	0.01
2045	5.5	0.4	0.03	0.01

Table 10- CO_2 emissions for different pathways in Mton

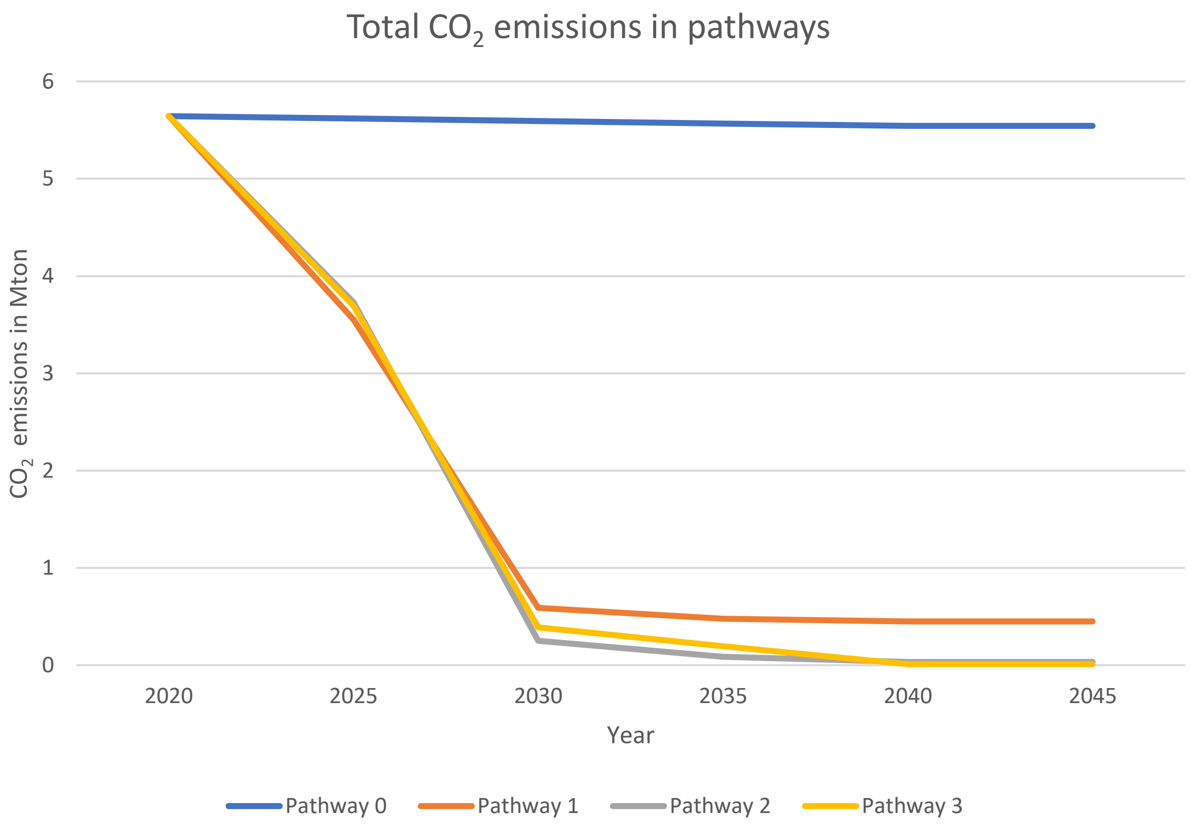

Figure 12- CO_2 emissions from the Swedish iron and steel industry from 2020-2045

The results from Table 10 are presented in the graph above. The graph presents a significant difference in the CO_2 emissions from BF/BOF and the other pathways. As presented in the graph the steel production using BF/BOF has much higher amount CO_2 emissions from 2020-2045. Interestingly, pathways 1, 2 and 3 show a steady decline in the emissions after the year 2025.

3.2 Cement industry

This section shows the three alternative pathways for cement industry when compared to the conventional one and the different substitution potential of Biomass. As the main aim of the thesis is to identify the CO_2 impact and the biomass demand of each technology which will be presented in this section.

3.2.1 Comparing the CO_2 Emissions of different Pathways

As it can be seen in the table and graph below carbon emission has been compared for different years and for different pathways to identify which pathway is more effective in reducing the emissions. But these results are depending on various factors such as cement production, cement clinker substitution, Biofuel increase, and CCS captured.

		Emissions cement ($MtCO_2e$/year)						
Pathways	Process	**2017**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Pathway 0	Conventional fuel	2.51	2.48	2.45	2.42	2.38	2.31	2.26
Pathway 1	Alternative fuels & amine CCS/ Post combustion CCS	2.51	2.46	2.31	1.18	1.10	0.35	0.17
Pathway 2	Alternative fuels & oxyfuel CCS	2.51	2.46	2.31	2.15	0.92	0.84	0.00
Pathway 3	Electrification & CCS	2.51	2.46	2.31	1.18	1.10	0.18	0.00

Table 11-CO2 emissions from different pathways

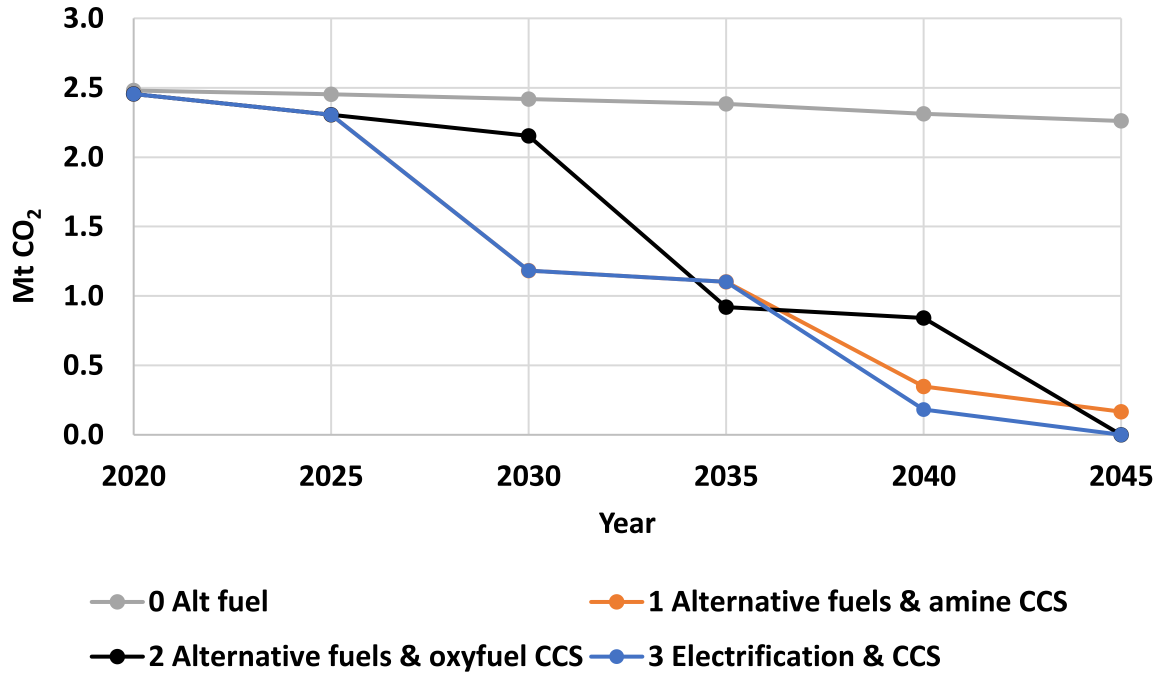

Figure 13- CO2 emissions from the year 2020-2045

3.2.2 Comparing the Electricity use of different Pathways

In the below table and graph the electricity required by different pathways and process is compared as it can be seen expect for pathway 3 the electricity consumption is maintained the same always and for pathway 3 as the conventional fuel use and biofuel use is replaced by electricity the electricity consumption goes up.

		TWh/year						
Pathways	Process	**2017**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Pathway 0	Conventional fuel	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Pathway 1	Alternative fuels & amine CCS/ Post combustion CCS	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Pathway 2	Alternative fuels & oxyfuel CCS	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Pathway 3	Electrification & CCS	0.39	0.39	0.39	1.86	1.86	3.33	3.66

Table 12- Electricity use by different pathways

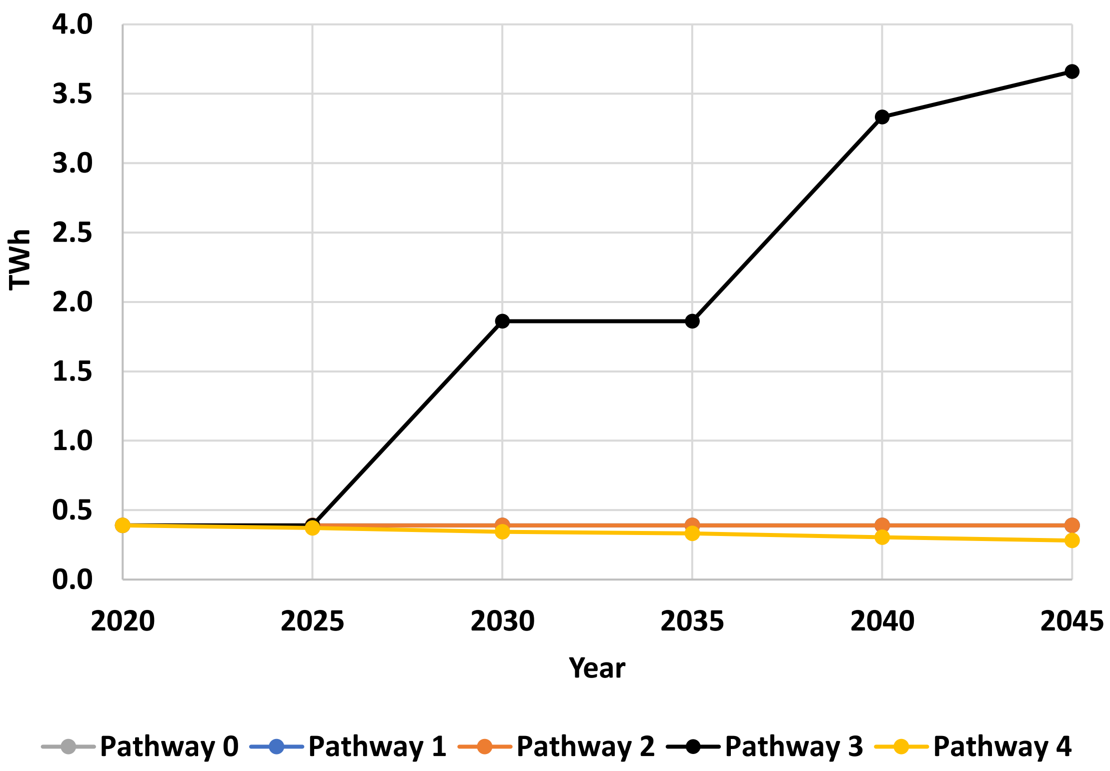

Figure 14- Electricity consumption from the year 2020-2045

3.2.3 Comparing the Biofuel use of different Pathways

The Table and graph help to understand the different amounts of Biofuel used in different pathways in different years as it can be seen the main reason biofuel required will keep on increases is because it helps in replacing the conventional fuel quantity and try and make the cement manufacturing process a more sustainable and green process but except for pathway 3 whereas usual due to Electrification of the whole system the use of biofuel is reduced.

		TWh/year						
Pathways	Process	**2017**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Pathway 0	Conventional fuel	0.65	0.67	0.84	0.96	1.08	1.32	1.50
Pathway 1	Alternative fuels & amine CCS/ Post combustion CCS	0.65	0.67	0.78	0.83	0.88	1.00	1.07
Pathway 2	Alternative fuels & oxyfuel CCS	0.65	0.67	0.78	0.83	0.88	1.00	1.07
Pathway 3	Electrification & CCS	0.65	0.67	0.65	0.35	0.33	0.06	0.00

Table 13- Biofuel % used in different pathways

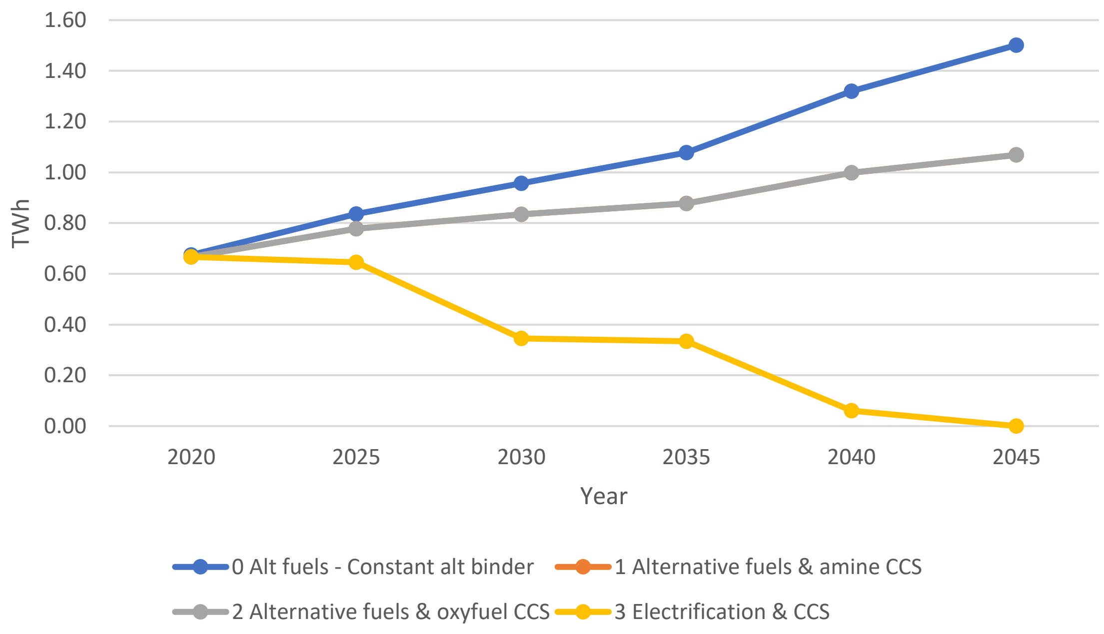

Figure 15-Biofuel consumption from the year 2020-2045

3.2.4 Bio Coal Substituted in Pathway 1 (Post Combustion)

The below table and graph were obtained by replacing Fossil fuels and alternative fossil fuel with Bio Coal and due to this implementation, the CCS penalty cost will be eliminated.

	TWh/yr					
Process/ Years	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electricity	0.39	0.39	0.39	0.39	0.39	0.39
Biofuel	0.67	0.78	0.83	0.88	1.00	1.07
Bio Coal	2.04	2.03	2.78	2.50	2.82	2.61

Table 14- Bio coal Substitution

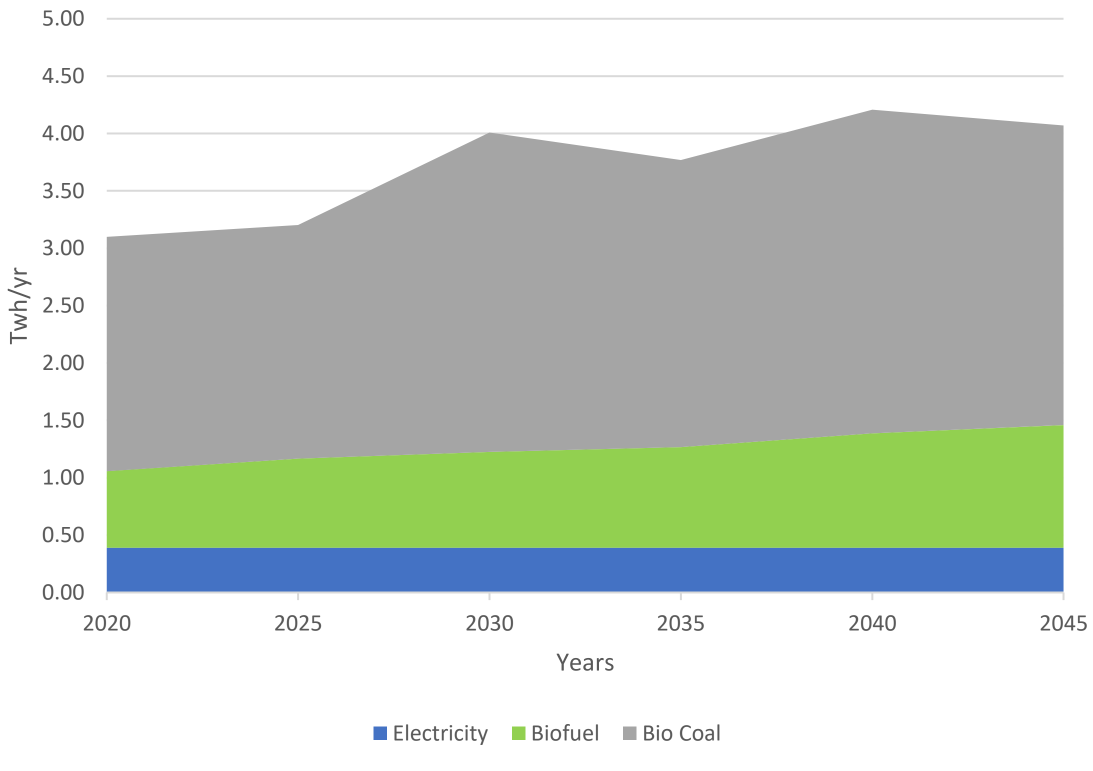

Figure 16- Bio coal replacing other fuels

3.2.5 Sensitivity Analysis

Sensitivity analysis is done for the post combustion CCS pathway which is more prominent when compared to Oxy-fuel CCS so while comparing the other pathways to the base one the main difference in the pathways is that in the optimized pathway the overall cement production is reduced over the years by increasing the binder intensity to see how this plays a role in reducing the CO_2 emissions and in the other pathway the overall cement production has been increased to notice how this effects the increase of CO_2 emissions. Thus, all these 3 pathways CO_2 emissions have been compared.

			Emissions ($MtCO_2$/year)					
Method	Pathways	Process	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Conventional Pathway	Pathway 1	Alternative fuels & amine CCS/ Post combustion CCS	2.46	2.31	1.18	1.10	0.35	0.17
Sensitivity analysis	Pathway 4	Optimisation and amine CCS Post combustion CCS	2.46	2.19	1.04	0.94	0.27	0.12
Sensitivity analysis	Pathway 6	Consumption increases and CCS Post combustion CCS	2.51	2.64	1.44	1.41	0.47	0.23

Table 15- Comparison of post combustions CCS by using different methods

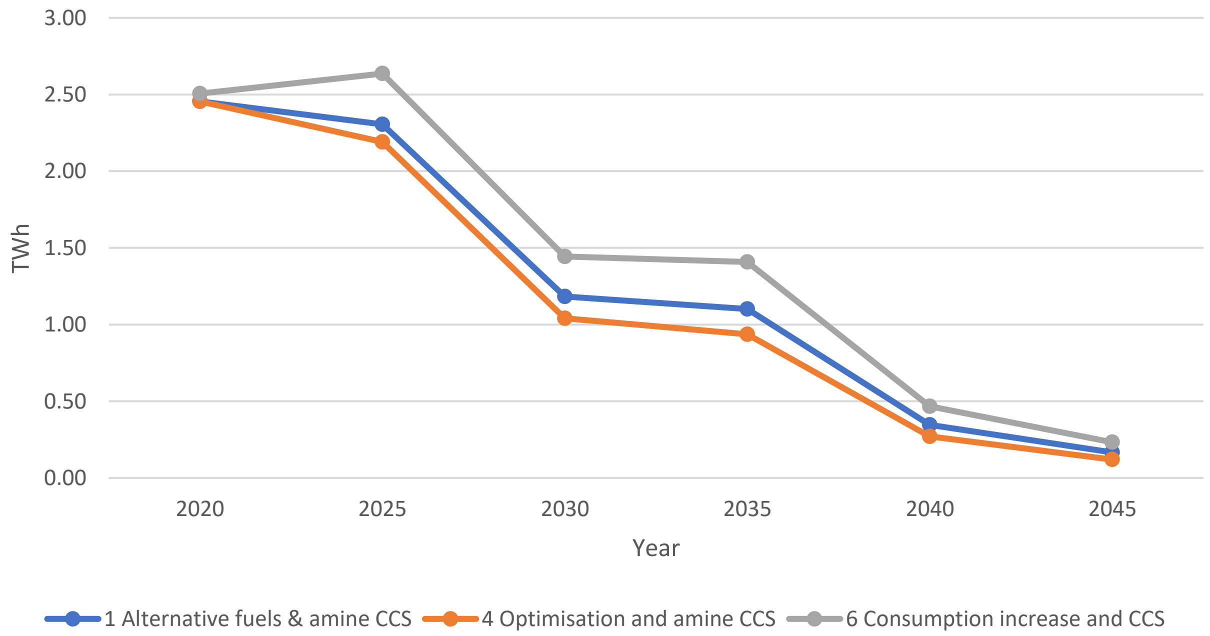

Figure 17- Post combustion Sensitivity Analysis by changing different parameters

3.3 Combined Results for biomass

The results shown in the table are based firstly on the steel industry that uses the conventional Pathway 0 i.e, BF/BOF which requires the most amount of biomass which is approximately around 20.03 TWh/yr and as for the cement industry it is also for pathway 0 in the year 2045 where maximum amount of Biomass is needed when compared to other pathways which is around 1.50 TWh/yr. The table below shows the maximum biomass demand for both the cement and steel industry combined which is an estimate of 21.53 TWh/yr and the overall available demand in Sweden is approximately 208.2 TWh/yr. Also, the least amount of Biomass is required by the electrification pathway which is almost 0 TWh/yr in the cement industry since all the biomass demand is replaced by electricity and the HRDI pathway in the iron and steel industry which is roughly around 0.38 TWh/yr.

Industry	Biomass Demand (TWh/yr)	Available Biomass in Sweden (TWh/yr) (Chinedu Maureen Nwachukwu, 2021)
Min Demand for Steel & Cement Industry combined	0.38	208.2
Max Demand for Steel & Cement Industry combined	21.53	208.2

Table 16- Combined Biomass Result

DISCUSSION

This study sets out with the aim of assessing the importance of biomass and biofuels in combination with other technological options to decarbonizing the Swedish industrial sector. The study focuses on the substitution of biomass and biofuels in heavy industries and assessing their CO_2 impact. However, it is worth mentioning that the aim of the thesis is not to assess if the biomass is sustainable or not but on the contrary, it was hypothesized that biomass is a sustainable and greener alternative for emission reduction. Also, as very little data was found in the literature about exact biomass potential thus assumptions have been made on the substitution rates.

The current study focused on finding the demand for biomass, biogas, and electricity demand for different pathways in the steel industry along with the CO_2 emissions from different pathways. As the annual steel production varies every year the steel production volume was considered as 4.8 million tons. The results of the study indicate that there is a significant demand for coke /coal in the BF/BOF and TGR-BF routes as compared to the other pathways. This is because even after substituting biomass as an alternative the substitution rate is in the range of 40-100 %. This is key factor due to which pathways 0 and 1 have higher CO_2 emissions compared to other pathways. Another important finding was that there is a much higher demand for electricity in HDRI, this is due to the use of electrolyzer and EAF as primary and secondary steel manufacturing methods. But it is important to be noted that after comparing the results for electricity demand with actual production, the results show a strong relationship that the electricity demand can be met using the current supply. However, more research findings on the HYBRIT initiative suggest that this demand would be met by greener alternatives which will has a significant impact on the reduction of CO_2 emissions.

Another important finding was that in BF/BOF and TGR-BF, the emissions are significantly reduced due to the use of biomass and biogas in place of coke, coal, and natural gas but still this pathway fails to achieve negative emissions by the year 2040. One unanticipated finding was the correlation between DRI and HDRI as both pathways 2 and 3 have a major decrease in emissions after the year 2025. The most remarkable results emerge from pathway 3 (HDRI) where the results show close to negative emissions. It can thus be suggested that HDRI/EAF technology can be implemented to pursue the goal of zero emissions, but as mentioned this results in an increase in electricity use around three times compared to the rest of the pathways.

This study has however been unable to take into consideration the charcoal conversion efficiency as there is limited studies that suggest the exact conversion ratio from raw biomass to charcoal. Hence this may cause some variation in biomass demand, thus for further research the conversion efficiency of raw biomass must be considered. Further work is required to establish the exact conversion rates and the how the bio-gas demands can be met.

And as it goes for cement manufacturing industry the study was focused on the different biomass substitutes that can be used and electricity demand and different pathways and sensitivity analysis of how the CO_2 emissions can be reduced. As it is mentioned above the annual cement production value varies every year but in this experiment the production of cement was considered to be 3 Mton/year throughout the years and in all the different pathways. Thus, in Pathway 0 the CO_2 emissions are dependent on amount of cement production, Percentage of Biofuel increase and Cement clinker substitution and as the share of biofuel increases in the system the CO_2 emissions decreases other ways of decreasing the CO_2 emissions is by increasing the cement clinker substitutions and by replacing fossil fuels with alternate fossil fuels. But Pathways 1 and 2 involves CO_2 capture by CCS for reducing the overall CO_2 emissions the only difference between the two pathways is one involves pre combustion CO_2 capture and the other is post combustion CO_2 capture. And as for Pathway 3 the from the year 2030 the whole system slowly starts getting electrified and due to which lower fossil fuels are required and thus lower CO_2 emissions.

Among all the pathways the ones found most effective to reduce the CO_2 emission to net zero by the year 2045 were pathways 2 and 3 which involves post combustion CCS capture and electrification of the system. There is also sensitivity analysis done for the post combustion pathway as this seems to be the future when compared to other pathways since when it comes to Pathway 3 which involves electrification of the system this will increase the electricity usage drastically. There is also research being done towards combing pre and post combustion CCS to reduce the overall CO_2 emissions to net zero.

As there is an abundant room for further progress, the future research questions could include the availability of scrap for EAF, carbon credits for CO_2 emissions, and the investment plan as conversion of raw biomass into bio-charcoal requires high investments, the cost factor for different process and pathways for both the industries and more data on oxy-fuel technology for the cement industry as it is still in the development stages.

Another important issue is the court ruling by the Swedish Supreme Land and Environmental Court for the Cementa plant at Slite in Gotland could be forced to end production and shut down the plant by 1st November. This plant produces around three-quarters of all the cement used in Sweden. It is also the second-largest source of greenhouse gas emissions in the country, responsible for three per cent of all CO_2 emissions. Thus, unless they reduce the CO_2 emissions from mining of limestone and other process there could be a danger of this plant being shut down. (Fairs, 2021).

Other research's that investigate biofuels is as mentioned by Nordic Energy Systems (Research, 2021) the usage of biomass for energy will most certainly go from just power and heat supply to transportation and industry fuel. Also, Bioenergy, which is used for heating and electricity generation, has the potential to offer energy security and flexibility in electrical networks which have large shares of VRE as bioenergy can be stored and thus may be utilized to meet demand during periods when VRE supply is low. Furthermore, biofuels can be engineered to have chemical properties that are almost equal to those of fossil fuels, making them an appealing and near-term replacement for fossil fuels in transportation while also being one of the few choices for heavy transportation and aviation

Bioenergy in the Nordics is mostly based on wood waste and wood residue resources, and it has been and will likely continue to be a major fuel in Nordic power and heat supply in the future decades. The potential for bioenergy growth is majorly seen in heavy and long-distance transport, and different industrial processes. Also, it plays a vital role in developing the future for a carbon neutral energy system as biomass can be stored at low costs for long periods of time and can provide negative CO2 emissions when combined with CCS. (Research, 2021).

CONCLUSION

The main goal of the study was to investigate how biomass and biofuels in combination with other technological options can contribute towards decarbonizing the Swedish steel and cement industrial sector. Also, the thesis explores how a switch from fossil fuels to biomass/biofuels affects these industries and how much of it can be implemented in these industries.

The study investigated into the different technological options available to reduce the CO_2 emissions in steel and cement industry. In case of steel industry, the conventional pathway using BF/BOF route has higher emissions dues its dependency on fossil fuel. If the steel production is still done using this pathway results show that the zero-emission target cannot be achieved. But on the other hand, results from Pathways 2 and 3 show that the zero CO_2 emissions target can be achieved by 2045 by using biomass/biofuels as an alternative to fossil fuels. In the case of the cement industry the best technological option to decarbonize the Swedish industry would be to choose the electrification pathway as that would reduce the CO_2 emissions drastically but the only drawback with this technology would be the excessive need for electricity as compared to a conventional plant thus the next best option would be post combustion CCS technology also more the share of biomass used in this pathway the lower will be the CO_2 emissions. Another Future technological option would be to combine Oxy-fuel CCS and Post combustion CCS technology into one plant.

The results from this study indicate that the demand for biomass in the form of charcoal for the steel and cement industry will be 21.53 TWh/yr. However, it is important to note that the results are possibly the extreme estimates as the substitution rates may vary and thus should be interpreted accordingly. Also, there will be a higher demand in electricity if the alternative pathways are to be adopted. The present study confirms previous findings from different articles sources and contributes additional evidence that the demand for electricity and biomass can be met for the production volume.

These findings provide some insights for future research mainly looking into the conversion efficiency of raw biomass for actual use. It would also be interesting looking into the financial aspects of the biomass use and the investment plan to convert this raw biomass for industrial use.

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APPENDIX

Biomass substitution in Iron and steel Industry

The table below presents the detailed description of the energy consumption and biomass/SNG substitution in each process step of Iron and steel making.

Iron ore Preparation -

Processing Unit	**Fossil Fuel used**	**Actual use** (Rainer Remus, 2010)[1]	**Unit**	**Bio-product Substitute**	**Substitution rate in %** (Suopajärvi, 2017) (Chinedu Maureen Nwachukwu, 2021)[2]	**Charcoal Substitution Value**	**Unit**
Feed Preparation	Coke	42	Kg/t	Charcoal	0-100	21	Kg/t
	Light and Heavy Fuel oils	43-186	MJ/t Pellets	L-SNG	0-100	110	MJ/t
	Electricity	54-99	Mj/t			74.5	Mj/t
	Natural gas	14	Mj/t	L-SNG	0-100	7	Mj/t
Coke Ovens	Coking Coal	1220-1350	Kg/t	Charcoal	0-5	128.5	Kg/t
	Electricity	20-230	Mj/t			240	Mj/t

[1] These values were obtained from the (Rainer Remus, 2010) reference document and assumptions have been made wherever necessary.
[2] The values are obtained from the two reference sources and substituted on a scale of 0-100 percent of the actual use obtained from [1]

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Primary steelmaking- BF/BOF

Processing Unit	Fossil Fuel used	Actual use	Unit	Bio-product Substitute	Substitution rate in %	Charcoal Substitution Value	Unit
Tuyere injection	Oil	30.1	kg/t HM				kg/t HM
	Oxygen	54.4	kg/t HM				kg/t HM
	Sintering Solid Fuel	76.5-102	kg/t HM	Charcoal	50-100	89.25	kg/t HM
	Coke making (Coking Coal)	480-560	kg/t HM	Charcoal	2-10	32.8	kg/t HM
	BF tuyere Fuel Injectant (Pulverized Coal)	150-200	kg/t HM	Charcoal	50-100	150	kg/t HM
	Bf Nut Coke Replacement	45	kg/t HM	Charcoal	50-100	22.5	kg/t HM
	Bf carbon/ore Briquette	10-12	kg/t HM	Charcoal	0-100	6	kg/t HM
	Pre- reduced Carbon /ore composites		kg/t HM	Charcoal		18	kg/t HM
	Recarburizer carbon	0.25	kg/t	Charcoal		0.25	kg/t
Energy	Electricity	107-850	Mj/t			268	Mj/t
	Natural Gas	168	Mj/t	L-SNG	0-100	84	Mj/t

Secondary steelmaking – EAF

Processing Unit	Fossil Fuel used	Actual use	Unit	Bio-product Substitute	Substitution rate in %	Charcoal Substitution Value	Unit
Raw material	Scrap	1039-1232	kg/t				kg/t
	DRI (HBI)	0-215	kg/t				kg/t
	Coal (including Anthracite and Coke	3-28	kg/t				kg/t
	Charge Carbon	12	kg/t	Charcoal	50-100	6	kg/t
	Slag Foaming carbon	5	kg/t	Charcoal	50-100	2.5	kg/t
	Recarburizer Carbon	1.4	kg/t	Charcoal	50-100	0.7	kg/t
Energy	Electricity		Mj/t			1476	Mj/t steel
	Natural Gas	150	Mj/t	SNG	0-100	75	Mj/t steel

Steel finishing

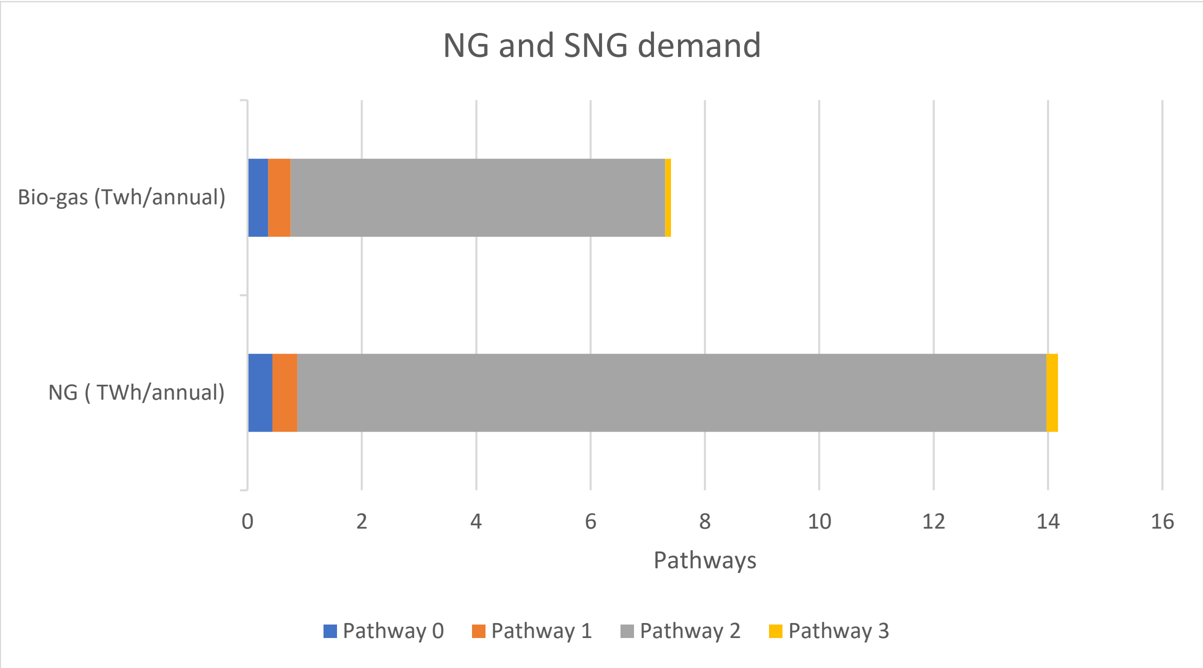
ali	Fossil Fuel used	Unit	Actual use	Substitution Value	Unit
Hot Rolling	Fuels	Mj/t	1100-2200		Mj/t
	Electricity	Mj/t	260-500	420	Mj/t
Cold Rolling	Electricity	Mj/t	320		Mj/t
Tandem Mills	Fuel	Mj/t	0.036		Mj/t
	Electricity	Mj/t	0.3	0.3	Mj/t
Annealing	Natural gas	Mj/t	1.8	1.8	Mj/t
	Electricity	Mj/t	0.3	0.3	Mj/t

DRI and HDRI

Processing Unit	Fossil Fuel used	Actual use	Unit	Bio-product Substitute	Substitution rate in %	Substitution Value	Unit
Gas Based DRI	Natural gas	9839	Mj/ton	SNG	0-100	4919.5	Mj/ton
	Oxygen	55	Mj/ton				Mj/ton
	Nitrogen	10	Mj/ton				Mj/ton
	Electricity-	1221	Mj/ton				Mj/ton
H-DRI	Hydrogen	51	kg/t				kg/t
	Electricity	2955	Kwh/t				Kwh/t

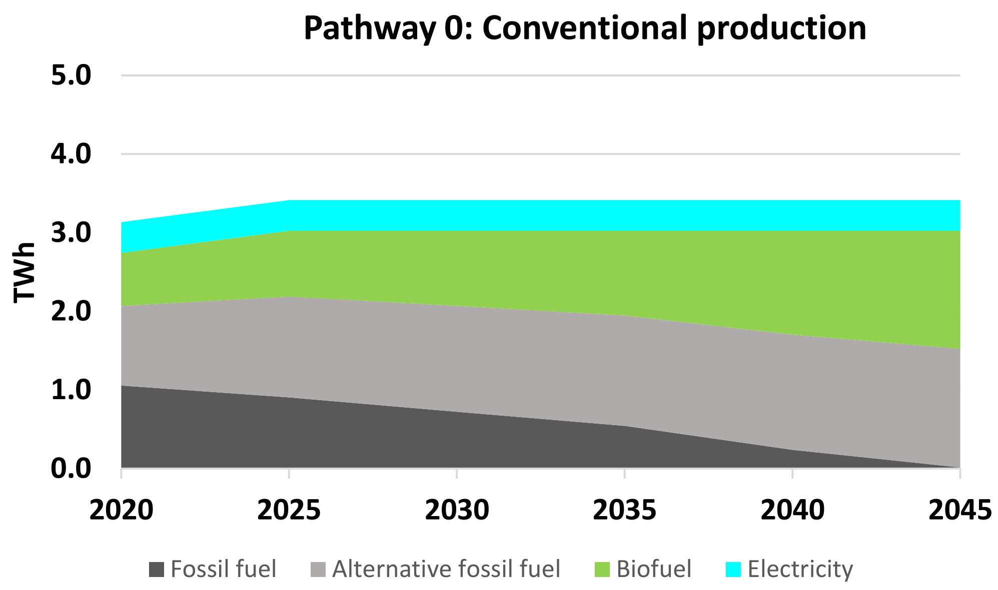
NG and SNG demand in different pathways

Pathway	NG (TWh/yr)	SNG (TWh/yr)
Pathway 0	0.43	0.36
Pathway 1	0.43	0.38
Pathway 2	13.09	6.55
Pathway 3	0.19	0.10



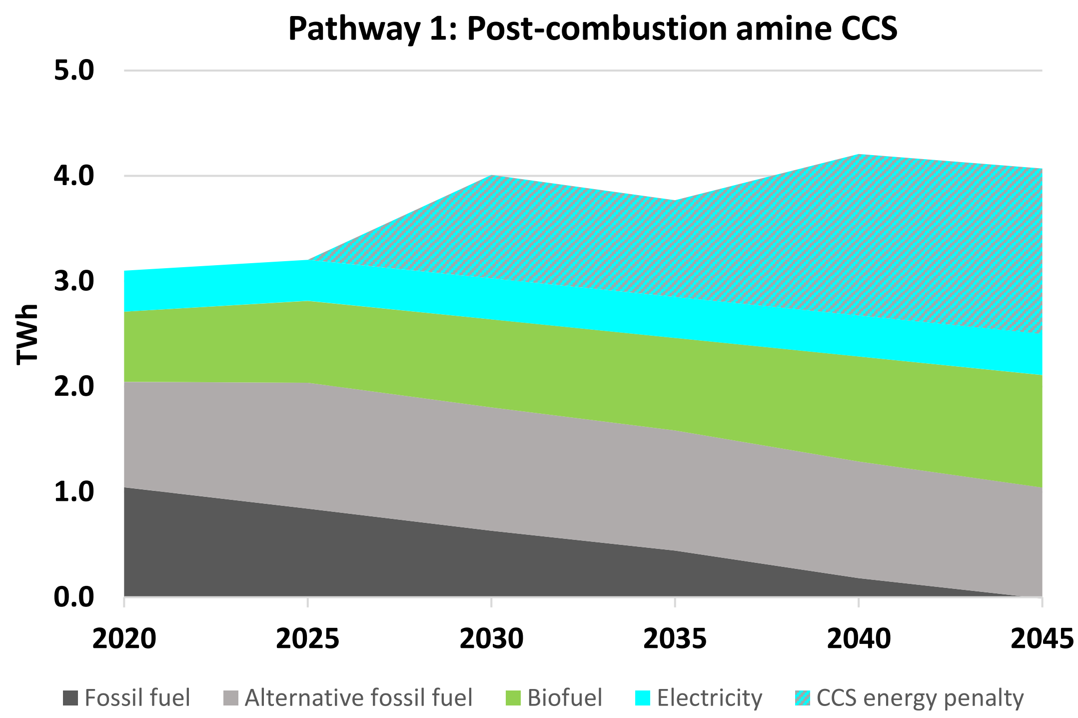
Cement Conventional Pathway

	2020	**2025**	**2030**	**2035**	**2040**	**2045**
Production cement (Mton / year)	3	3	3	3	3	3
Production cement clinker (Mton/ year)	2.58	2.58	2.58	2.58	2.58	2.58
Cement clinker substitutes (Mton/year)	0.42	0.42	0.42	0.42	0.42	0.42
Emissions cement (MtCO2e/year)	2.480	2.454	2.418	2.383	2.313	2.261
Captured emissions (MtCO2/year)	0.00	0.00	0.00	0.00	0.00	0.00
CCS energy penalty (TWh/yr)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (TWh/yr)	0.39	0.39	0.39	0.39	0.39	0.39
Bio Coal (TWh/yr)	0.27	0.33	0.38	0.43	0.53	0.60
meat & bone meal (TWh/yr)	0.20	0.25	0.29	0.32	0.40	0.45
sewage sludge (TWh/yr)	0.09	0.12	0.13	0.15	0.18	0.21
Other Biomass (TWh/yr)	0.11	0.13	0.15	0.17	0.21	0.24
Fossil fuel (TWh/yr)	1.06	0.90	0.72	0.54	0.24	0.01
Alternative fossil fuels(TWh/yr)	1.01	1.28	1.34	1.40	1.46	1.51
Total energy use (TWh /year)	3.13	3.41	3.41	3.41	3.41	3.41



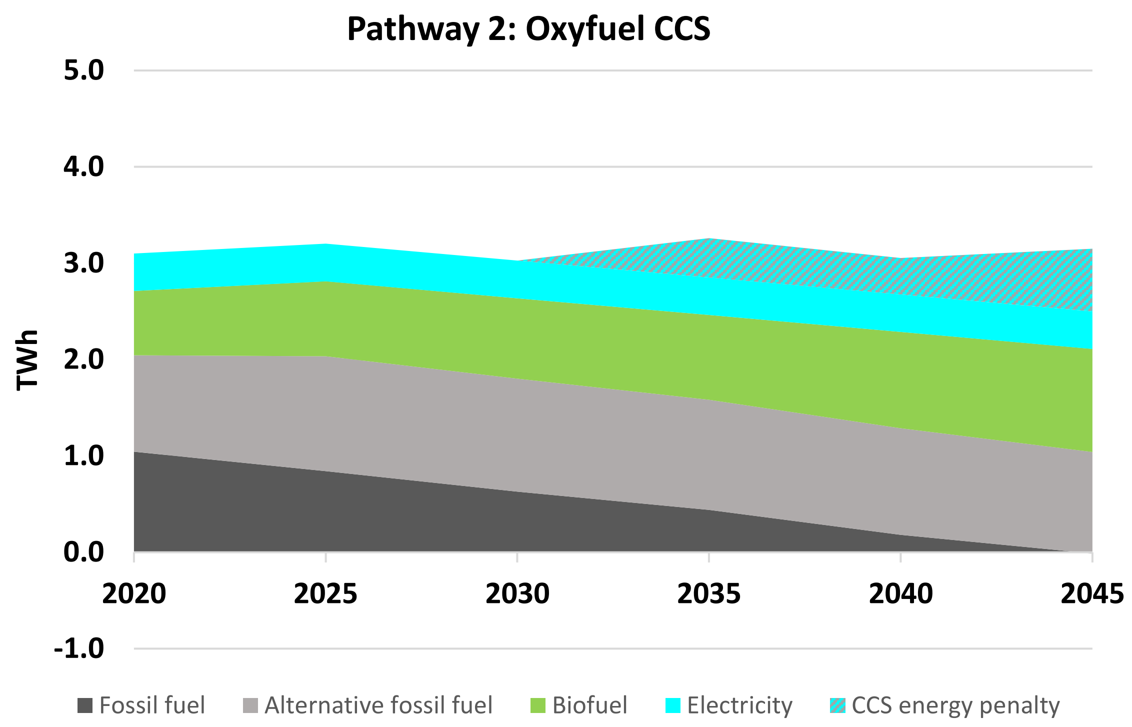
Post Combustion Pathway

	2020	2025	2030	2035	2040	2045
Production cement (Mton / year)	3	3	3	3	3	3
Production cement clinker (Mton/ year)	2.55	2.40	2.25	2.10	1.95	1.80
Cement clinker substitutes (Mton/year)	0.45	0.60	0.75	0.90	1.05	1.20
Emissions cement (MtCO2e/year)	2.46	2.31	1.18	1.10	0.35	0.17
Captured emissions (MtCO2/year)	0.00	0.00	0.81	0.76	1.27	1.30
CCS energy penalty (TWh/yr)	0.00	0.00	0.98	0.92	1.53	1.57
Electricity (TWh/yr)	0.39	0.39	0.39	0.39	0.39	0.39
Bio Coal (TWh/yr)	0.27	0.31	0.33	0.35	0.40	0.43
meat & bone meal (TWh/yr)	0.20	0.23	0.25	0.26	0.30	0.32
sewage sludge (TWh/yr)	0.09	0.11	0.12	0.12	0.14	0.15
Other Biomass (TWh/yr)	0.11	0.12	0.13	0.14	0.16	0.17
Fossil fuel (TWh/yr)	1.04	0.84	0.63	0.44	0.18	-0.01
Alternative fossil fuels(TWh/yr)	1.00	1.19	1.17	1.14	1.11	1.05
Total energy use (TWh /year)	3.10	3.20	4.01	3.77	4.21	4.07



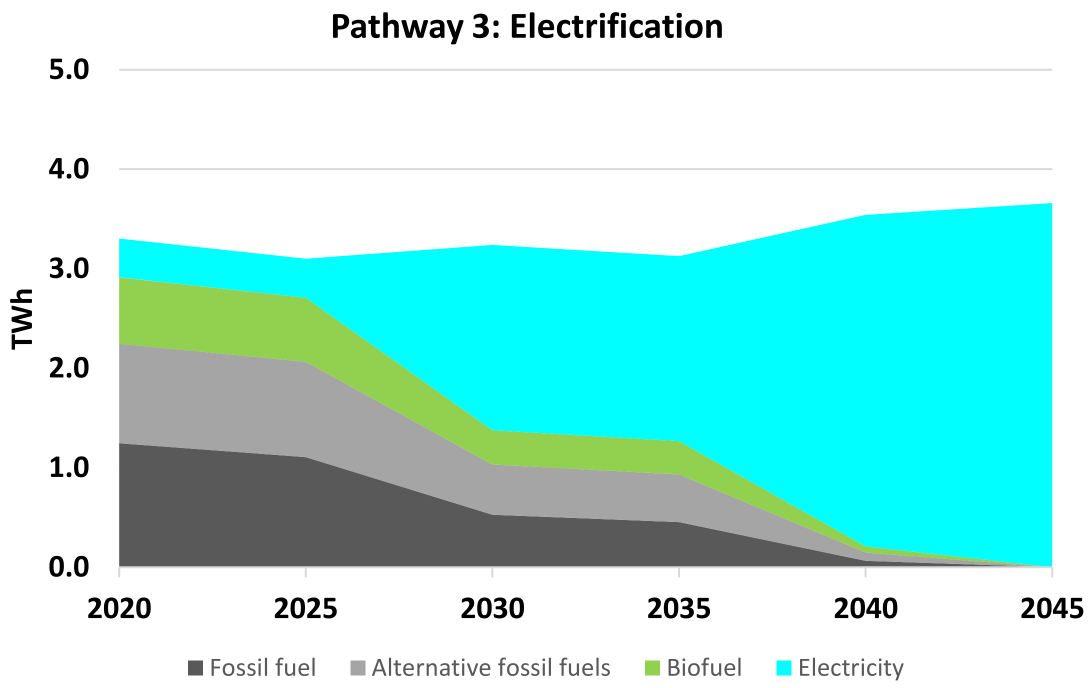
Post Combustion Pathway

	2017	2020	2025	2030	2035	2040	2045
Production cement (Mton / year)	3	3	3	3	3	3	3
Production cement clinker (Mton/ year)	2.58	2.55	2.40	2.25	2.10	1.95	1.80
Cement clinker substitutes (Mton/year)	0.42	0.45	0.60	0.75	0.90	1.05	1.20
Emissions cement (MtCO2e/year)	2.51	2.46	2.31	2.15	0.92	0.84	0.00
Captured emissions (MtCO2/year)	0.00	0.00	0.00	0.00	0.91	0.84	1.44
CCS energy penalty (TWh/yr.)	0.00	0.00	0.00	0.00	0.41	0.38	0.65
Electricity (TWh/yr)	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Bio Coal (TWh/yr)	0.26	0.27	0.31	0.33	0.35	0.40	0.43
meat & bone meal (TWh/yr)	0.20	0.20	0.23	0.25	0.26	0.30	0.32
sewage sludge (TWh/yr)	0.09	0.09	0.11	0.12	0.12	0.14	0.15
Other Biomass (TWh/yr)	0.10	0.11	0.12	0.13	0.14	0.16	0.17
Fossil fuel (TWh/yr)	1.45	1.04	0.84	0.63	0.44	0.18	0.00
Alternative fossil fuels(TWh/yr)	0.92	1.00	1.19	1.17	1.14	1.11	1.05
Total energy use (TWh /year)	3.41	3.10	3.20	3.03	3.26	3.06	3.15



Electrification Pathway

	2020	2025	2030	2035	2040	2045
Production cement (Mton / year)	3.00	3.00	3.00	3.00	3.00	3.00
Production cement clinker (Mton/ year)	2.55	2.40	2.25	2.10	1.95	1.80
Cement clinker substitutes (Mton/year)	0.45	0.60	0.75	0.90	1.05	1.20
Emissions cement (MtCO2e/year)	2.46	2.31	1.18	1.10	0.18	0.00
Captured emissions (MtCO2/year)	0.00	0.00	0.53	0.49	0.91	0.94
CCS energy penalty (TWh/yr)	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (TWh/yr)	0.39	0.39	1.86	1.86	3.33	3.66
Bio Coal (TWh/yr)	0.27	0.26	0.14	0.13	0.02	0.00
meat & bone meal (TWh/yr)	0.20	0.19	0.10	0.10	0.02	0.00
sewage sludge (TWh/yr)	0.09	0.09	0.05	0.05	0.01	0.00
Other Biomass (TWh/yr)	0.11	0.10	0.06	0.05	0.01	0.00
Fossil fuel (TWh/yr)	1.25	1.11	0.53	0.45	0.07	0.00
Alternative fossil fuels(TWh/yr)	1.00	0.96	0.50	0.48	0.08	0.00
Total energy use (TWh /year)	3.30	3.10	3.24	3.13	3.54	3.66



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