The Bio Steel Cycle –
net-zero CO_2 emissions steel production

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Abstract

This research critically analyses global data on CO_2 emissions from the iron and steel industry, including related sub-sectors, to propose low-carbon and clean solutions for the sector. The different stages of resource extraction, transformation, and finally steelmaking and finishing have been examined to establish the current state of knowledge regarding CO_2 emissions at each stage. A UK-centric PESTEL and SWOT analysis with the view to implementation of a green steel production cycle called Bio Steel Cycle accompany the data.

The "Bio Steel Cycle" framework could be adapted to apply to a range of industrial activities, not only the steel industry. The working title of the study: "CO_2 reduction in the steel industry" led to the development of three specific research questions: 'Which level of CO_2 emissions are being produced at which stage of the steel production process?' and 'How can CO_2 emissions be effectively reduced in steel production?' and as a consequence 'Can the newly developed Bio Steel Cycle framework support energy independence?'. The aim of this study was to create a universally applicable model and strategy to reduce CO_2 emissions effectively and sustainably in steel production; and to refine the model in line with circular economic principles.

The different stages of the overall steelmaking process have been examined, and a comprehensive overview has been established, based on the blast furnace – basic oxygen furnace route. All emissions identified have been calculated based on the assumption of steelmaking in a 330 metric tonnes capacity furnace.

Verified industry and scientific data, such as parameters and specifications published by Thyssen-Krupp, ArcelorMittal, Voestalpine, Saint Gobain, Tata Steel, Rio Tinto and British Steel played a significant role in fact-finding, alongside peer-reviewed academic publications. Mathematical modeling and software process simulation (Aspen Plus, Simul8 and INOSIM) was used to verify and further analyse the gathered data.

It is my understanding that – theoretically – when attempting to address the three research questions, the implementation of all components within the Bio Steel Cycle, technology and mechanisms currently exist could almost eliminate the currently produced 4,760.61t of CO_2 emissions along the whole line of process stages in iron and steel manufacturing. Additionally, a higher degree of energy independence of up to ~90% could be achieved and a stronger incentive to accelerate the efforts to transform the energy market into an industry based on renewable energy technologies seems achievable with the technology currently available.

Although considerable time and resources have been devoted to this study, there are clearly limitations to desktop research. Variability of data collection methods, reference points and research populations among the publications reviewed also made the acceptance of some publications difficult for the purpose of this study. However, some journal articles based on research investigating several hundred steel plants in specific countries, including carbon reports and process simulations, have provided valuable secondary data for verification.

The data contained within the production process simulation software packages are designed to be close to real-life applications but there are some areas where this appears to be lagging recent technical and knowledge advancement in industry and academia. Furthermore, until there are clear instructions, globally, on how to measure, evaluate and report greenhouse gas emissions in any given industry, the reported data provided so far, by industry and academia, requires to be treated with caution.

Acknowledgement

It needs to be clearly stated that, without the incredible support from the University of Staffordshire, and namely my supervisors and mentors Hamidreza Gohari Darabkhani and Abdel-Hamid Soliman, this study would quite possibly never have come to be.

Nomenclature

BAT - Best available technology
BCA - Border carbon adjustment

BF - Blast furnace
BOF - Basic oxygen furnace
BS EN ISO - British Standard / European Standard / International Organization for Standardization [British national version of ISO Standards (International Organization for Standardization)]
CapBF - Total capacity (kg) Blast furnace
CapBOF - Total capacity (kg) Basic oxygen furnace
CapEAF - Total capacity (kg) Electric arc furnace
CAPEX - Capital expenses
CCUS - Carbon capture and utilisation or storage
CGE - Computable general equilibrium
CH_4 CCS - Methane CCS – Carbon capture and storage
CO_2 - Carbon dioxide
DRI - Direct reduced iron
EAF - Electric arc furnace
EAF - Electric arc furnace
E_{imp} - Total imported energy (kg/steel)
$E_{mSp.El.}$ - CO_2 emission savings/avoidance potency factor
Fe_2O_3 - Hematite l Hydrogen feed ratio
FeO - Wuestite
GEI - Grid emission intensity
GHG - Greenhouse gas emissions
H_2O – Water, chemical formula
HBI - Hot-briquetted iron
H-DR - Hydrogen direct reduction
HHV - Higher heating value
I4.0 – Industry 4.0
IEA -International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
IRENA - International Renewable Energy Agency
LHV - Lower heating value
LKAB - Luossavaara-Kiirunavaara Aktiebolag (Swedish Mining Corporation)
LS - Tonne liquid steel (metric)
MAC - Marginal abatement cost
MCDA - Multi criteria decision analysis
$MCO_{2,proc}$ - Onsite CO_2 emission (kg/steel)
M_{ind} - Production rate of steel (kg) capacity
$M_{O.Ind}$ - Usage of oxygen on site
N_G - Natural gas, fossil derived methane
OandM - Operation and maintenance
O_2 - Oxygen, chemical formula
OPC - Ordinary Portland Cement
OPEX - Operating expenses
PC – Pulverized coal
P_{CC} - Electricity import for CO_2 capture/savings process (MJ)
PEM - Proton exchange membrane
Pind - Electricity import for the industrial process (MJ)
PV - Solar Photovoltaic Cells
Q - Net heat transferred into the system, Q is the sum of all heat transfer into and out of the system
SEC - Specific energy consumption
SOE - Solid oxide electrolysis
SSAB - Svenskt Stål AB (Swedish Steel Corporation)
TGRBF - Top gas recycling blast furnace
W - Network done by the system, W is the sum of all work done on/by the system
WTO - World Trade Organization
ΔU - Change in internal energy U of the system

Chapter 1 Introduction

1.1 Area of research

The area of research was broadly defined as the iron and steel industry. The discipline likely to yield the most suitable expertise at Staffordshire University was the Department of Engineering supervising the research degree program PhD Electrical and Electronic Engineering. The expertise in this department includes experts in the field of renewable and sustainable engineering, and low carbon and renewable energy systems, as well as signal processing and communication technology. Utilising a multi-disciplinary approach, this PhD brings together innovation in science and technology to applications, ranging from carbon capture, utilisation and storage to inert system energy generation and use of electrical energy (including renewable energy). Areas of research strength include biophysics, chemical transformation science, process simulation science used for the design, development, analysis, and optimisation of technical processes used in iron and steel process industries, and production process engineering.

1.1.1 The scope and challenges researching decarbonisation of the steel industry

To begin with, the extent of the area this research concerns itself with, meaning: the scope of this research, requires to be specified. Some of the topic matter is sensitive and requires detailed exploration. The scope of this research is broadly defined as the iron and steel industry and ancillary industries directly within the value chain of the steelmaking process. This entails a thorough investigation of the CO_2 emissions per metric tonne of product for all materials and resources required to make steel, and the identification of the level of CO_2 emissions per metric tonne of steel produced. Furthermore, the creation of a model for the production of near zero CO_2 emissions steel, and the compilation of a strategy implementing the newly created model for the production of near zero CO_2 emissions steel. Additionally, it is required to extend the development of the zero CO_2 emissions steel production strategy to simultaneously increasing energy independence in steel production.

As with every attempt into pushing the boundaries of the known, there are potential challenges during the development of deliverables to the items specified within the scope of this research. Determining CO_2 emissions per tonne of steel in the iron and steel industry and ancillary industries with the aim of determination of the CO_2 emissions per tonne of product and to determine the CO_2 emissions per tonne of steel produced, presents several challenges. Some of these are data availability and transparency, variations in production methods, regional differences, carbon emissions measuring and reporting issues and accounting complexities. It so seems that steel producers do not tend to publicly disclose detailed emissions data, at least not in the UK, within the directors' reports. It could be suspected that some companies in the EU, UK and elsewhere may under-report CO_2 emissions and greenhouse gas emissions figures, possibly due to the distinct lack of a legal reporting framework, reporting guidelines and data extraction point determination. Additionally, there is no legal framework setting out the technical specifications of emissions monitoring systems. The variability of steel production methods is not only confined to the production route itself but is also partially due to the variation in age of the production lines and the machinery used. Recently updated production infrastructure is more likely to be energy efficient than older machinery. Geographical challenges need to be considered, too, as some regions rely more on coal-based processes, such as China, and India, leading to higher CO_2 emissions due to the high carbon content of coal (Shao *et al.*, 2022; Morrow et al., 2014; eia, 1994, 2021, 2023a). Countries with a clean energy grid, such as the Nordic countries (Sweden, Norway, Finland), are using hydropower and other sustainable energy sources (Sovacool *et al.*, 2018) and therefore have lower emissions. Government policies, incentives, subsidies, and embedded carbon emissions and carbon pricing schemes affect the overall emissions intensity.

There are also carbon accounting issues, which were partly addressed in the UK by developing the scopes 1, 2 and 3 equivalent calculation emission factors for CO_2 and greenhouse gas emissions (Department for Energy Security and Net Zero, 2024). These are relating to steel plants, as follows:

- Scope 1 Emissions: Direct emissions from steel plants (generated by the combustion of coke in the blast furnaces; transport mileage)
- Scope 2 Emissions: Indirect emissions from purchased electricity (variations due to the different methods of generating energy: a) fossil fuels, b) renewable energy (wind, solar, hydro, geothermal), and c) biomass, biogas.
- Scope 3 Emissions: Emissions from raw material extraction, transportation, resource transformation (coking, sintering, calcification, (hydrogen) direct reduction, and upstream/downstream use – which are often ignored, due to their complexity of determination.

There is also the variability in raw materials and energy sources to be considered, namely the quality of iron ore and coking coal. The quality of these materials affect the amount of energy required (eia, 1994). Some plants use carbon capture technology, which reduces the emissions to be recorded and reported (Tanzer, Blok and Ramirez, 2021). Access to low-carbon alternatives such as green hydrogen is still limited in many places (Colla and Matino, 2021). As mentioned before, there is a distinct lack of standardised reporting and a range of different methodologies exist, such as the Intergovernmental Panel on Climate Change (IPCC) guidelines, country-specific GHG (greenhouse gas) protocol, and industry-specific frameworks leading to inconsistent numbers (IPCC, 1996,2006,2019,2022,2023; HM Government UK, 2008). It has come to light that - due to the lack of standardised reporting - some companies measure emissions per tonne of crude steel with emissions from the BF/BOF route only (Tata Steel Europe, 2020, 2024), others per tonne of finished steel product (WSA, 2022), with data recorded from widely differing emissions extraction points along the production process line. Also, lifecycle emissions (LCA) can differ depending on system boundaries. Technological advancements and industry changes, innovative and emerging technologies, such as hydrogen-based steelmaking, carbon capture, utilisation and storage and direct electrolysis complicate historical company record comparisons. Efficiency improvements in existing plants have the potential to lower emissions significantly, but not all facilities upgrade at the same rate, to the same extent, at the same time.

Researchers can possibly overcome these challenges by using a variety of different data sources (industry reports, academic studies, government data, associations' literature, scientific discourse) and comparing regional emissions factors from electricity grids and raw materials, standardising of emissions calculations using established methodologies by the legislature, considering all Scope 1, 2 and 3 emissions and upstream/downstream impacts, and collaborating with industry experts to obtain primary data, if possible.

A researcher attempting to create and implement a model for near zero CO_2 emissions steel production whilst simultaneously increasing energy independence will face a range of technical, economic, policy-related, and practical challenges. Some of these are technological uncertainty and innovation gaps. As an example: hydrogen-based steelmaking (H_2-DRI) is a leading alternative, but green hydrogen (produced using renewable energy) is not yet available at scale. Also, electrowinning & molten oxide electrolysis are still in the experimental stage and require further research and development. Furthermore, carbon capture and storage (CCS) whilst eliminating most GHG emissions also adds cost, and some CCS solutions are even increasing the energy demand, which is counter-productive. There are also material and resource constraints to be considered, as the shift to green steel depends on access to either high-quality iron ore or scrap steel, which is both limited, and the infrastructure for steel recycling is not yet universally established or accessible. Large-scale hydrogen-steelmaking requires substantial amounts of renewable electricity and water for electrolysis and rare materials for additional equipment, such as platinum for electrolysers, might create supply chain bottlenecks. Which implies there are energy efficiency vs. emissions reduction trade-offs to be taken into careful consideration. Additionally, there are process integration challenges, as retrofitting existing plants vs. designing new plants arrives with modeling complexity and uncertainties, as there is a variability of GHG emissions in energy sources to be considered, as well as the lack of real-world data on emissions from experimental processes to be taken into account. And there are also regional differences in electricity grid carbon intensity, which will affect the total emissions from production. The compilation of a strategy for implementing the newly created model comes up against the realities of economic barriers and investment risks, as the costs of producing zero-carbon steel varies widely, depending on geographical as well as topographical location. Producing green steel seems to be only competitive with sufficient policy support, and legislative instruments to aide implementation, as there is high capital expenditure (CAPEX) for new infrastructure and renewables installations (such as hydrogen production facilities) to be considered. Additionally, there is a high level of uncertainty in long-term demand for green steel, which could deter investors. The infrastructural limitations are making decisions for CAPEX projects concerned with renewable energy technology difficult. As an example: the lack of hydrogen transport and storage infrastructure makes scaling very challenging and could be an obstacle for retrofitting existing steel plants with zero-emission and renewables technology.

Furthermore, the iron and steel industry has grown over centuries and long-established ways of thinking have generated an inherent natural resistance across the industry, as steel producers are reluctant to adopt new methods without financial incentives, as much as downstream industries (i.e. automotive and construction) may be slow to adopt green steel without encouragement through government policy guidelines and government incentives.

It is my understanding that an inevitable consequence of any innovative model and strategy for decarbonisation will require raw material supply chain adaptation, such as establishing supply routes and sourcing suitable scrap steel or the creation of steel recycling facilities nearby. Regulatory and policy uncertainty requires to be overcome as well as carbon pricing and incentives variation, by country and region, pose an additional challenge to be considered for the compilation of a meaningful solution.

Extending the innovative strategy to increase energy independence in steel production needs to take into account the renewable energy constraints. As an example: even perovskite solar panels are only able to reach a 28% maximum efficiency (Harter *et al.*, 2024). As green hydrogen steelmaking requires reliable, consistent renewable electricity, the varying infrastructure and availability, from country to country, needs to be taken into account, too.

Large-scale renewable projects (solar, wind, hydro, hydrogen, geothermal), which are required to make the implementation of any carbon emissions reducing strategy a reality, are facing planning permission issues, change of land use obstacles, and grid expansion delays. Particularly in terms of hydrogen production upscaling, there are challenges with regards to the electrolysers required for the production of green hydrogen – as the production requires significant infrastructural scale-up. Hydrogen storage and transportation technologies require functionality and efficiency improvements and pose CAPEX challenges. There are also grid stability and energy security issues as well as pressures from high-energy consumers (steel plants) to be considered, and therefore, shifting to renewables requires careful planning and phased implementation.

Countries dependent on imported fossil fuels may struggle to secure alternative energy sources quickly or find it challenging to create an energy infrastructure based on renewables – as afore mentioned. The geopolitical risks and market uncertainty needs to be considered, as global competition for hydrogen resources and renewable energy project investments and dependency on specific regions for critical materials can derail any carefully crafted carbon emissions reduction model and strategy implementation. It is my understanding that the immediate potential solution for researchers to work within the set scope, to overcome the numerous challenges and to create a viable model and strategy seems to be engaging in a hybrid approach. A mix of geopolitical factors and levels of variation and uncertainty are built-in as fail-safe, and the incorporation of bio energy carbon capture and storage (BECCS), and carbon capture utilisation and storage (CCUS) processes, as well as hydrogen and electrification technologies, are providing the viable technologies for the implementation of an innovative concept.

1.2 Importance of this research

With the natural environment declining and our climate heading for catastrophe, the main driver for climate change – CO_2 – and its companion greenhouse gas emissions need to be reduced as much and as quickly as possible, in all sectors (IPCC, 2023a, 2022, 2022a).

Every effort needs to be made across all disciplines to reduce CO_2 emissions (EMAF, 2023) – therefore, this research has focused on the iron and steel industry, as this sector alone is responsible for between 7% and 11% WSA (WSA, 2021a) of global industrial CO_2 emissions, although there are voices who claim these could be much higher (Morrow *et al.*, 2014; Hasanbeigi *et al.*, 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Ren *et al.*, 2021; Swalec, 2021; Wang, *et al.*, 2022; Zhang, *et al.*, 2022) Without any global legal or practical framework or reporting structures in place on how to measure CO_2 emissions and consequences of non-compliance, all these statements have to be viewed with caution. The literary sources used show to have used data sets accumulated and defined using a range of methods, with data and information partially provided voluntarily by industry, and without a clear framework of how, where, and when to measure CO_2 or GHG emissions, or in which format to report these, the definition of de facto emissions is very challenging, indeed. China is currently thought to be responsible for 50% of these GHG (Ren *et al*., 2021).

1.3 Significance of the research

As the global iron and steel industry is still heavily reliant on coal (80% carbon in anthracite coal)(IEA, 2023c), due to the blast furnace / basic oxygen furnace steelmaking process still being the main method of producing steel (80% BF/BOF and 20% electric arc furnace and other methods) this industry was chosen as the subject of this thesis due to the immense potential for decarbonisation (Proctor *et al.*, 2000; IETD, 2021a, 2021a; Li *et al.*, 2022; Encyclopedia Britannica, 2023; Kildahl *et al.*, 2023a, 2023b).

The model, strategy and processes developed during this research are easily implemented within existing steel plants, but also across most heavy industries (EMAF, 2023). This study and its findings will reveal the immense potential and opportunities not only to decarbonise the steel industry, but its replicability in most manufacturing operations.

It is my understanding that the decarbonisation of production processes is technically possible in most emission-intensive manufacturing processes. Additionally, this study and findings will provide a glimpse into the analysis, implementation gaps and the potential for energy independence in the steel industry but is not limited to this one sector.

Institutions like the European Commission are now actively promoting the development of circular economic technologies throughout their member states and also governments of other countries and international corporate businesses:

Table 1- 1: Countries and institutions making a real effort towards a circular economy

Country / Institution	Reference
European Commission	Szulecki, 2016; Szulecki and Claes, 2019; Perissi and Jones, 2022
China	Li *et al.*, 2022; Lee *et al.*, 2023 Sakamoto *et al.*, 2021;
Japan UK	Rattle and Taylor, 2023 Stephenson *et al.*, 2019; Griffin and Hammond, 2019; Griffin and Hammond, 2021; Sovacool, Iskandarova and Geels, 2024
France	Sachs *et al.*, 2014; Mathy *et al.*, 2016
Canada	Government of Canada, 2016; EDC, 2022; Hendricks and Hung, 2021; Rudd *et al.*, 2021; Ministry of Agriculture, Food and Rural Affairs Canada, 2023
The Netherlands	Baldino, 2021; van den Bergh and Savin, 2021; Yang *et al.*, 2022; Carmona-Martínez *et al.*, 2024
Sweden	Bramstoft and Skytte, 2017; Nasiritousi and Grimm, 2022; Urban, Nurdiawati and Harahap, 2024
Australia	Denis *et al.*, 2014
Finland	Sovacool *et al.*, 2018; Su *et al.*, 2022; Tran and Egermann, 2022
International corporate businesses	Siemens, 1885, 2022, 2023a, 2023b; Jones, 2011; Tata Steel, 2023; Tata Steel Europe, 2020, 2023, 2023a, 2024; Tata Steel Nederland, 2023; McKinsey & Company, 2021; ArcelorMittal, 2023b, 2023a; Voestalpine, 2023

The European Commission has investigated the positive economic impact a circular economy would have on GDP and estimated that circular economy-type economic transitions can create 600 billion euros annual economic gains for the EU manufacturing sector alone, based on figures 2000-2015 (COM, 2023a; CIRAIG, 2015). The first country in the world to have adopted a law for the circular economy, was China in 2008 (CIRAIG, 2015), and circular economy is recommended as an approach to economic growth that is in line with sustainable environmental and economic development (EMAF, 2019, 2023).

As the EU and several countries have realised, new approaches to the modus vivendi are required, as growth at all costs is destroying the planet and will lead inevitably to the end of the world as we know it (IPCC, 2022, 2023a).

Radical restructuring and behaviour change are required, as far as consumption and production processes are concerned. To reduce the ecological impact, and also the impact on natural resources, and reduce supply chain pressures, it would make more economic sense to produce only recyclable materials in a sustainable way, for which suitable regulation and legislation development are required (EMAF, 2019, 2023).

There are areas of human behaviour which will be difficult to adjust, and this being humans' need for water, food and habitat. However, there are plenty of opportunities where humans can change their modus operandi: demonstrated already in 2018, when Bataille et al. argued, that reducing energy-intensive industrial GHG emissions to Paris Agreement (UN, 2016) compatible levels might not just be technically possible but can realistically and easily be achieved with sufficient prioritisation by industry and policy effort in the echelons of political power. The findings of their work provided valuable input and a feasibility argument of the author's developed Bio-Steel Cycle theory and strategy.

Sustainable, circular production starts at the design stage, for which we need skilled people with knowledge to create infinitely recyclable products, to replace the existing products which are the result of linear production. The smaller the cycle, the higher the products' value retention and longer life span in accordance with its original purpose. Within the longest cycle, the value or residual value of the product is at its lowest and a different application must be found. Therefore, questions need to be asked, re-evaluating the status quo and redefining design procedures to ensure value retention.

1.4 Establishing the research questions as basis for setting aims and objectives

1.4.1 Introduction

The aims and objectives of this study were established as a result of setting the research questions, after conducting the literature review, which is described in section 2.2 Research Philosophy:

1) Which level of CO_2 emissions are being produced at which stage of the steel production process?
2) How can CO_2 emissions be effectively reduced in steel production?
3) Can the newly developed Bio Steel Cycle model and strategy support endeavours for energy independence?

The resulting research work therefore aimed at devising the objectives as per section 1.5, and a methodology with the aim to find answers to the three research questions.

1.4.2 Aims

The set aims as a result of establishing the research questions are, as follows:

1) Creating a universally applicable model and subsequent strategy which have the potential to reduce the CO_2 emissions effectively and sustainably in steel production.

2) Defining the afore mentioned model and strategy in line with circular economic principles

3) Providing evidence to prove that the newly developed Bio Steel Cycle model and strategy support endeavours for energy independence.

The whole project – and in the following, the objectives - were established with reference to the research being conducted with a practical approach, in response to the authors knowledge of the industry. The author has worked in a professional capacity in multi-metal manufacturing and renewable energy technology manufacturers and has therefore an invaluable insight into the internal and external mechanisms which have driven the iron and steel industry into the current situation, which is unsustainable in the long-term (Price *et al.*, 2002; Muslemani *et al.*, 2021; Bhaskar *et al.*, 2022; Kiessling, Gohari Darabkhani and Soliman, 2024).

1.5 Objectives

The topics of focus were:

a) defining all stages related to and necessary for steelmaking
b) identifying global decarbonisation efforts and steel production process improvement endeavours currently underway
c) utilise the gathered data to compile a technically sound and economically viable model and strategy based on circular economic principles (EMAF, 2019, 2023).

The topics informed the setting of the objectives, which were chosen as the necessary building blocks to find evidence for constructing answers to the research questions and resulting aims. The classifications of technical readiness levels (TRL) 6-9 by industry was accepted as key performance indicators for the decarbonisation projects and processes and was chosen as the technology selection criterium for consideration as components in the newly to be developed model and strategy.

The author has worked in multi-metal manufacturing and consulting positions for three decades and is painfully aware of the issues in metal manufacture, and which areas of research to choose from to provide meaningful data and evidence for this research. Some of these issues are:

- increased resource scarcity as a result of unsustainable business practice,
- vast volumes of unreported greenhouse gas emissions (GHG) being produced daily in production without businesses having to fear legal consequences or sanctions,
- profit being the all-defining business aim, and profit as the ultimate gain and seen to be more important than people and the natural environment.

It was not the focus of this research to delve into all the technical and other details with regards to the technologies chosen as components for the innovative model and strategy. Merely their TRLs and viability within the project in development and their potential for avoiding, saving or utilising CO_2 emissions was the deciding factor.

Therefore, the objectives were set, as follows:

- Conducting a literature review, covering the following aspects:
  - Carbon life cycle
  - Resources for and stages in steel production

  - Steel production CO_2 emissions
  - Biomass as alternative fuels
  - Energy and Exergy analysis
  - Energy, emissions and cost
  - Decarbonisation of the steel industry and selected case studies
  - Energy consumption and emission mitigation of emerging processes
  - HM Government "The Ten Point Plan for a Green Industrial Revolution"
  - Carbon Capture, utilisation and storage
- Identifying the gaps in knowledge and understanding regarding the CO_2 emissions for the entire steel production processes and stages, within the afore mentioned areas of specialism
- Investigating existing steel production processes with regards to greenhouse gas emissions, and particularly, CO_2 emissions
- Developing a universally applicable model, suitable for the iron and steel industry
- Designing an ecologically and technically sound strategy, based on the afore mentioned model
- Establishing hypotheses and investigating these against standard mathematical principles
- Providing proof of viability and replicability by creating process simulations in suitable software applications.

Table 8-2 in section 8.6.3 will provide the links between the set objectives, and at which position in the thesis the aims and objectives have been met.

1.6 CO_2 Emissions and Global Warming

The highest level of anthropogenic CO_2 emissions since the industrial revolution has been identified as the main driver for climate change, the destruction of the natural world and the 6th mass extinction of all species happening right now (IPCC, 2021, 2021a, 2022, 2022a, 2023a, 2023b; Rockström *et al.*, 2024). Further detail to be found in section 1.7., within the 2023 IEA reports (IEA, 2023a) from the Intergovernmental Panel for Climate Change (IPCC, 2023a) and from February (IPCC, 2022a) 2022 and April 2022 (IPCC, 2022) as they have issued a clear warning of the consequences of inaction and procrastination. Globally, we need to act quickly, decarbonise industry, significantly reduce CO_2 emissions in energy generation and radically change agriculture and arboriculture, whilst restoring natural habitats which have been lost due to anthropogenic activity.

The research for this thesis is the result of the author's long-standing affiliation with the metal-manufacturing industry and the commitment to mitigating industries' negative environmental impact, starting with efforts to improve the steel industry and affiliated sub-sectors.

1.7 Heavy Industries

As the results of the extensive literature review have shown, CO_2 emissions have been seemingly underreported and underestimated up to now, in heavy industries. With the new knowledge and awareness of looming climate catastrophe, global thought and innovation leading organisations, such as the eia (eia, 2021, 2021a, 2021b, 2023, 2023a) and the IPCC have investigated the global CO_2 emissions and reported significant increases (eia, 1994, 2021, 2021a, 2021b, 2023, 2023a; IPCC, 2022, 2022a, 2023). Global energy-related CO_2 emissions increased at a rate of 0.9% and 321 Mt in 2022, arriving at a new record of over 36.8 Gt CO_2 emissions (eia, 1994, 2021, 2023a; Canadell *et al.*, 2003; IEA, 2000, 2018, 2021a, 2021b, 2021c, 2022, 2023a, 2023b, 2023c; Global Carbon Project, 2020; Liu *et al.*, 2020; Liu *et al.*, 2022; Mehmood *et al.*, 2020; IPCC, 2022; Statista, 2022; NASA, 2023; IPCC, 2022a). Recorded emissions from combustion processes for energy generation increased by 423 Mt, although at the same time emissions from industrial processes decreased by 102 Mt (eia, 1994, 2021a, 2023a; IPCC, 2022, 2022a). Climate Change related challenges in 2022, posed by extreme weather events, contributed to the growth in emissions. The proportion of 60 Mt CO_2 can be attributed to cooling and heating requirements, with regards to the 321 Mt CO_2 increase, and an additional 55 Mt CO_2 to nuclear power plants being offline (eia, 1994, 2021, 2023a; Canadell *et al.*, 2003; IEA, 2018, 2021b; Global Carbon Project, 2020; Liu *et al.*, 2020; Liu *et al.*, 2022; Mehmood *et al.*, 2020; IPCC, 2022; Statista, 2022; NASA, 2023; IPCC, 2022a). This leads to the conclusion, that not only are nuclear power plants a risk to the planet's existence by their very nature, but these also generate emissions when they are not even producing energy to (eia, 1994, 2021, 2023; Canadell *et al.*, 2003; IEA, 2018; Global Carbon Project, 2020; Liu *et al.*, 2020; Liu *et al.*, 2022; Mehmood *et al.*, 2020; IEA, 2021b; IPCC, 2022; Statista, 2022; NASA, 2023; IPCC, 2022a).The increase in CO_2 emissions from coal combustion more than offset the decrease in emissions from natural gas at 1.6% or 118 Mt. CO_2 emissions from coal grew by 1.6% or 243 Mt, reaching a new record high of almost 15.5 Gt (The Rodney and

Otamatea Times, 1912; eia, 1994, 2021; Bogunovic *et al.*, 2009; Yi *et al.*, 2018; U.S.E.I., 2021, 2023a; Turnbull, 2021; Yang *et al.*, 2021; Government of India, 2023; IEA, 2023a, 2023c). Additionally, emissions from using oil outgrew emissions from coal, rising by 2.5% or 268 Mt to 11.2 Gt of CO_2 (eia, 2021, 2023a; IEA, 2022). 50% of this increase resulted from transport, and specifically aviation. The most significant sectoral increase in CO_2 emissions in 2022 came from electricity and heat generation, where emissions increased by 1.8% or 261 Mt CO_2 emissions. Global emissions from coal-fired power plants and for heat generation grew by 224 Mt or 2.1%, led by the BRIC economies (eia, 1994, 2021, 2023a; Canadell *et al.*, 2003; IEA, 2018; Global Carbon Project, 2020; Liu *et al.*, 2020; Liu *et al.*, 2022; Mehmood *et al.*, 2020; IEA, 2021b; IPCC, 2022; Statista, 2022; NASA, 2023; IPCC, 2022a). Emissions across the US grew by 0.8% or 36 Mt, with the buildings sector recording the highest emissions growth (ECRA, 2009, GCCA, 2021; WBCSD, 2017; Ren and Li, 2023). Although other countries reduced their natural gas use, the US saw an increase of 89 Mt in CO_2 emissions from gas, due to peak electricity demand during recent summer heat waves, as a result of anthropologically induced Climate Change (USEPA, 2015; Cumicheo, Mac Dowell and Shah, 2019; Desai and Camobreco, 2020; EEA, 2020,2021; EERE, 2021; Pandit, Qader and Lim, 2021; SHELL, 2022; eia, 2023; USEPA, 2023). Emissions from Asia's developing economies, excluding China, increased by 4.2% or 206 Mt CO_2, with more than 50% of the increase in emissions attributed to coal-fired power plants (Price *et al.*, 2002, 2002; Li and Zhu, 2014; Chen *et al.*, 2018; Shao *et al.*, 2022; Liu *et al.*, 2022; Zhang, *et al.*, 2022; IEA, 2023c).

Implementing the BiSC - using the provided seven-steps-strategy (Kiessling, Darabkhani and Soliman, 2022) - can potentially result in achieving net-zero CO_2 emissions in steel manufacturing much sooner than 2030 (UNIDO, 2011). The UK Government has set a target which will require the UK to bring all greenhouse gas emissions to net-zero by the year 2030. The concept and strategy of the BiSC is transferrable to most heavy industries.

1.8 Iron and Steel Manufacturing

The steel industry is thought to be responsible for between 7–11% of global CO_2 emissions, but some scientists are of the opinion it could be significantly higher (Griffin and Hammond, 2019; Griffin and Hammond, 2021; Morrow et al., 2014; Hasanbeigi et al., 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Baena-Moreno et al., 2021; Ren et al., 2021; Wang, 2022), due to high fossil-fuel and energy consumption and the fact that there is no unified way of recording or reporting CO_2

emissions. The wide-ranging difference in percentage shares can largely be attributed to the different approaches to a) which level of carbon emissions have been observed, b) how many different stages and processes in (steel) production have been included and measured, c) which methods have been used to measure the quantity of CO_2 emissions, and d) the different geographical physical locations they have been observed at. As mentioned in 1.2, there is currently no existing globally applicable legal framework with guidance to report greenhouse gas emissions or guidance for any industry to pinpoint the emissions data extraction points for emissions level determination. The methods of data collection and collation vary wildly and there is no unified method. Therefore, these %-level statements need to be taken cautiously, as the GHG emissions could be even higher than the already identified levels (IEA, 2023b; Zhang, 2022; Wang, *et al.*, 2022; Swalec, 2021; Ren *et al.*, 2021; Morrow *et al.*, 2014; Hasanbeigi *et al.*, 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022) .

The onus is partly on industry, and the urgent requirement to remedy the environmental damage caused and to decarbonise production. This desk research explores the Bio Steel Cycle (BiSC) model and strategy and proposes a seven-step system to overcome the emission challenges within the iron and steel industry. Additionally, the multi-disciplinary approach of the Bio Steel Cycle will be explored for its potential to increase energy independence with part- or full implementation. The measured levels of combined CO_2 emissions from mining, crushing, pelletising, lime burning, coking, sintering over to blast-furnace and basic-oxygen-furnace operation, casting, rolling and finish machining have been investigated.

The BiSC includes CO_2 capture and utilisation, implementing renewable energy sources (solar, wind, micro-turbines, green H_2), plantation of biomass for DAC, CO_2 absorption and provision of biomass. Additionally, the well-established technology of waste management, anaerobic digestion (HM Government, 2020a), will feature as the source of green hydrogen and biogas, working in tandem with turbines (Kabeyi, 2022; Bazooyar, 2020; Nezhad, *et al.*, 2019), for utilisation in the steelmaking process. The 7-step-implementation-strategy, as discussed in detail in the author's first publication in the UK (Kiessling, Darabkhani and Soliman, 2022), starts with switching to an energy provider who derive their energy at 100% from renewable sources, develops over improvements in process technology and installation of flue gas carbon capture, and concludes with the utilisation of biogas and – as an additional benefit - biogas-derived hydrogen. Hydrogen and biogas are the two main products from anaerobic digestion of the grown agrifood in the cycle, but fertiliser pellets from residual digestate and effluent are a carbon-neutral by-product of the Bio Steel Cycle, as they naturally develop during the anaerobic digestion process (Kiessling, Darabkhani and Soliman, 2022).

1.9 Thesis Structure

The thesis contains nine chapters, starting with Chapter 1, providing information about the setting and background of and the reason for this work to be carried out.

Thesis chapter 2 paves the way with insight into the employed methodology.

Thesis chapter 3 takes the reader on a journey through the literature review, starting with a description of the carbon life cycle. It follows with detailing resources for and stages in steel production, after which the usage of biomass as alternative fuels in steelmaking is being explored. Steel production CO_2 emissions investigation and energy and exergy analysis are providing greater detail about the steel industry and the machinations within. With decarbonisation of the steel industry and selected case studies the literature review concludes with a sight of where we are at present to fulfil the so urgently needed net zero CO_2 emissions economy.

Thesis chapter 4 investigates in detail the aspects of the innovative model and strategy of the Bio Steel Cycle (BiSC) and the 7 steps to net zero carbon emissions in steel production and provides insight into the engineering aspects of process simulation software solutions.

Thesis chapter 5 with the findings of a thorough investigation highlights the opportunities of the Bio Steel Cycle implementation and components within such as heat loss recovery, retrofitting a variety of renewable energy technology, and a thorough MCDA (multi-criteria decision analysis) has been compiled to add a dimension of providing supportive decision-making aspects.

Thesis chapter 6 offers flowcharts and process simulations in software solutions such as Aspen, Simul8 and Inosim. The analysis of results in Chapter applies standard mathematical procedure, data modeling features, statistics, and showcases an overview of the total CO_2 emissions along most procedures along the steelmaking process.

Chapter 7 details the results and findings from the different pathways of investigation and analysis.

In thesis chapter 8, the knowledge contributions are summarised, starting with a PESTEL and SWOT analysis of the situation for green steel in the UK, then a summary of CO_2 emissions for the entire steelmaking process, and finally, pinpoints the advantages of the innovative BiSC model, concept, and strategy as well as the significant opportunities of achieving a higher degree of energy independence.

Thesis chapter 9 provides a summary of the conclusions derived from all investigations and methods of analysis and describes opportunities for further research.

Chapter 2 Methodology

2.1 Introduction

The research design process is quite complex, as each of the potential research questions, resulting from the extensive literature review - might require a different approach to data collection, and – potentially – the same process of data collection and subsequent evaluation might not be suitable to answer every one of the aspects of the questions. The population of the planned study will consist of contemporary academic and scientific authors, members of The Worldsteel Association, members of the Mineral Products Association (formerly British Lime Association), fellow researchers from ResearchGate, the author's professional network, peers, mentors and lecturers from Staffordshire University and Keele University, UK. Therefore, the tools for data collection require careful consideration of the requirements for each one of the groups of participants. Zotero was used for crediting the various contributors and sources of data and information, producing in-text citations and the reference list. An original investigation plan to include participants was created and mapped out, and the ethical approval for this work was sought accordingly - but later abandoned during the course of the project as the focus of the work changed. Hence why there is a reference to participants in the ethics form.

2.2 Research Philosophy

The desire for change initiated the first step on the research journey, the literature review, which has resulted in pursuing answers for the following research questions:

1) Which level of CO_2 emissions are being produced at which stage of the steel production process?
2) How can CO_2 emissions be effectively reduced in steel production?

Political unrest and wars in Eurasia and beyond, the global energy price hike and the cost-of-living crisis, not only in the UK, have given the research an additional path to pursue.

Another research question has developed as a result of these factors:

1) Can the newly developed Bio Steel Cycle model and strategy support endeavours for energy independence?

The ensuing research therefore aimed at devising a methodology which would provide answers to the questions above.

2.3 Research Approach

The research approaches, namely plans and procedures for research, which span the steps from notions and broad assumptions to detailed methods of data collection, analysis, verification, validation and interpretation, shall be laid out in detail in the following paragraphs. The approach might change during the course of the research project, and the ethical approval might become obsolete, as the challenges of this research on sensitive topics might require adjustment of the research tools of data collection: surveys, interviews, focus groups.

2.4 Research Paradigm

In order to establish the paradigm for this study, the researcher decided to rely on Punch's (2009) guidance, as it is important to be able to locate the research paradigm within which the research sits. The author will be taking a *pragmatic* and not a *paradigm-driven* approach to this piece of research as it is primarily driven by professional interest. It could be argued that the epistemological position of this research is *interpretive*. The epistemological position was set in line with Crotty's (1998) work, where the findings could be grounded either in objectivism or subjectivism. Conclusively, the theoretical perspective will be paramount for finding suitable research methods to carry out this study.

The pragmatic approach and the interpretive position of this research have informed defining the topics, aims and objectives (sections 1.4 and 1.5) and the research design. The author's decades of experience in multi-metal manufacturing and intrinsic industry knowledge of the unsustainable business practices informed the decision to embark on this research.

The desire to conduct this research was largely driven by the realisation that – to date – there is no publication available **which** would outline all stages and phases involved in steelmaking and their CO_2 emissions. Also, as far as the author was able to determine, as per publication date, no issue in literature has stated the total CO_2 emissions per metric tonne of steel produced. The purpose of this research (and resulting publications reflecting the results) is to make a contribution to global efforts on the path to averting climate disaster, in line with the Paris Agreement (UN, 2016) however small.

The pragmatic approach and interpretive epistemological position of this research were deemed to be appropriate in this context, as the work is driven by a practical issue and there are no research frameworks in existence, due to the novelty of this research. There were no research programs or curricula in existence for industrial CO_2 emissions determination at the time of starting this work, comparable to medicine or chemical engineering, were set research projects have a framework to follow during their studies.

2.5 Sampling – Research Design

Taking a pragmatic approach to conducting this research has far-reaching consequences for the research design, as compromises seem inevitable. Methodologically, the research will have to take a mixed approach and quantitative as well as qualitative data collection will play a significant role.

The *quantitative* data elements will consist of information relating to the respondents' demographic setting, and professional context and background information to ensure validity. The *qualitative* data, however, will be primary data and also secondary data and consist of information about the perceptions of contemporaries, relating to the steel industry and affiliated sub-sectors, integration of Industry 4.0 and an overview of valuable insights into multiple disciplines and how their technical specifics can play a role in providing answers to the research questions, serving the aims and fulfilling the set objectives. The participants will be academics (Professors Rockström and Dastoor), industry leaders and experts (Blue Planet (US), Tata Steel

(UK/EU), ArcelorMittal (F), Siemens (D), Thyssen-Krupp (D), British Steel (UK)), politicians and governmental organizations (Angela Merkel, Justin Trudeau, Joe Biden, Chambers of Commerce, HM Government departments and others – to be confirmed), and members of associations (World Steel Association, European Commission).

Participants' responses, specifically from the organisations such as Worldsteel and ResearchGate will be secondary data, as data will be evaluated which had been collected by the organisations from their members' bases. The interview questions as such will be largely the same, to add validity and replicability.

2.6 Data sources and data collection

For conducting literature reviews for all segments of this study, literature from the steel industry, associations, governing bodies and academia will be assessed and used. Additionally, the databases from Staffordshire University will be used (Table 1), as well as data provided by fellow researchers on ResearchGate, the author's professional network and correspondence, professionals in technical disciplines at Staffordshire University and Keele University. As part of the piloting process, the researcher will utilise informal exchanges with colleagues and peers which are aimed at finding out whether the chosen topic is likely to generate sufficient data for analysis at this level. Accessing the afore mentioned network and resources, the researcher is able to establish a significant global reach, which will help to establish justification for and validity of this study and the connected trials and projects.

Additionally, worldwide associations' information, governmental guidance and experts' publications will be accessed within a thorough literature review, to provide a broad base of information from a variety of data sources. Punch (2009) warns of potential respondents' bias, where participants might have a specific personal interest and might respond in a certain way to fit their agenda and possibly use this survey to perpetuate their opinion, without the risk of being personally identifiable.

In line with the GDPR (General Data Protection Regulation), the gathered data will only be accessed by the researcher and will be stored on an encrypted server for the purpose of this study, for the duration of the related projects. The analysis of the gathered data will be stored on the researchers' personal, encrypted USB device and the data will be destroyed with conclusion of the projects.

With reference to Mouly (1978), Basit (2010) stated that research must be seen as the process of achieving verifiable results through repetitive processes and engagement with critical analysis of data. Additionally, Basit (2010) cited Howard and Sharpe (1983) when claiming that research largely entails seeking advanced information only when thorough, replicable, methodical processes are being applied, which would be adding to the researchers' own knowledge and that of the wider public, when actually new factual information and findings are being discovered.

2.7 Ethics

Should personal data be required, informed consent will be obtained by participants via providing an information sheet and consent form, or oral information if so requested. If they chose to take part in this not-for-profit online survey, a new window should open and provide the participant with the opportunity to accept or decline to partake– after which they will be free to either go ahead with the questionnaire or to leave the website again.

Ethical approval of this study has been obtained from Staffordshire University (Appendix 1).

2.8 Research Methods

An interestingly alternative approach to establishing parameters in research methods has been chosen by Hendry (2010), when stated that all research should be seen as making an inquiry, resulting in meaning-making – rendering all research (enquiries) conclusively being a narrative. Hendry (2010) investigated the history of research and established earliest human storytelling as narrative – with narrative meaning "to account", which is derived from the word "gno" (Indo-European root gno from which the English word "knowledge" is derived) meaning: to know. It could be argued that the epistemological origins of scientific customs could also be seen as narrative, as this was considered the traditional way in which humans made meaning throughout the centuries and all ages. This conclusively repositions all research as narrative and provides the opportunity to consider all research beyond the current limitations of dualism and bifurcation.

Therefore, the researcher may allude to anecdotal observations, discussions and correspondence but is at the same time mindful that this can only be part of a survey process if the participants did have the opportunity to give fully informed consent.

However, it remains to be seen if the findings of the anecdotal data are going to be supported by the analysed secondary data. Because, unless the anecdotal data will – in fact – be supported by the secondary data, more research needs to be carried out to see if there are existing overlaps or if a completely novel approach needs to be found.

The extensive research during the literature review has revealed some interesting sources of information and new lines of enquiry/research questions have been found. The researcher has chosen action research, as it could be argued that a thoroughly researched project at a greater scale requires an available time frame of at least 12 months, if not significantly more, which is available throughout this 3-year-PhD-project.

The research was based on the following components, with the research questions as their basis, displayed in Figure 2-1:

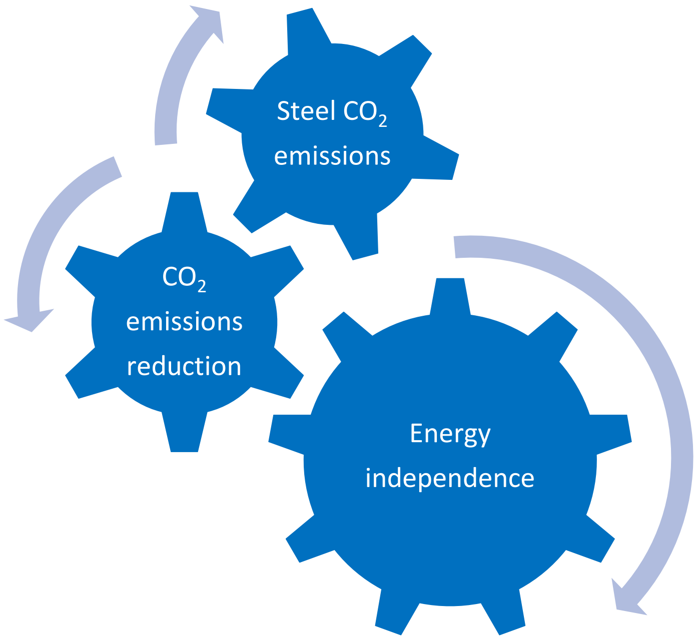


Figure 2-1 Research methods and instruments flowchart

Referring to Basit (2010), it can be said that research should be a systematic, repeatable process, adding timely, credible/verifiable facts and findings, which are arguably useful and justifiable, whilst being simultaneously trustworthy and adding value and new knowledge to the subject at hand. Marshall and Rossman (2006) were referred to in Basit (2010), when it was felt it was necessary to add that it is of paramount importance that the findings should be useful for practitioners and also be adding new facts to the existing knowledge base. Conclusively, it could be argued that research should inevitably be the process of taking a systematic approach which adds and advances knowledge and provides solutions for existing issues. Basit (2010), referring to Stenhouse (1975), concluded that research is a systematic enquiry made publicly accessible and 'a systematic, critical and self-critical enquiry, which aims to contribute to the advancement of knowledge and wisdom' according to Bassey (1999).

Online surveys are cited by Cohen, Manion and Morrison (Cohen, Manion and Morrison, 2018) and Punch (Punch, 2009) as an efficient and cost-effective way to access a wide population and to gather data, as one has the option of sending the link to a vast number of participants without the need for costly printing, postage or time-consuming face-to-face interviews to collect responses. This desktop research has taken a pentagonal approach for achieving maximum validation of the research results and findings, as displayed in Figure 2-2 in a pyramidical graph:

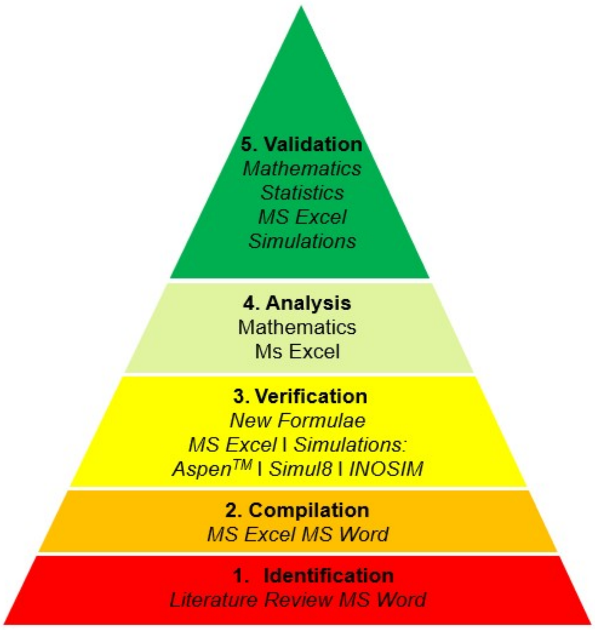


Figure 2-2 Pentagonal approach pyramid

Step 1 is the identification of the gaps in knowledge, identified during the literature review. Step 2 the compilation of gathered data for ease of access in MS Excel and expanded in MS Word. Step 3 demonstrates the paths taken for data verification: new mathematical formulae were developed and replicated and verified in MS Excel. Then the results were used to build process simulations in Aspen, Simul8 and INOSIM. In step 4, analysis of the reported values within the process simulations were performed with standard mathematical procedures, using the newly developed formulae and MS Excel extrapolations and processing. Finally, in step 5, validation of results and findings was achieved by comparing and analysing the results of the previous 4 steps against one another and compiling an overview of the results.

2.9 Research Instruments

According to Punch (2009), issuing and evaluating the responses of a pilot survey is part of the consent process, as it helps to identify any issues with the questions in or the format of the questionnaire, which can then be amended before the surveys are being sent to the participants, therefore eliminating the risk of invalidating issues impacting the collected data.

Hendry (2010) critically views current state-controlled processes of research in all science as a threat to democracy and science when suggesting that all inquiry and narrative is research (including pilot surveys and anecdotal evidence), beyond the limitations through state-controlled standards of what does and does not constitute "proper" research. Based on Hendry's (2010) work, the decision was therefore made by the researcher to include the opinions and statements gathered during informal conversation and by nature of observation as valuable sources of information. It is worth reiterating at this point that all correspondents and participants will have been informed of the researcher's interest and project and that the volunteered information might potentially be utilised for the purpose of research.

In line with Punch's (2009) recommendations, a best-methods-approach to collection and analysing data from all three streams has been chosen: qualitative, quantitative and mixed methods data collection. The research instruments applied are explained in more detail within the following flowchart in Figure 2-3:

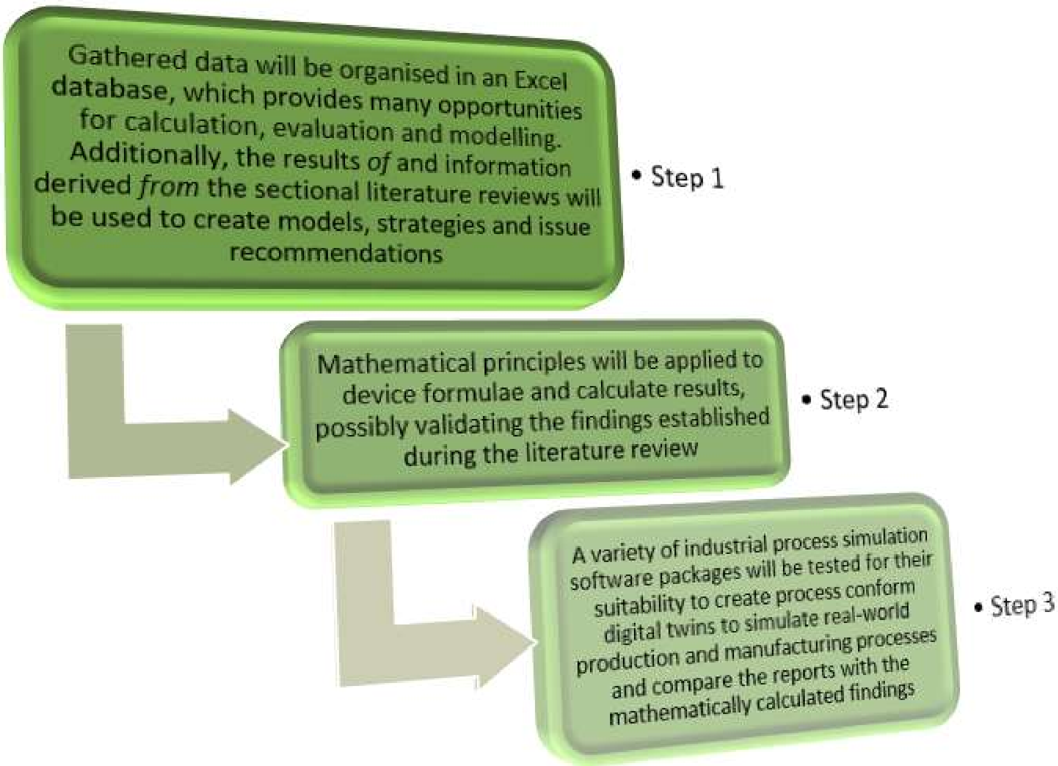


Figure 2-3: Research instruments in detail

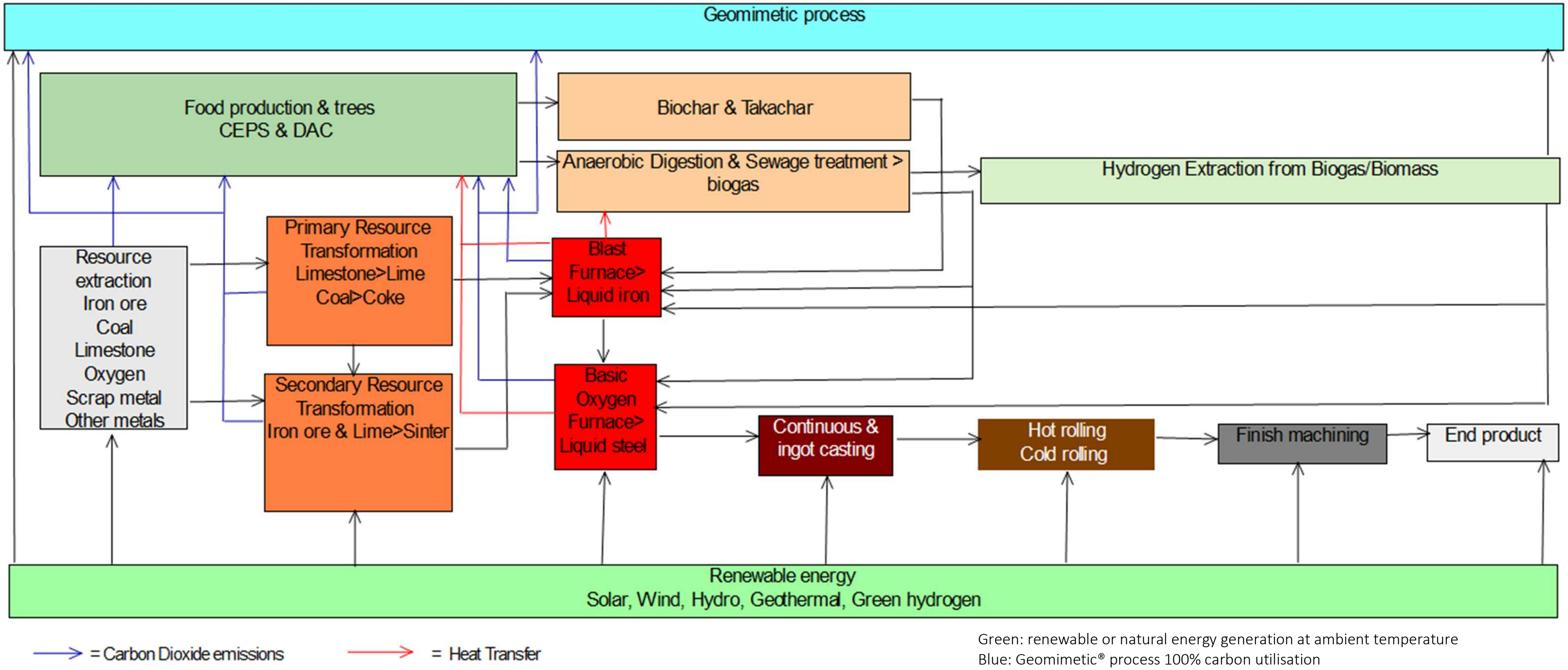
The literature in step 1 is set to identify the research gaps, inform the research questions and provide preliminary data for evaluation. In step 2, the usage of mathematical principles (Julia, 1918; Kuramochi *et al.*, 2011, 2018; Chen *et al.*, 2018; Kench, 2023) will ensure correct analysis of the gathered data, in independence from software and other IT equipment. This will also be used for devising formulae and report compilation and possibly validation of the findings. In step 3, the gathered information and data will be used to create near-real-time process simulations in a range of software applications, for added validation and external replication purposes.

2.10 Process simulation approach

Staffordshire University is well-placed in the heart of Stoke-on-Trent in the so-called Potteries. In this urban part of Staffordshire, a large proportion of business activity has transformed since the 1980s from mainly producing earthenware and fine China, to an overwhelmingly service and retail orientated business environment. Hence there are not many opportunities for initiating cooperations, process trials and test riggs, to prove or disprove innovative hypotheses. Process simulation software provides an alternative to in-situ testing environment are process simulation software applications. These applications have been developed to replicate manufacturing environments digitally. In the chemical industry, the creation of digital twins has been most successful in a range of applications. For the compilation of mechanical and metallurgical engineering applications and for the purpose of this study, Aspen, Simul8 and INOSIM were chosen to provide proof of concept and viability. The difference between the graphics is a visible reminder of the varying approaches within the software applications, each having their individual advantages to use in process simulations.

2.11 Data analysis techniques

Emphasising the requirement for validity and reliability in research, citing Punch (2009), the significance for the chosen process is to measure the data *accurately* and questioning if it would provide the researcher with the answers sought. A clear definition had to be found which correlates to the chosen process and the answers which it is supposed to measure and evaluate. Meaning, have the participants been asked the right questions? The accumulated data will be analysed using mathematical (Julia, 1918; Kuramochi *et al.*, 2011, 2018; Chen *et al.*, 2018; Kench, 2023) and physical principles, analytic tools via MS Excel, Simul8 and Aspen+V10-12.1 and Inosim, utilising a broad variety of presentational options. According to Snape and Spencer (2003), one has to conclude that – due to the sheer multitude of available processes and decisions which have to be made – carrying out qualitative research is most challenging, considering the requirement for highly skilled and dedicated researchers to overcome the barriers to access the desired information. Snape and Spencer (2003) have provided guidance on how to design a qualitative research study, how to collect data through in-depth interviews or focus groups and information on effective data analysis and assessment of the conducted research. The t-test has been identified of potentially being useful as a statistical tool for analysis and assessment, as it is one type of inferential statistics. It is mainly applied to determine whether there is a significant difference between the mean values of two chosen groups, the t-test, and generally statistics are being compared with a critical value identified in a table, to determine whether the results indeed fall within an acceptable range/level of probability or if the identified differences have occurred by sheer chance. The analysis via t-test should provide answers to the research questions (Fernandez, 2020). This study was motivated by the urgency of the climate emergency (IPCC, 2022) and the call on heavy industry to develop immediately efficient decarbonisation strategies (UN, 2016). The research was not confined to any specific country, but rather cast the net wider to global data and literature on sustainability (EMAF, 2019), decarbonisation (Wang *et al.*, 2022) and CAT, CCS and CCUS technology, to account for any recent technological development which could be considered supportive of the multi-disciplinary model development. The main reason underpinning this choice and course of research is that, as suggested by the World Steel Association (WSA, 2021a), the global iron and steel industry is responsible for between 7% and 11% WSA, 2021a) of global industrial CO_2 emissions, although some scientist are opining that this share could be much higher (Zhang, *et al.*, 2022; Morrow *et al.*, 2014; Hasanbeigi *et al.*, 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Ren *et al.*, 2021; Swalec, 2021; Wang, *et al.*, 2022). As there is no global legal or practical framework currently in existence on how to measure CO_2 emissions (i.e. from which data points to extract data), defined reporting structures and consequences of non-compliance, all these statements have to be viewed with caution. The literary sources used show to have used data sets accumulated and defined using a range of methods, with data and information partially provided voluntarily by industry, and without a clear framework of how, where, and when to measure CO_2 or GHG emissions, or in which format to report these, the definition of de facto emissions is very challenging, indeed. China is currently responsible for 50% of these GHG (Ren et al, 2021). To study the impact of different technologies (Toktarova *et al.*, 2020) on the processes at all stages in the steelmaking process (Griffin and Hammond, 2019; Griffin and Hammond, 2021), iron and steel manufacturing (WSA, 2021a) and related databases and corresponding literature were utilised. Additionally, literature with regards to CAT, CCS and CCUS and circular economic economy, sustainability and decarbonisation of the steel industry were investigated for their potential to point towards mechanisms and processes which could be built into the innovative model of the Bio Steel Cycle. For data collection purposes, an Excel database has been compiled, which provides many opportunities for evaluation, modeling and supporting simulation applications and also delivers the components for mathematical calculations. The Excel key calculation parameters were defined as t of CO_2 per t of product produced, although further parameters for future research are being allowed. The research was based on metric tonnes only. Additionally, engineering simulation software, such as Simul8, Aspen+V10-12.1-5 and Inosim, has been used. The simulation models are being adjusted continuously to meet the different applications of carbon avoidance, carbon saving, and carbon utilisation technologies. In order to demonstrate the placing and implementation potential of CAT, CCS and CCUS technology, basic and advanced steel production simulation models have been designed in Simul8 (Figure 2-6):



Green: renewable or natural energy generation at ambient temperature
Blue: Geomimetic® process 100% carbon utilisation
Orange: Energy intensive resource transformation >1400°C
Red: BF/BOF operation highest energy consumption and heat generation >1700 °C
Dark brown: Casting 1520°C
Brown: Hot-Cold rolling and drawing: > 1200°C
Grey: Extraction and finish machining Ambient temperature

Figure 2-4: Simulate steel linear production configuration *

*The colour-coding within Figure 1 is identical to the MASTER database (Excel), which has been created to gather and display findings, facts and figures, and is supposed to signify the energy intensity and heat development at the different stages of the steelmaking process in °C.

This shows the process simulation where some of the BiSC components were built into a simulation on S8, to be utilised and adapted going forward. The colour coding of the different stages within the steelmaking process was chosen to demonstrate the different levels of energy consumption and heat generation, in line with their carbon emission intensity. Also, to categorise the different technologies, such as renewables in green, Geomimetic® in blue, resource extraction and finish machining in grey for ambient temperature (although the energy intensity of resource extraction will have to be further investigated). Resource transformation in moderate orange, heat-and energy intensive BF/BOF operations in red, brown was chosen for casting 1520°C and rolling 1200°C, in line with the decrease in temperature.

The investigated policies and reports influencing research and investment decisions were in the UK the Climate Change Act 2008 (HM Government UK, 2008), the Energy Independence and Security Act of 2007 in the U.S.A. (USA Congress, 2007), the Paris Agreement (United Nations, 2016), and the Intergovernmental Panel on Climate Change reports (IPCC, 2022; IPCC, 2022a). The Paris Agreement (UN, 2016) was to be aiming for limiting global warming to ±1.5°C and all signatory nations agreed to invest into policies and processes to ensure that this target was met. Methodologically, our findings expand the current state of research by considering multi-disciplinary interaction and slope heterogeneity in the interactions between CO_2 emissions and implementation capacity of the iron and steel sector, to provide unbiased results.

To adhere to validity, replicability and transparency requirements, formulae were developed - based on the IPCC (IPCC, 2019) refined guidelines based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for carbon footprint methodology - a mathematical carbon footprint analysis model to calculate the CO_2 emissions at every stage (by capacity/day/week/month) of the steelmaking process. The CO_2 emissions in iron and steel industry consist of three parts: fossil fuel combustion (Efos = Energy consumption originally derived from fossil fuels), consumption of flux and carbonaceous products (Eflu = Energy from fossil fuels used by consumption of flux and carbonaceous products) and there is allowance for a part carbon sequestration product (Eseq), which is not required for the sum of the conventional steelmaking linear process, as there are no sequestration products negating the values to be included (Zhao *et al.*, 2020; Kuramochi *et al.*, 2011, 2018; Khakimov *et al.*, 2019). The total of carbon dioxide is therefore (Emissions of carbon dioxide) ECO_2 and is expressed in CO_2E_{total}.

The basis equation $ECO_2 = E_{fos} + E_{flu} - E_{seq}$ expressed as $CO_2E_{total} = \sum x \Omega$ ($\sum$ Sigma as sum of Ω Omega products) (Zhao *et al.*, 2020; Kuramochi *et al.*, 2011, 2018; Khakimov *et al.*, 2019; Arnold, 1980; Julia, 1918) have been developed to simplify calculating the greenhouse gas emissions and the possible effect in real term carbon savings and in percentages of the identified technologies in steel production. More detailed calculations will be provided in chapter 7.2 Mathematical calculations.

2.12 Engineering a zero-carbon steel manufacturing cycle development

The processes involved in accordance with the pentagonal pyramid approach require a verification and validation element, for matters of transparency and replicability. Staffordshire University does not currently have access to engineering environments providing real-time, empirical data, as industry is very reluctant to open their facilities to investigators potentially identifying their environmental sins. Although the author of this study has a wide-ranging international network of contacts, the reluctance to allow access to data of currently produced emission levels was universally almost absolute. Hence another method of investigating and validating the merits of innovative theories, models and strategies in real-time and investigating hypotheses for their viability. For this purpose, process simulation software was chosen as supposedly capable of replicating digital twins to manufacturing sites, as these are allegedly working with real-time plant data, to replicate existing manufacturing processes. The author has worked with a variety of CAD and process simulation software packages in professional capacity and is therefore aware of the benefits, merits and issues of process simulation software solutions in general. Most tried and tested solutions work with the principle of flow, meaning streams of heat, work, or materials, and the underlying equations and formulae carrying out the operations are supported with MS Excel and similar modules, widgets and plug-ins. Therefore, the decision was made not to rely on just one process simulation software solution, but to use the four deemed most useful applications: MS Excel flowcharts, and Inosim, Simul8 and Aspen process simulation software. Parallel to running the simulations and resulting reports were compared with standard mathematical procedure and extrapolation in MS Excel. The literature review in Chapter 3 will highlight the aspects of ten key areas such as the carbon life cycle, CCUS and BECCS.

Chapter 3 Literature Review

3.1 Introduction

Utilising the afore mentioned databases, a thorough literature review of circular economic principles, industrial processes, contemporary and historical publications with regards to the steel industry, greenhouse gas- and carbon dioxide emissions and decarbonisation efforts throughout steel manufacturing has provided a vast array of valuable insights. Data and information gathered have led to the development of a model and strategy for decarbonisation of the steel industry, whilst identifying the factual CO_2 emissions which the steel industry is required to eliminate as thoroughly and as soon, as technically possible. The IPCC reports from 2022 and 2023 (IPCC, 2022, 2022a, 2023a) are sending a clear message: decarbonisation now.

For this purpose, a thorough literature review will be conducted, investigating the areas of knowledge, as follows in figure 3-1:

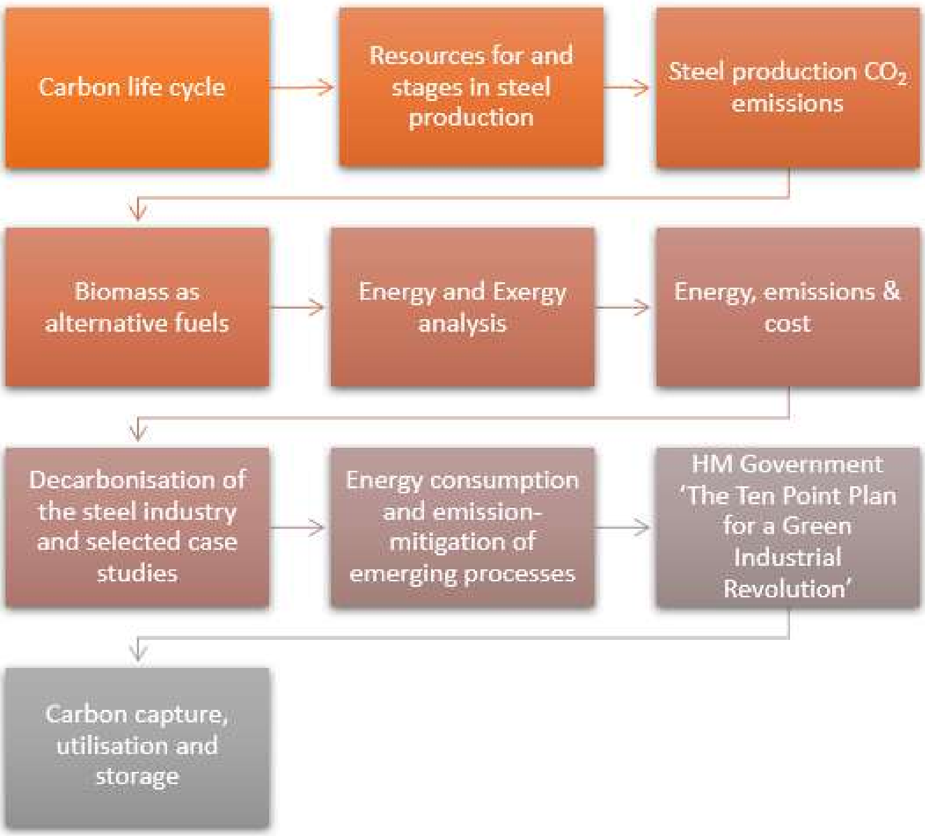


Figure 3-1: Areas of specialism, to be investigated during the literature review

The variations and differences in the findings can be attributed to the lack of a systematic legal and practical recording framework for carbon emission reporting and warrants further research.

3.2 Carbon life cycle

In order to understand the steel production process and to identify CO_2 emissions and energy usage, the carbon lifecycle within requires focused attention (NASA, 2023). Our atmosphere consists not only of oxygen, but a range of natural gases, shown as follows in Table 3-1:

Table 3-1: Gaseous composition of the earth's atmosphere (dry) (NASA, 2023)

Gas	Percentage
Nitrogen (N_2)	78.084%
Oxygen (O_2)	20.946%
Argon (Ar)	0.9340%
Carbon Dioxide (CO_2)	0.039%
Neon (Ne)	0.001818%
Helium (He)	0.000524
Methane (CH_4)	0.000179%
Krypton (Kr)	0.000114%
Hydrogen (H_2)	0.00055%
Nitrous Oxide (N_20)	0.00003%
Carbon Monoxide (CO)	0.00001%
Xenon (Xe)	0.000009%
Ozone (O_3)	0.000007%
Nitrogen Dioxide (NO_2)	0.000002%
Iodine (I_2)	0.000001%
Ammonia (NH_3)	trace

To start, one needs to understand what carbon actually represents. Carbon is one name of a greenhouse gas called carbon dioxide (CO_2) (USEPA, 2023), by which it is commonly referred to. CO_2 is the result of combustion processes, mainly fossil fuels (coal, gas, oil) (USEPA, 2023; Rudd *et al.*, 2021), but also solid waste, plant matter, and also as a result of industrial processes, i.e., manufacturing cement (GCCA, 2021). CO_2 is sequestered from the atmosphere when it is absorbed by terrestrial and aqueous plants via DAC as part of the natural carbon cycle (FC, 2003). Plants utilize CO_2 during the biological process called photosynthesis,

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$, where CO_2 is being absorbed and oxygen released (FC, 2003). In steel production, CO_2 is being emitted at every stage of production, from extraction to finish machining, as shown below in Figure 3-2:

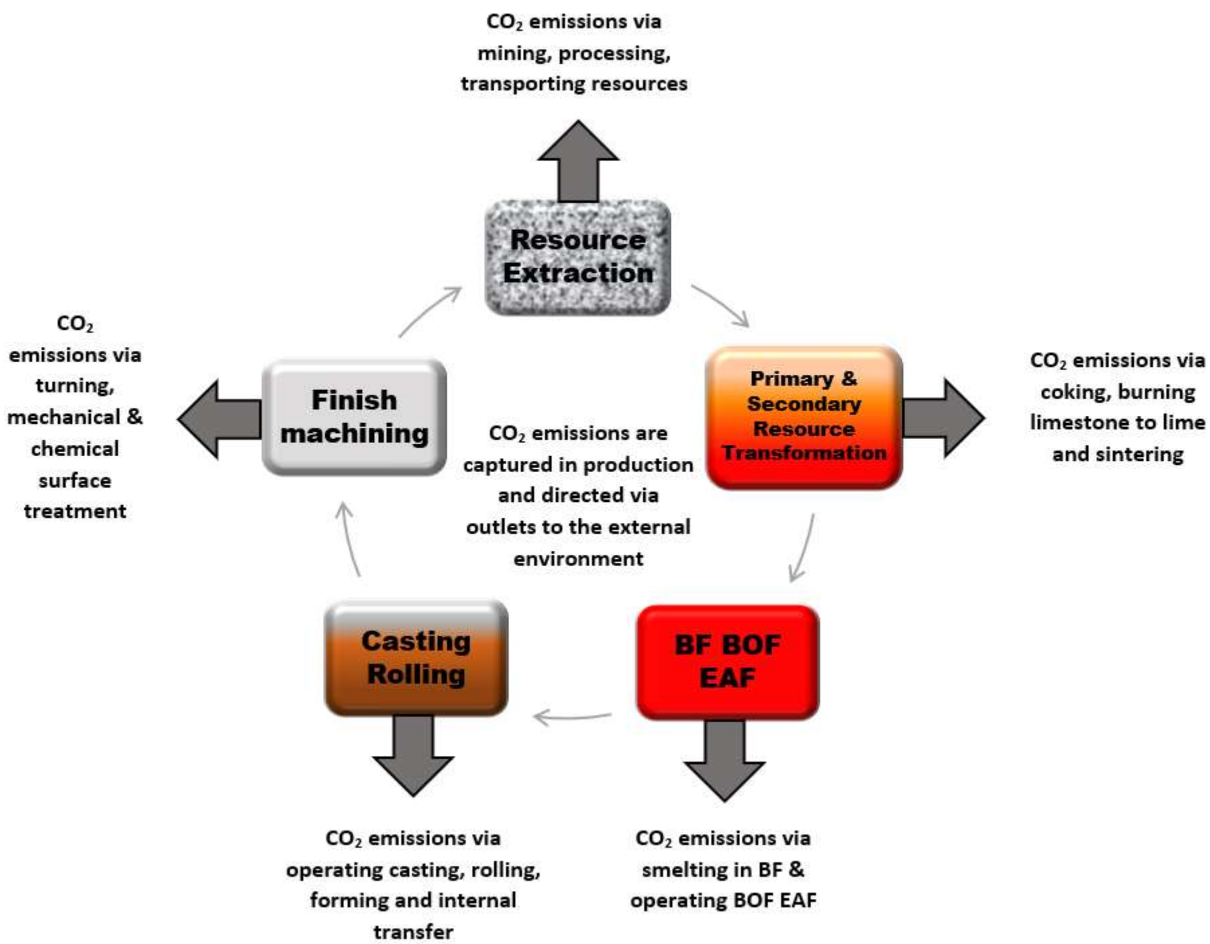


Figure 3-2: CO_2 life cycle in steel production

The CO_2 being emitted during industrial processes is then to a certain extend sequestered by plant matter and converted to O_2; broadleaved tree planting can sequester up to 500 t/CO_2/ha/60 years (Nix, 2020), and bamboo species are able to sequester almost 2 ½ times this amount (Seethalakshmi, Jijeesh and Balagopalan, 2016).

As to date, the UK government have failed to set policies, regulate carbon emissions and set definitive limits. A review of the UK Green Industrial Revolution paper can be found in Appendix 3.

3.3 Resources for steel production

Steel is an alloy of iron and carbon containing less than 2% carbon and 1% manganese and small amounts of silicon, phosphorus, sulphur and oxygen (WSA, 2020, 2021). Steelmaking starts with mining the resources required to produce steel: iron ore, coal and limestone. Oxygen, used in the blast furnace and basic oxygen furnace operations, needs to be extracted from ambient air and compressed to specifications. Not only during the in-ground or above-ground quarrying of coal, iron ore and limestone can CO_2 emissions savings be made, but also in the then following steps of coking, calcination and sintering processes, in the blast furnace and likewise in the basic oxygen furnace operations. More about the carbon saving and decarbonisation opportunities in the steelmaking sector are to be found in section 3.6.

3.4 Stages in steel manufacturing

There are more processes and stages involved in steelmaking than one might initially assume. It all starts with extraction of the resources (iron ore, limestone, coal, and oxygen), preparation of these resources (crushing, pelletising, coking, calcination, and sintering), until these material streams are fed into the blast furnace and subsequently into the basic oxygen furnace, after which casting, rolling and finishing takes place. The following graph (Figure 3-3) will lay out more clearly the stages involved in producing steel.

The production of steel, manufacturing of steel products and their distribution are tightly organised, in the respective countries. The following Table 3-2 will provide an overview of the organisations who organise their member businesses involved with steelmaking and subsidiary production processes:

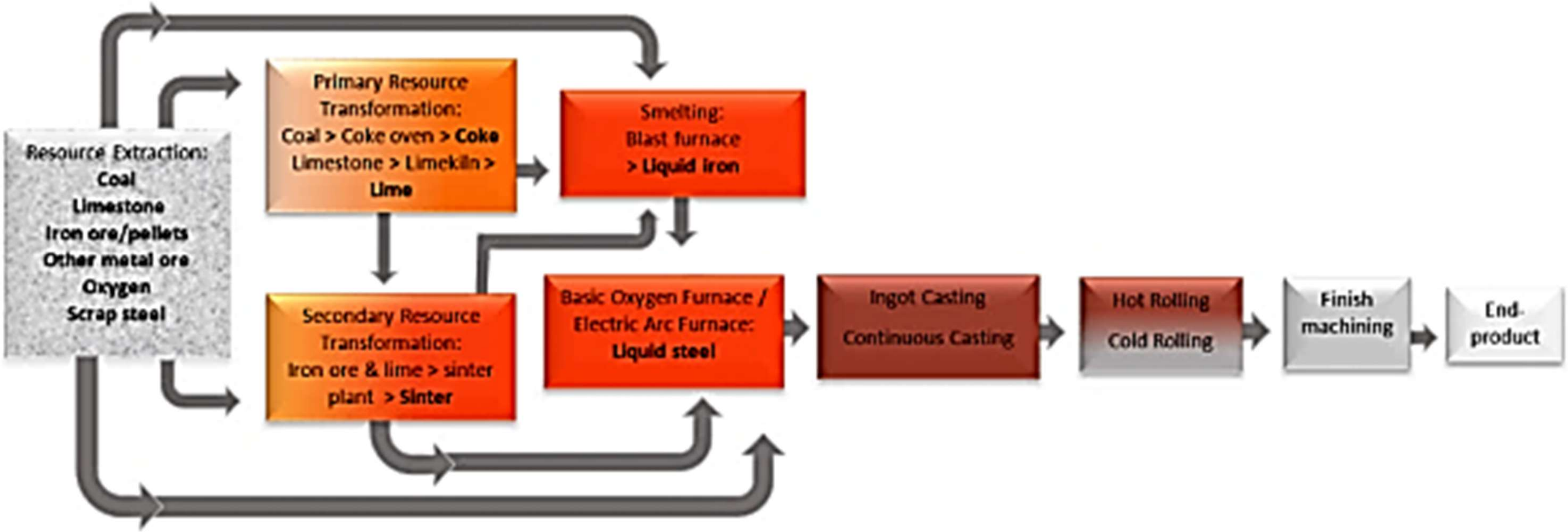


Figure 3-3: Simplified flowchart of the steelmaking process with the colouring indicating the journey of temperature intensity and subsequent cooling during the various stages

Table 3-2 : Steel associations by country

ORGANISATION / ESTABLISHED	MAIN OFFICE	DESCRIPTION	MEMBERSHIP	MISSION, GOALS AND PRIORITIES	REFERENCE
STAHLINSTITUT VDEH (1860)	Düsseldorf (Germany)	Stahlinstitut Verein Deutscher Eisenhüttenleute	Members are the industry leaders in Germany and Europe	Providing service and promoting technical and scientific cooperation in development of steel technology	(VDEH Stahlinstitut Verein Deutscher Eisenhüttenleute, 2023)
AMERICAN IRON AND STEEL ASSOCIATION (AISA) (1855)		American Iron Association in 1855, changed to American Iron and Steel Association	US integrated and electric arc furnace steelmakers: ArcelorMittal, Cleveland-Cliffs Inc., DTE Energy Resources, Harsco Environmental, North American Stainless, Nucor Corporation, Outokumpu, SSAB, Tenaris Bay City and associates	AISI is the voice of the US steel industry in the public policy arena and promotes steel globally	(AISI American Iron and Steel Association, 2023)
WORLDSTEEL / WORLDSTEEL ASSOCIATION (1967)	Brussels, (Belgium / EU)	Initially founded as the International Iron and Steel Institute, the name changed on 06 October 2008 and celebrated its 50th anniversary in 2017.	Worldsteel has members in every major steel-producing country and its members represent 85% of global steel producers	Global leadership on (social) sustainability, economic, and environmental matters, Benchmarking analysis and driver for global environmental protection, technology and safety. Promoting steel to stakeholders and the world at large	(WSA World Steel Association, 2023b)
SOUTH EAST ASIA IRON AND STEEL INSTITUTE (1971)	Shah Alam, Malaysia (Asia)	South-East Asian Steel Association	Members are leading steel companies, material- and equipment suppliers	SEAISI is a technical institute, and its main objective is to promote the iron and steel industry and facilitating global technological knowledge-transfer particularly from Australia, Japan, Korea and Taiwan	(SEAISI South East Asia Iron and Steel Institute, 2023)
EUROFER (1976)	Brussels, (Belgium / EU)	The European Steel Association AISBL	It has 54 members based across the EU and it represents the entirety of steel production in the EU - major steel companies and national steel federation of Turkey/the United Kingdom are associate members	Promoting EU-US transatlantic partnership and tackling global trade distortions and climate change	(EUROFER European Steel Association, 2023)
AISA (1986)	Zimbabwe	African Iron and Steel Association	African Union (AU) and United Nation Industrial Development Organization (UNIDO)	Promoting co-operation at sub-regional/regional levels and establishing bilateral co-operation arrangements in steel-related fields	(AISA African Iron and Steel Association, 2022)
STEEL MANUFACTURERS ASSOCIATION (SMA) (1992)	Washington (US)	The Steel Manufacturers Association—the largest EAF industry steel association in America	Members are US steel producers using EAF technologies, accounting for 70% of domestic steel produced.	Stewards for safety and sustainability, Pioneers for innovation and change, Trade and Economic Competitiveness, Transportation and Infrastructure, Energy Self-Sufficiency, Environmental Stewardship, Workforce Engagement	(SMA Steel Manufacturers Association, 2023)
NORSK STÅLFORBUND	Oslo (Norway)	Norwegian Steel Association	Members are: The Norwegian Steel Group, The Norwegian Steel Structures Association, The Steel and Metal Wholesalers Association, IGS, individual entities	Promotes the development of the steel industry and aims for utilisation of available resources and to encourage the exploitation of steel	(NORSK STÅLFORBUND Norwegian Steel Association, 2023)
NP RUSSKAYA STAL	Moscow (Russia)	Russian Steel Manufacturers Association	NP Russkaya Stal integrates the largest producers of metallurgical products in Russia	Development of rules and standards of activity of the metallurgical companies of Russia; Cooperation with state/municipal authorities and public associations; improvement of operating conditions of the member companies;	(NP RUSSKAYA STAL, 2023)

Steelmaking involves a range of different stages; one preliminary step is making liquid iron. There are a range of chemical reactions involved in first making liquid iron, and subsequently, making steel. An overview of the processes at which stage, the temperatures at which the reactions take place and their position in the blast furnace can be found in Figure 3-4:

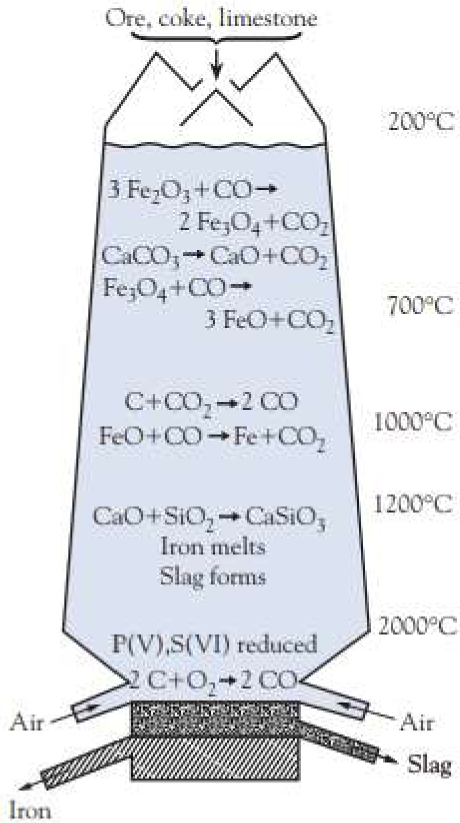


Figure 3-4: Blast furnace and the chemical reactions taking place at temperature (Rayner-Canham and Overton, 2010)

The trigger reaction, which will result in producing the molten iron and subsequently produces the main chemical reaction, is:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

However, this reaction involves more than one step. Initially, 1000°C preheated O_2 I is blown into the furnace with lances (tuyeres), at 220psi. The O_2 then reacts with the carbon content in the coke to produce CO and 1700°C heat:

$$2\,C + O_2 \rightarrow 2\,CO$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

This hot CO is the reducing agent for the iron ore and reacts with the Fe_2O_3 to produce molten iron and CO_2. The blast furnace is the hottest at the bottom, due to the injected oxygen, where at 1700°C the iron is reduced (again: in several steps). At the top of the furnace, where temperatures range between 200 °C and 700 °C, the iron oxide is partially reduced to iron(II,III) oxide, and Fe_3O_4.

$$3\ Fe_2O_3 + CO \rightarrow 2\ Fe_3O_4 + CO_2$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

Lower down in the furnace, at temperatures of ca. 850 °C, the iron(II,III) is reduced further to iron(II) oxide and will result in the release of CO_2, too:

$$Fe_3O_4 + CO \rightarrow 3\ FeO + CO_2$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

The hot CO_2, the quantity of unreacted CO, and N_2 from the air travel upwards through the furnace vessel, just as fresh flux (CaO) material journeys down into the reaction zone. The ensuing counter-current gases preheat the feed charge and decompose the limestone to $CaO_{(s)}$ and CO_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

The calcium oxide as a result of decomposition reacts with the acidic impurities in the iron (mostly silica), to form a fayalitic slag (calcium silicate $CaSiO_3$). (Rayner-Canham and Overton, 2010)

$$SiO_2 + CaO \rightarrow CaSiO_3$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

Gravity causes the iron(II) oxide to travel downwards to an area of ca. up to 1200 °C temperature, where it is reduced further to iron metal:

$$FeO + CO \rightarrow Fe + CO_2$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

The CO_2 formed in this process is re-reduced to CO by the added coke:

$$C + CO_2 \rightarrow 2\ CO$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

This temperature-dependent situation in equilibrium is controlling the gas atmosphere in the furnace, and it is called the Boudouard reaction:

$$2CO \rightleftharpoons CO_2 + C$$

(Rice University, 2023; Rayner-Canham and Overton, 2010)

The result of all of the afore mentioned reactions is called “pig iron”. At this stage, the pig iron produced by the blast furnace still has a carbon content of ca. 4–5%. Additionally, it contains sulphur, which makes the metal very brittle.

In one of the next steps, some pig iron is cast, making cast iron. The majority of pig iron produced in the blast furnace, however, undergoes further processing. The desulphurisation is done by adding calcium oxide, which reacts with the iron sulphide contained in the pig iron to form calcium sulphide (called lime desulfurization). (Rice University, 2023; Rayner-Canham and Overton, 2010). The aims are to a) reduce the carbon content and b) reduce the sulphur content, so it is possible to produce grades of steel in accordance with set specifications.

During the next processing step, in the bottom-blown basic oxygen furnace, the carbon content in the liquid iron is oxidised by injecting 99% oxygen at ambient temperature and 150psi into the liquid pig iron, resulting in crude steel output.

The chemical reactions in the basic oxygen furnace are occurring at different levels of the vessel, and at different temperatures and stages:

BOF Steelmaking:

$C + O2 \rightarrow CO_2$

$CO_2 + C \rightarrow 2CO$

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$

BOF Oxidation at jet impact zone:

$C + O_2 \rightarrow CO_2$

$Si + O_2 \rightarrow SiO2$

$2Fe + O_2 \rightarrow O_2 \rightarrow 2MnO$

BOF Desulphuration:

$(FeS) + CaO \rightarrow CaS + FeO$

$(FeS) + MaO \rightarrow MaS + FeO$

$3Fe_2O_3 + CaS \rightarrow CaO + 6FeO + SO_2$

$2CaS + 3O_2 \rightarrow 2CaO + 2SO_2$

BOF Desilication:

$CaCO_8 \rightarrow CaO + CO_2$

$CaO + SiO_2 \rightarrow CaSiO_3$

BOF Dephosphorisation

$4P + 5O_2 \rightarrow 2P_2O_5$

$P_2O_3 + 3CaO \rightarrow Ca3(PO_4)_2$

Evaluating the whole steelmaking process, it needs to be stated that, although there is work underway to improve the efficiency of blast furnaces, the chemical reactions and the process inside the blast furnace largely remained the same, to date.

One of the most environmentally damaging by products of blast furnace and basic oxygen furnace operations is the – so far - inevitable carbon monoxide and carbon dioxide production as iron is reduced from iron oxides by the addition of carbon. At the time of writing, there are, however, various economically viable substitutes for the blast furnace/basic oxygen furnace process of steelmaking. Some detail will be provided further on in this chapter, but in greater detail explained in the chapter "Decarbonisation of the steel industry". Steel is used in the building industry, cars, trucks, white ware, oil and refineries, energy industry, ships and machinery and therefore a commodity of great importance. Inevitably, supply chain pressures, not only identified by Fischedick *et al.* (2014) and Bataille *et al.* (2018), who are experienced in matters of the steel industry and affiliated sub-sectors, triggered the development of more sustainable production processes. Considering the existing primary steel production levels, the iron/steel-industry has acknowledged that they will fail to meet the set 80%-emission-reduction-target (UN, 2016) without introduction of breakthrough-technologies. The usage of steel on a global scale is making clear the sheer scale of the required resources to produce steel products. Evaluated and stated, as follows, in Figure 3-5:

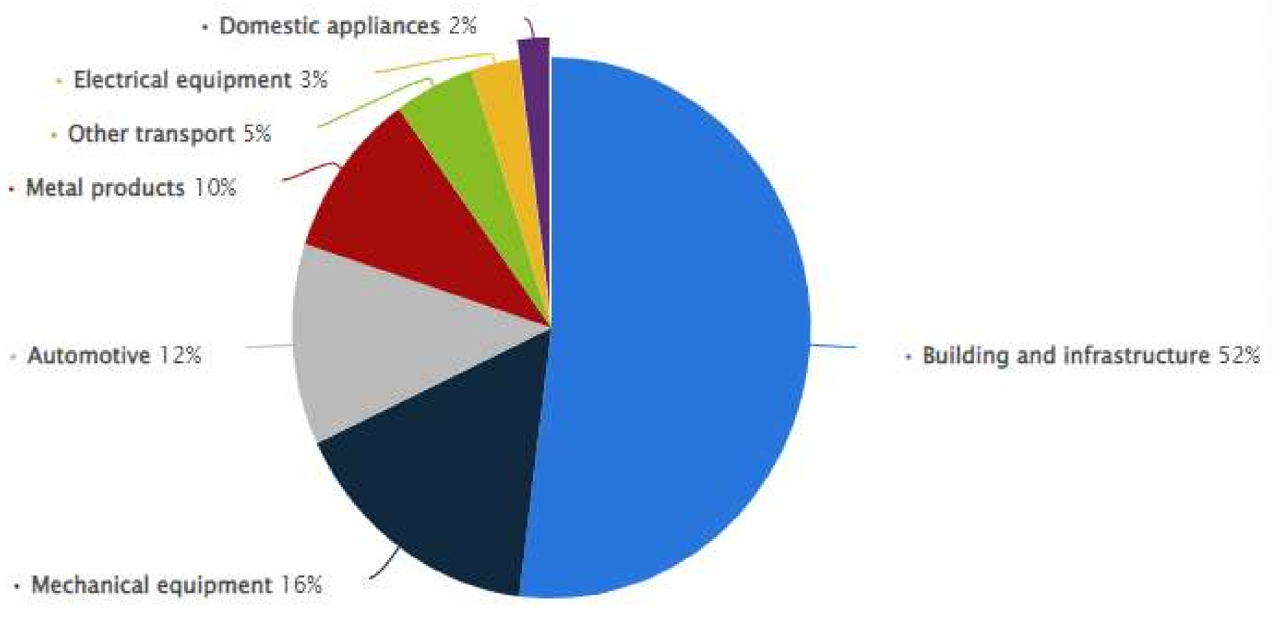


Figure 3-5: Distribution of steel end-usage worldwide in 2019, by sector (Statista, 2022)

Similar to Bataille *et al.* (2018), Fischedick *et al.* (2014) analysed the technical and economical long-term potential of novel steel production technologies and used techno-economic models to model three research-stage, ore-based steelmaking routes versus BF-BOF-route. The BF with CCS1 (BFCCS), hydrogen direct reduction (H-DR), and iron ore electrolysis (EW) were investigated to that effect, and they concluded that energy and raw material efficiency is significantly higher for H-DR and EW, and the 80%-reduction-target by 2050 was thought to be perfectly achievable in the scenario. Bataille *et al.* (2018) emphasised the urgency for sufficient prioritisation throughout all industries and political willingness (subsidies) to create a viable commercial environment, due to the required high capital investment and a significant dependency on electricity prices.

3.5 Biomass as alternative fuels

Coal is technically biomass, or at least has biomass as its origin (Yang *et al.*, 2021) millions of years ago, the earth was covered in wetlands, swamps and ancient plant species such as ferns. When the plants died, they sank to the bottom of the swamps. Over the years that followed, the layers of plants were covered by dirt, organic matter from animals and water, compacted by the weight bearing down. Over millions of years, heat and pressure converted the plants into coal, with a high carbon content (60% in lignite, 80% in anthracite coal) (eia, 1994; IEA, 2023c). The coal seams we excavate today have taken millions of years to form. It is finite - we cannot just ‘make’ new coal. Hence the term ‘nonrenewable’ (Yang *et al.*, 2021).

The efforts for conversion of biomass from plants into renewable energy and reducing the resulting CO_2 emissions has seen extensive efforts across a variety of industries, using thermochemical and biochemical approaches (Chen *et al.*, 2018; Keung, 2021; Wei *et al.*, 2022). Converting biomass thermochemically, nitrogen oxides (NOx), particulate matter (PM), and tar are the environmentally hazardous byproducts, which can fortunately be recycled using existing technology (Chen *et al.*, 2018a; Keung, 2021; Wei *et al.*, 2022). During bioconversion of biomass, namely anaerobic digestion as an example, volatile organic compounds (VOCs), such as sulfur-containing gases (hydrogen sulfide/H_2S), wastewater, and biogas slurry (Lacy and Rutqvist, 2015; Mosayeb-Nezhad *et al.*, 2019; Nezhad, *et al.*, 2019; Zhao *et al.*, 2020; Kabeyi, 2022; eia, 1994) are being produced. These can be utilised as a value-added resource, and wastewater and VOCs can be treated via physical-chemical or biological methods in sewage treatment plants (Yi *et al.*, 2018; Zhao *et al.*, 2020). Developing new industrial technologies or processes that use biomass and its byproducts as a source of energy should be seen as the future direction of clean production (Benetto *et al.*, 2004). Fortunately, there are multiple suitable varieties of plants, which could be exploited for the production of biomass. Mainly, the dry matter content is an important factor, as this determines the species' value in carbon-reliant combustion processes. The dry matter content of *Chusquea culeou* (Chile), as an example, can be determined at 156-162t/ha, while that of *Phyllostachys pubescence* (Japan), and *Gigantochloa alter* (Indonesia) levels at approximately 138t/ha, and 45t/ha (Seethalakshmi, Jijeesh and Balagopalan, 2016). The lowest level of dry matter was recorded for *Bashania fangiana* (China), at 0.35t/ha. Bamboo species in year 4, 6 and 8 have been reported to have 122, 225 and 286t/ha, of dry matter. They are therefore to be seen as performing as well as a plantation of 10-year-old, fast growing *Causarina equisetifolia* (292.68t/ha) or *Eucalyptus tereticornis* (254.97t/ha). UK native, deciduous plants (trees) are able to sequester approximately 9t/ha/year (Nix, J., 2020), whereas bamboo species are able to store almost double this amount, at 17t/ha/year (Seethalakshmi, Jijeesh and Balagopalan, 2016). The gasification of biomass as by-product form forestry and agriculture, with high dry matter content, undergoes several steps, which, unfortunately, themselves are emitters of CO_2 and other greenhouse gases, as displayed in Figure 3-6:

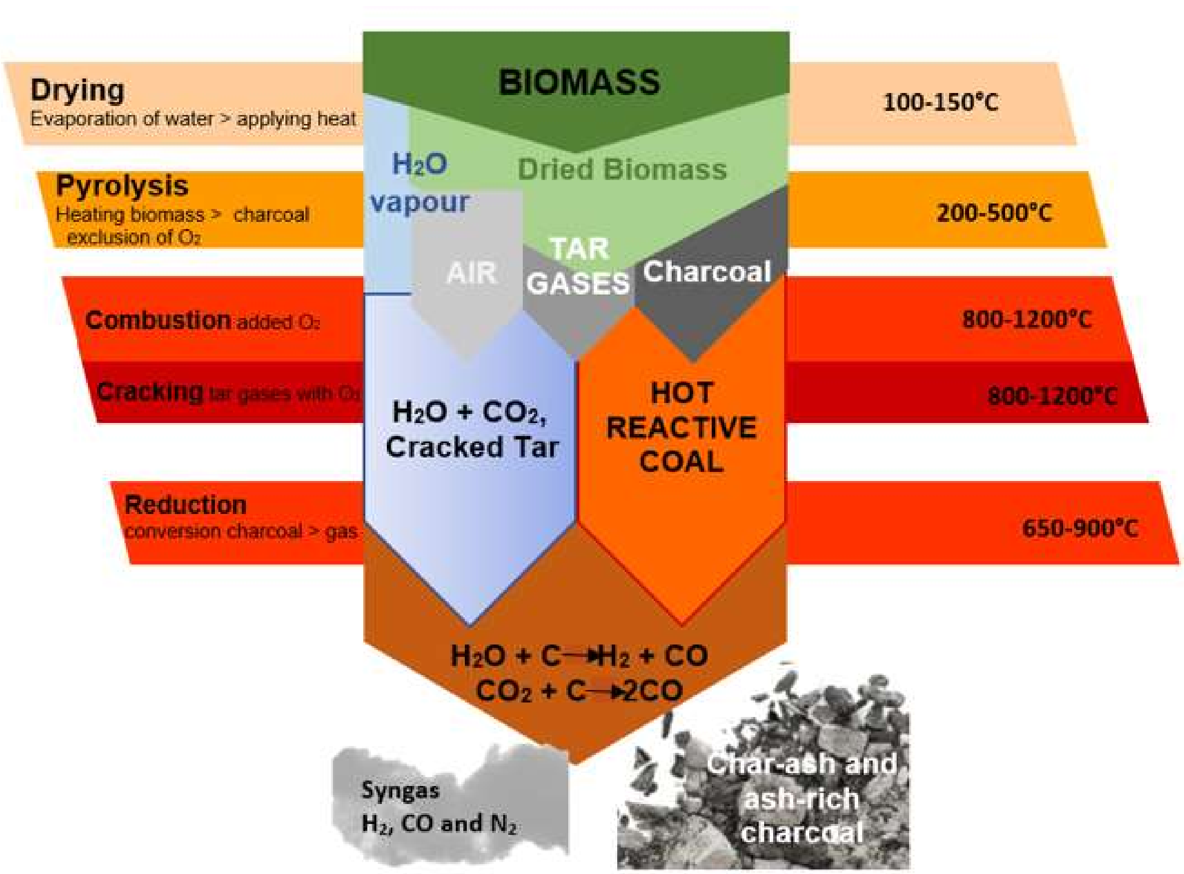


Figure 3-6: Biomass gasification process flowchart

In 2023, the UK has been rated as one of the most nature-depleted countries on Earth (RSPB, 2023), which makes creating woodlands not only important for heavy industry, but also for saving and supporting the rehabilitation of natural assets. In order to determine the validity of current findings established during the literature review process, the gasification of biomass has been simulated using software packages from S8, Aspen+ and InosimV13. More to this in Chapter 7: Results.

An additional type of biomass is biochar – it is biomass which has undergone extensive transformation.

Due to power plants being the largest stationary source of anthropogenic CO_2, developing effective and affordable post-combustion CO_2 capture technology has attracted substantial research attention. This study assessed the adsorption of CO_2 onto biochar, a low-cost adsorbent that can be produced from waste biomass through low-temperature pyrolysis. Sugarcane bagasse (BG) and hickory wood (HW) feedstock converted into biochar at 300, 450, and 600 °C. The sorption of CO_2 on each of the resulting biochar was measured by monitoring its weight changes in CO_2 at 25 or 75 °C. The biochar was found to be effective for CO_2 capture and the adsorption process could be described by the second-order kinetics model. In general, the biochar produced at higher temperatures had better CO_2 capture performance. The BG biochar produced at 600 °C showed the most adsorption of CO_2 (73.55 mg g−1 at 25 °C). However, even when the feedstock was exposed to only 300 °C pyrolysis, the biochar was still able to capture more than 35 mg g−1 CO_2 at 25 °C. Experimental results suggest that CO_2 weakly bound to the surface of the biochar through physisorption, so the surface area was a significant determinant of CO_2 adsorption (Pearson's r = 0.82); nevertheless, the presence of nitrogenous groups also played a role, when the surface area was sufficient. Biochar's porous structure and unique surface properties enable it to be an efficient CO_2 adsorbent while being sustainable and inexpensive. It, therefore, requires careful consideration of the implications, and specifically, the capture of the emitted greenhouse gases, so as not to add to the CO_2 balance sheet.

An additional source of biomass to be utilised in steelmaking and other production as an alternative to imported energy is biogas. Biogas can be made in anaerobic digestion from waste products such as cow manure: 1kg will result in ~40litres of biogas, and 1kg of chicken dung in ~70 liters. Biogas has an energy content equivalent to that of fossil fuel. The calorific value of 1m^3 biogas is equivalent to 0.6 - 0.8 liters of kerosene (Kabeyi, MJB, 2022).

The resources for making energy without producing a large amount of GHG emissions are basically being produced on a daily basis, namely manure and other organic matter. Figure 3-7 shows the transformation pathway and stages of biomass → biogas → to hydrogen:

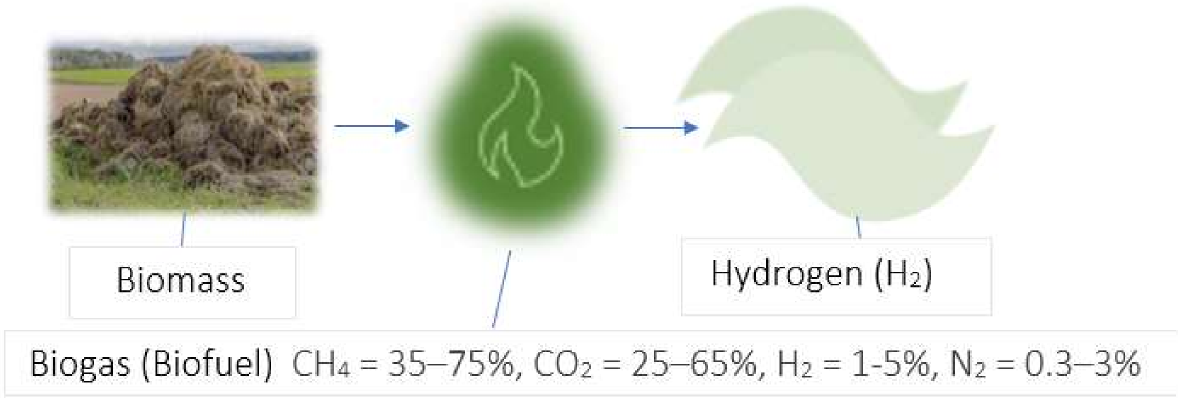


Figure 3-7: Biomass conversion transformation pathway

It needs to be pointed out that generating green hydrogen can be done faster, with less energy input for the electrolysis process and a higher yield by using seawater, which is currently being piloted by Tata Steel in Ijmuiden (Bhaskar *et al.*, 2022; SIEMENS, 2022, 2023a; ArcelorMittal, 2023a; Tata Steel Nederland, 2023; Voestalpine, 2023)

3.6 Steel production CO_2 emissions

Steel is an alloy of iron and carbon. It contains ≤2% carbon and 1% manganese and small amounts of silicon, phosphorus, sulphur and oxygen (WSA World Steel Association, 2021a).

In order to produce steel, essential resources need to be either mined, produced or manufactured. The primary BF-BOF process (Blast Furnace - Basic Oxygen Furnace) produces approximately 79% of the UK crude steel (UK) and the secondary EAF process (Electric Arc Furnace) accounts for the majority of the remaining 21% of UK crude steel production – the individual steps of which are going to be eluded to in further detail. The CO_2 emissions of all production steps have been investigated throughout (Price *et al.*, 2002; Prakash and Muller, 2007; UNIDO, 2010; Worrell *et al.*, 2010; Zakkour and Cook, 2010; Li and Zhu, 2014; IEA, 2021c; Chen *et al.*, 2018; Griffin, and Hammond, 2019; Morrow et al., 2014; Hasanbeigi et al., 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Mandova *et al.*, 2019; Liu *et al.*, 2020; Liu *et al.*, 2022; Mehmood *et al.*, 2020; Toktarova *et al.*, 2020; Toktarova, 2021; Garvey, Norman and Barrett, 2022). The flow-chart in Figure 9 illustrates the individual steps necessary to produce steel, using either a BF-BOF or EAF). All required stages in steel production needed to be identified first before an investigation into the individual CO_2 emissions and energy requirements could take place, as displayed in Figure 6. The flowchart is congruent with the colour coding of the MS Excel spreadsheet, which can easily be adapted to accommodate changes within the production process.

Steelmaking-related CO_2 emissions increased by 1.6% to 8.7 Gt CO_2 in 2020 (26% of global emissions), in large part because of a slowdown in industrial activity in some regions due to the Covid-19 crisis (IEA, 2021a). In the Net-Zero-Emissions-by-2050 scenario, industry emissions fall 2.3% annually to 6.9 Gt CO_2 by 2030 – despite expected industrial production growth (IEA, 2018, 2021a, 2021b, 2021c, 2022, 2023a, 2023b, 2023c). Greater material and energy efficiency, the uptake of renewable energy technologies, and the development and deployment of low-carbon process routes (including CCS and hydrogen) are all critical. Combustion of fossil fuels for transport (including aviation) and energy production are the biggest source of carbon dioxide emissions - worldwide (IEA, 2018, 2021a, 2021b, 2023a; Mandova *et al.*, 2019; Toktarova *et al.*, 2020; IPCC, 2022). Steel production is in close third place and the individual steps in steel production have been investigated with regard to the individual CO_2 emissions and energy requirements (IEA, 2018, 2021a, 2021b, 2021c, 2022, 2023a, 2023b, 2023c; eia, 2021, 2021a, 2021b, 2023, 2023a).

At this point, it needs to be said that the extensive literature review has resulted in gathering data with partly vast differences in results and sometimes even controversial material. Investigating the nature of these differences, it could be established that the main reason for the different findings, statements and results, was, that almost every reviewed publication had taken a different approach. Some were country-specific, some have only focused on one particular industry in one country, some have only taken steel plants in focus which were in close geographical proximity, some considered specific commercial parameters, land lifecycle analysis and some conducted a meta-analysis approach.

The results have been thoroughly analysed and balanced against carbon emissions per metric tonne of product. Analysis using standard mathematical procedure resulted in the total CO_2 emissions per metric tonne of product and steel, at the respective stages. Where only the total CO_2 emissions of the BF/BOF-route were given, a 70%BF/30%BOF weighting has been applied. 2 outliers, where the CO_2 emissions were multiple times higher and more upon investigation than what the range of other publications within the literature review was providing, have been disregarded as not to distort the overall picture. Upon closer investigation, it was carefully considered that the published results might possibly have been suffering either from bias, influenced by the entity providing funding for the studies in question, or a procedural mishap, which therefore disqualified the data for usage in this study. The results to date of research into the CO_2 emissions at the various stages of the steelmaking process and related sub-processes have been established, as displayed in Table 3-3:

Table 3-3: CO_2 emissions at various stages of steelmaking and subsidiary processes

Step in production / Resource / Process	**t $CO_{2\ \text{t product}}$**	**Author**
Extraction Resources		
Coal	5.43	eia, 1994; Bogunovic *et al.*, 2009 Li and Zhu, 2014; Liu *et al.*, 2020 McKinsey and Company, 2021 Griffin and Hammond, 2021
Iron Ore	0.3-2.19	Chen *et al.*, 2018 Griffin, and Hammond, 2019
Oxygen	0.2-0.26	Hegemann and Guder, 2020 Variny *et al.*, 2021
Limestone	0.01-0.04	IPCC, 1996; Lin *et al.*, 2011 Li and Zhu, 2014; Kittipongvises, 2017 Chen *et al.*, 2018
Primary Resource Transformation		
Coal>Coke Oven>coke	0.38-2.59	Li and Zhu, 2014; Chen *et al.*, 2018 Yang *et al.*, 2021
Limestone>Limekiln>lime	0.4-0.93	Li and Zhu, 2014; Shan, Liu and Guan, 2016; Riesbeck *et al.*, 2013
Secondary Resource Transformation		
Coke + Iron ore>Sinter	0.34-2.21	Ecofys, 2009; Li and Zhu, 2014; Chen *et al.*, 2018
Iron production		
Blast Furnace Smelting	2.1-3.2	Worrell *et al.*, 2010; Zakkour and Cook, 2010; Li and Zhu, 2014; EERE, 2010,2018,2021; Mandova *et al.*, 2018, 2019; Griffin, and Hammond, 2019; Toktarova *et al.*, 2020; Pandit, Qader and Lim, 2021; Suer, Ahrenhold and Traverso, 2022; Prakash and Muller, 2007)
Steel production		

Modern Basic Oxygen Furnace	1.6-3.13	Prakash and Muller, 2007;Worrell *et al.*, 2010; Zakkour and Cook, 2010; Li and Zhu, 2014; EERE, 2018; Mandova *et al.*, 2018, 2019; Griffin and Hammond, G, 2019; Morrow et al., 2014; Hasanbeigi et al., 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Mehmood *et al.*, 2020; Toktarova *et al.*, 2020; Pandit, Qader and Lim, 2021; Suer, Ahrenhold and Traverso, 2022; Garvey, Norman and Barrett, 2022; Tian *et al.*, 2022
Finishing		
Casting	0.2-1.22	Li and Zhu, 2014; Wänerholm, 2016
Hot Rolling	0.77	Li and Zhu, 2014; Schmitz *et al.*, 2021; Sun *et al.*, 2022; SSAB, 2022
Cold Rolling	0.26	Worrell *et al.*, 2010; Li and Zhu, 2014; Schmitz *et al.*, 2021; SSAB, 2022; Sun *et al.*, 2022
Passivation/Coating/Plating/Blackening	0.15	Worrell *et al.*, 2010; Li and Zhu, 2014; Schmitz *et al.*, 2021; SSAB, 2022; Sun *et al.*, 2022

As every step within the process leading towards the production of steel refers to metric tonnes of product at the relevant stage, a summary is not advisable at this stage. Where American, Australian, European or Asian measures, other than metric, have been provided, the values have been levelled to express in metric t per t of product.

A thorough investigation of research into every process step along the linear steelmaking BF/BOF route has taken place, to find the status quo. The extensive literature review has resulted not only in the identification of the knowledge gaps but also prompted the author to investigate a range of process simulation software packages, to adequately serve the individual requirements of transparency, replicability, and finding answers to the research questions.

As during the research work a research-relevant setting had to be chosen, the utilisation of process simulation software was deemed to be sufficiently accurate to investigate and replicate the findings from the literature, Excel modeling and mathematical analysis, of which more detail will be provided in Chapter 7: Results.

One of the process simulation software systems is Simul8 (spoken: Simulate), which allowed a simple yet effective process simulation of the basic steelmaking process, following the BF/BOF-route. The resulting report, in Figure 3-8, produced after having run the simulation, validated the research findings:

Carbon Emissions	**21,000.00 CO2e**
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Basic Oxygen Furnace	2,000.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	0.00 CO2e
Total Environmental Impact	**21,000.00 CO2e**

Figure 3-8: System report CO_2 emissions of the BF/BOF steelmaking process

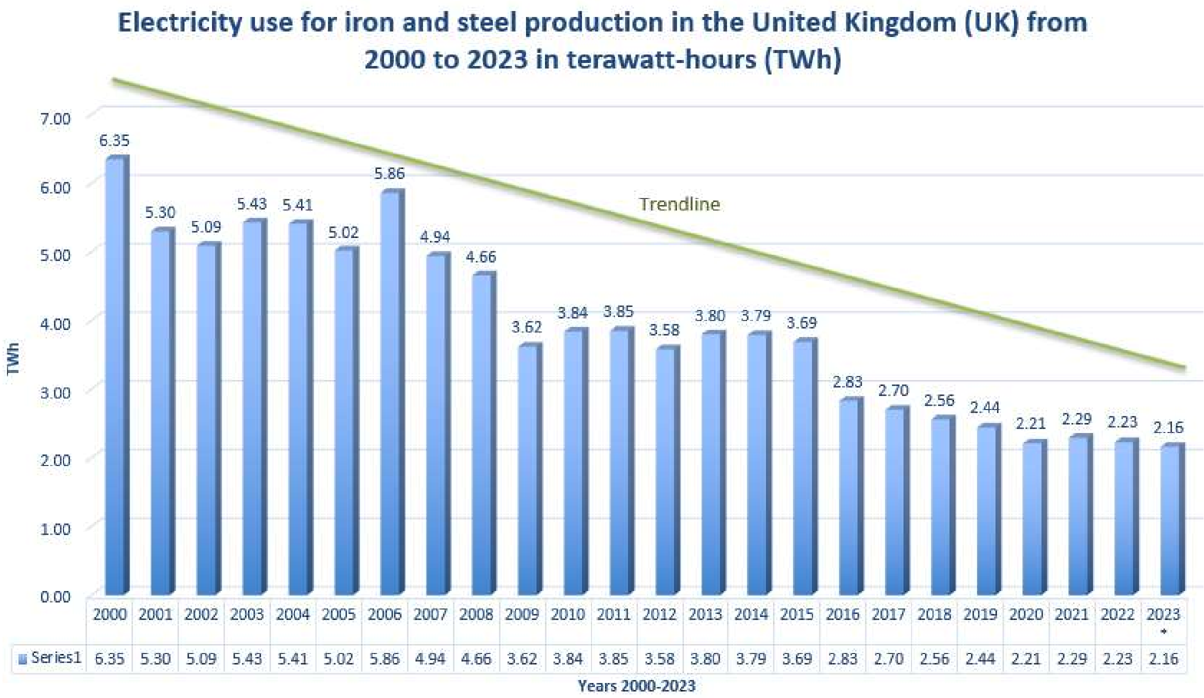
As with scientific findings in general, the findings of this work are only a snapshot of the current state of knowledge with regard to the CO_2 emissions in steel production. In Chapter 7: Results, a more detailed breakdown of facts and figures will demonstrate the challenges of the exact summation of the GHG emissions in steel production, as so many different approaches to reporting, evaluation and determination have been taken by industry and academia alike. Most don't seem to have taken in the energy required and thus emissions produced as a result of producing said energy for the usage of the injected, to 1000°C pre-heated O_2 at 220psi into the blast furnace. Or the energy required to inject O_2 at ambient temperatures into the basic oxygen furnace (from the top or bottom of the vessel) at 150psi.

As time goes by and better standards of reporting GHG emissions and frameworks and methods exacting the mechanisms might be developed, the data presented in this study might be seen as a first attempt to CO_2 emissions determination in the iron and steel industry.

3.7 *Energy and Exergy analysis*

3.7.1 Energy, emissions and cost

It is estimated that between 2.15MtCO_2/p.a. and 2.8MtCO_2/p.a. in the iron and steel industry are energy-related CO_2 emissions (Brodyanski, Sorin and Le Goff, 1994; Moran and Sciubba, 1994; IEA, 2018, 2021a, 2023a; Siefert, Narburgh and Chen, 2016; Brockett, 2017; IEA, 2018, 2021a; , 2021). As shown in Figure 3-9, the development of electricity usage in steelmaking has been on a downward trajectory since the year 2000, partly due to process and efficiency improvements across most industries:



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023*
Series1	6.35	5.30	5.09	5.43	5.41	5.02	5.86	4.94	4.66	3.62	3.84	3.85	3.58	3.80	3.79	3.69	2.83	2.70	2.56	2.44	2.21	2.29	2.23	2.16

Figure 3-9: Electricity use for iron and steel

production in the UK from 2000 – 2023 (Statista, 2023)

In stark contrast, quite the opposite observation was made for global electricity consumption (IEA, 2018, 2021a, 2021b), as displayed in Figure 3-10:

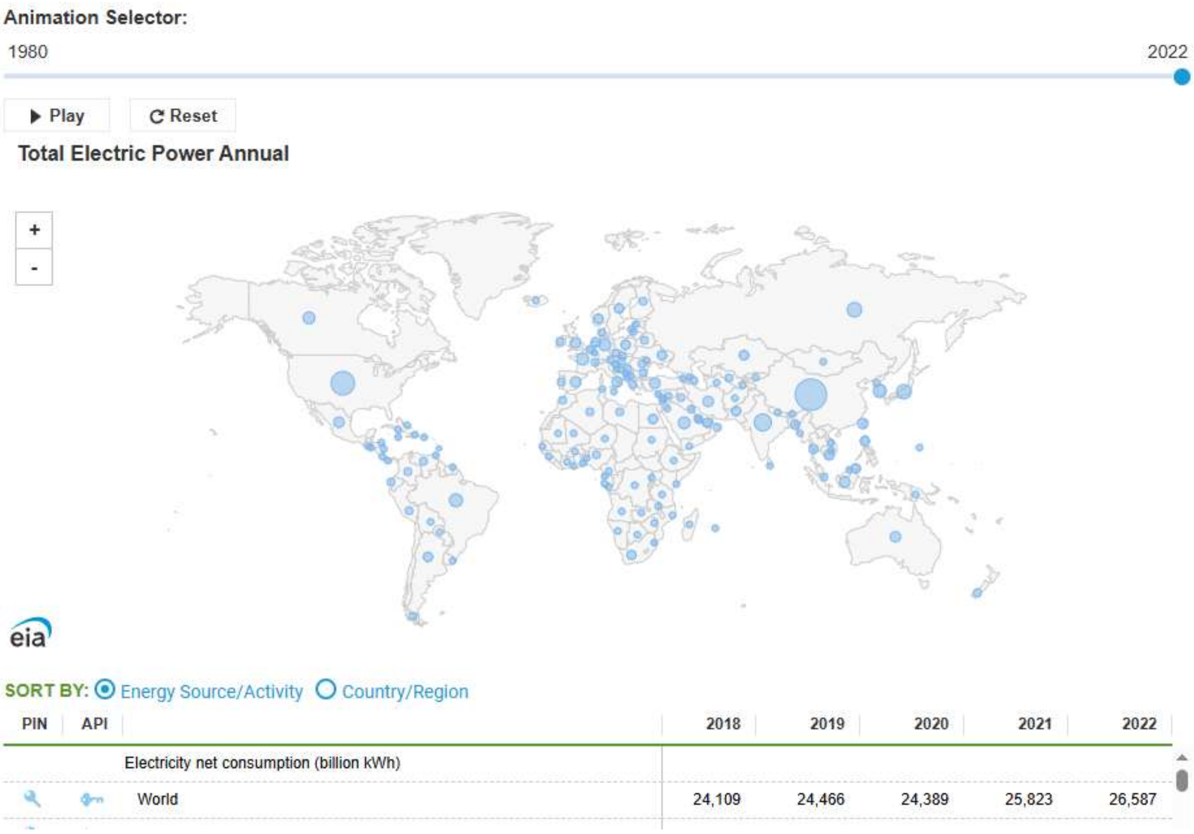


Figure 3-10: Global electricity consumption 2018-2022

(IEA, 2023a)

Global electricity consumption has continuously increased during the last 50 years, arriving at estimated 26,587 TWh (terawatt-hours) in 2022 (IEA, 2023a).

Since 1980 and up to 2022 (IEA, 2023a) , global electricity consumption has increased three-fold, and the global population increased by roughly 75 percent, simultaneously, as per image below: Figure 3-12

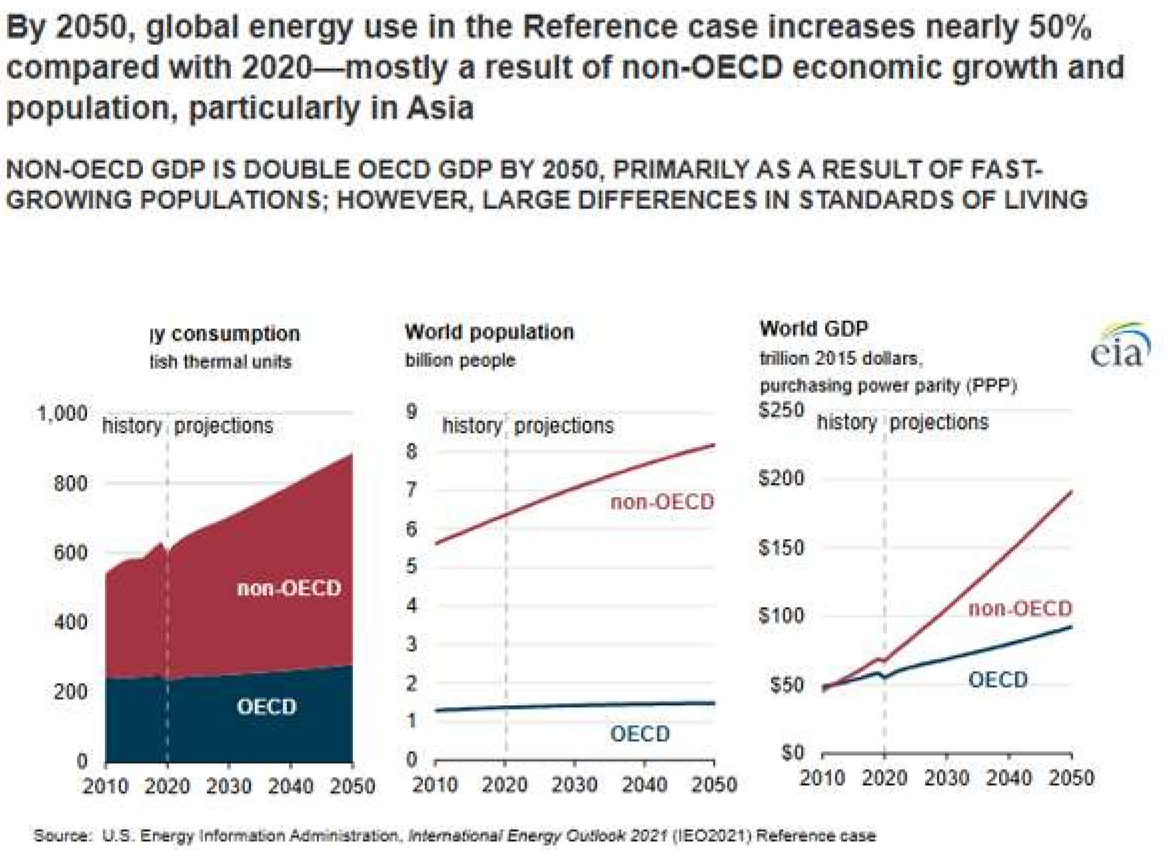


Figure 3-11**:** Overviews world energy consumption, world population development and world GDP (gross development product) development since 2010 and projected to 2050 (eia, 2021)

In line with extended industrialisation and infrastructural improvement (eia, 2021, 2021b, 2021c, 2023a, 2023b, 2023c), these factors caused a three-fold increased electricity demand, with an upward trajectory prognosis, as of the end of 2021. Mandova (Mandova *et al.*, 2019) established that their concept of Bio-CCS could help iron and steel production to become close to carbon neutral, under consideration of the estimated avoidance cost <u>(in the EU) of €80/ tCO_2</u>. Additionally, the authors found that the Netherlands, France, and Belgium currently have the lowest CCS deployment cost. It is currently given that (Mandova *et al.*, 2019):

Kilowatt-hour (kWh) to Kilojoules (kJ):

$$1\ \text{kWh} = 3.6 \times 10^6\ \text{J} = 3.6 \times 10^3\ \text{kJ}$$

Conversion formula:

$$\text{kWh} \times 3.6 \times 10^6 = \text{Joules}$$

or

$$\text{kWh} \times 3.6 \times 10^3 = \text{kJ}$$

Joules (J) to Kilowatt-hours (kWh):

$$1\,\mathrm{J} = 2.77777778 \times 10^{-7}\,\mathrm{kWh}$$

Conversion formula:

$$\mathrm{J} \times 2.77777778 \times 10^{-7} = \mathrm{kWh}$$

or

$$\mathrm{J} \div 3.6 \times 10^{6} = \mathrm{kWh}$$

Most energy suppliers provide estimated CO_2 emissions per kWh, which state that an estimated 0.46kg of CO_2 per kWh of energy produced is being emitted by using the current technology mix. Johansson and Söderström (2011) identified opportunities for both integrated and scrap-based electricity production, fuel conversion, methane reforming of coke oven gas and cooperation in complex industrial symbioses. Yang, Raipala and Holappa (2014) took a similar approach when they investigated the iron and steelmaking process. They established that 95% of energy for an integrated steelmaking plant is the result of using coke, 3–4% from gaseous, and 1–2% from liquid fuels. Furthermore, they identified that within the BF/BOF steelmaking route, an energy consumption of 19.8–31.2GJ/energy/t crude steel took place. In contrast, within the EAF route utilising almost 100% steel scrap, only 9.1–12.5GJ/energy/t crude steel was used. The authors investigating the BF/BOF-route of integrated steel attributed ~75% of the fossil-fuel (coal) derived energy had to be attributed to blast furnace operation. Johansson and Söderström (2011), Yang, Raipala and Holappa (2014) and Mandova *et al.*, (2019) established the role of coal with regard to energy consumption and found the following parameters: in the 1950s, coke constituted the single fuel used in the blast furnace operation, with a coke consumption of 950 kg/t of hot metal (THM). Fortunately, since then, as a result of technological advances and process improvements, the industry managed to significantly reduce the coke consumption to ~500–550 kg/THM in the 1970s, since the mid-1980s to powdered coal injection (PCI) gradually replacing some of the coke, reducing the coke consumption to ≤400 kg/THM. A vital part of this improvement process was the total injection of PCI and other fuel of approximately 100 kg/THM. Today (2025), a PCI rate of ~130–160 kg/THM is quite common. Increasing the PCI rate to ~250 kg/THM would possibly be resulting in reducing the coke consumption down to 250 kg/THM. Allegedly, in Japan BF are running at ~400 kg/THM. The average PC rate in Japan at the time was considered 120 kg/THM, but individual operations could have operated at 250 kg/THM – such as operation at 266 kg/THM at the Fukuyama No. 3 blast furnace. The authors found, though, that the higher PPCI rate was compromised by the increased total reducing agent consumption, being inextricably tied to the minimum requirement of the reduction of FeO and the energy required for maintaining the optimum thermal state in the blast furnace reactor. Additionally, the optimum temperature of the liquid products of hot metal and slag needs to be maintained. To date (2023), the energy efficiency of BF-BOF route steelmaking is surpassed by EAF operation. The Office of Energy Efficiency and Renewable Energy (EERE, 2010) provides an interactive, dynamic manufacturing energy Sankey tool, with the opportunity to display the manufacturing energy footprint data as dynamic Sankey diagrams. The volume of primary energy that flows to major energy end uses in manufacturing is demonstrated by the line widths and line colour-coding, which links the manufacturing process related consumed fuel, steam, electricity, and energy used or lost. In addition, energy is generated onsite and its journey through the production process stages is shown accordingly (displayed in Figure 3-12):

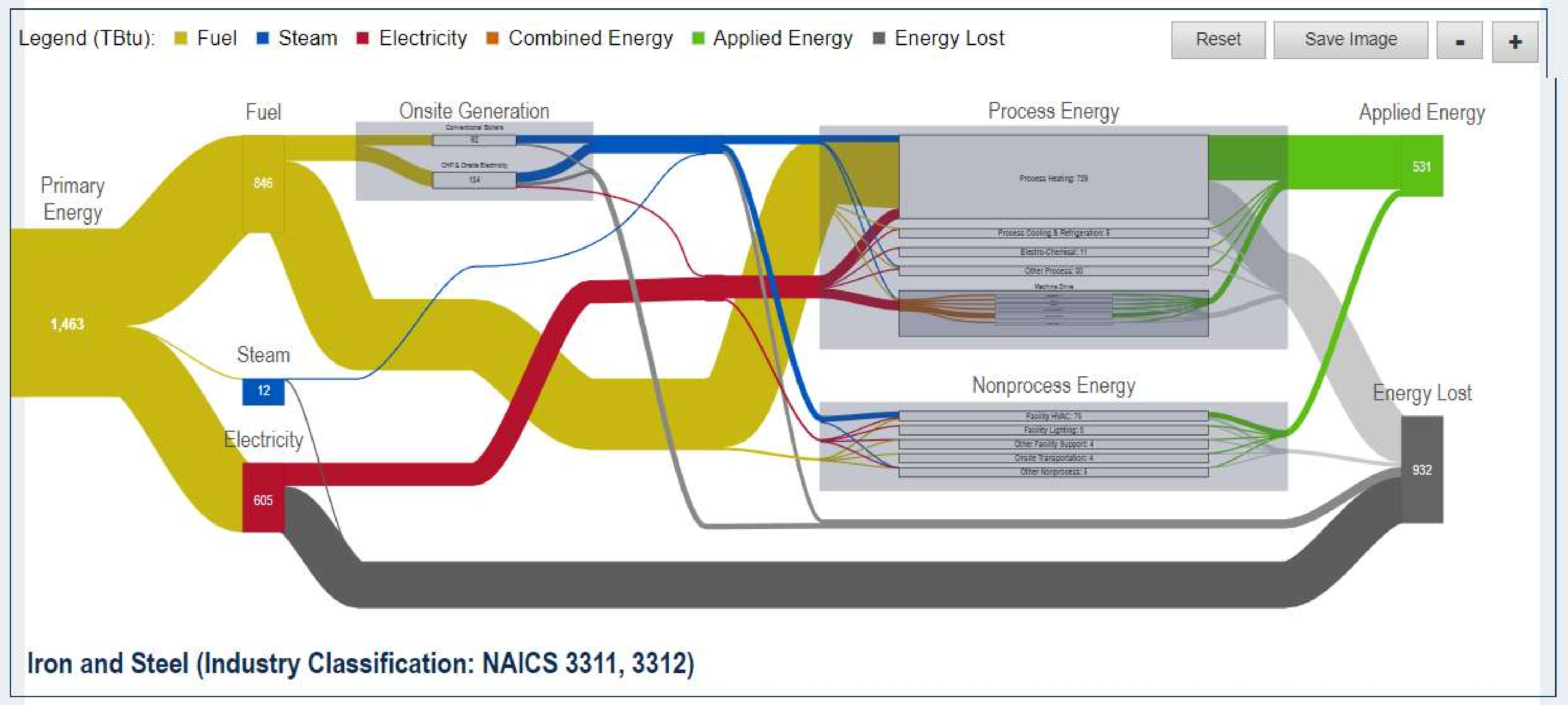


Figure 3-12: Sankey diagram of the iron and steel industry energy use,

loss and energy flow in trillions of British thermal units (TBtu) (EERE, 2010)

This Figure 3-12 Sankey diagram can be used to explore/compare energy flows across U.S. manufacturing and key subsectors, in volume of energy flow measured in trillions of British thermal units (TBtu). As demonstrated, the 15 manufacturing subsectors together consume 95% of all energy used by U.S. manufacturing – although this does not include the energy consumption of fuels which are being used as raw materials. The data for the compilation of this graph has been derived from the manufacturing energy and carbon footprints (EERE, 2010). Their diagram provides some indication of the energy flows in the iron and steel industry, and, although this was designed for the US market, one might argue that the same mechanism could be applied to the UK, too.

3.7.2 Exergy analysis

In order to discuss exergy, one must define what components and desired results exergy analysis in the context of steel production entails, in detail.

Cornelissen (1997) and Johansson and Söderström (2011) went to investigate exergy and its effects within the iron and steel industry and found, similar to Brodyanski, Sorin and Le Goff, (1994) and Moran and Sciubba (1994), that the *term* exergy had already been coined by Rant in 1956, being based on the first and second law of thermodynamics – which had already been established in the 19th century. In *thermodynamics*, was a Slovene mechanical engineer noted for his 1956 introduction of the term "exergy" as a new name for "technically available energy", which he followed up by "anergy" (1964) as a derivative term (Brockett, 2017).

Based on said first and second law of thermodynamics, approaching the issue from the component point of view, Demirel (2007) defines the first law efficiency or thermal efficiency as the ratio of the work output to the total rate of heat input and the second law of thermodynamics, associated with the definition of entropy S, dS = 6qrev/T – with entropy being a thermodynamic potential and the quantitative measure of irreversibility. Exergy is being described by Demirel (2007) as a unifying concept of various forms of energy - consisting of the physical resource properties and its surrounding environment.

Siefert, Narburgh and Chen (2016) provided an equation to demonstrate the first law of *thermodynamics* as $\Delta U = Q - W$. ΔU stands for the change of the internal energy, Q stands for the added heat, and W stands for the work being done within the system under investigation.

In heavy industry, it means that exergy *loss* means energy *transfer* (Brodyanski, Sorin and Le Goff, 1994; Waugh *et al.*, 2013; Siefert, Narburgh and Chen, 2016, 2016; Brockett, 2017)(BCSA, 2015). The work loss $T0_S$ in a continuous process is the difference in the energy (heat) H before and after the process – meaning that available energy $A = H - T0_S$ or exergy is a measure of the departure from the ambient or dead state (Brodyanski, Sorin and Le Goff, 1994; Waugh *et al.*, 2013; Siefert, Narburgh and Chen, 2016, 2016; Brockett, 2017; Li *et al.*, 2022).

Several attempts have been made in the past to establish a suitable component-based percentile formula, which would describe overall the exerted/destroyed energy, applicable to any processing in any setting. Already since the 1990s, scientists were convinced (Brodyanski, Sorin and Le Goff, 1994; Moran and Sciubba, 1994), that 30% of the heat energy entering any production process is a) lost and b) could be recovered. The technology to do so has experienced a steep learning curve and is now commercially viable and available. Excess heat from any production or manufacturing process can be reused to supply any production site with heat and warm water, partly, due to the simplicity of the technology required.

The energy basis and flow have been investigated thoroughly, and an energy industry defining and telling report and graph was produced by Moran and Sciubba, 1994. Figure 3-13 will display the exergy analysis power cycle:

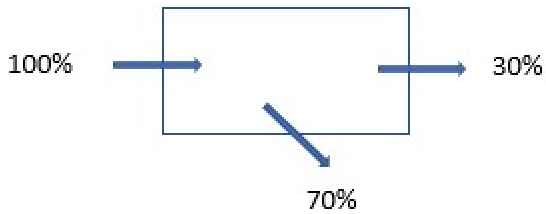


Figure 3-13: Exergy analysis power cycle

The theory of this exergy analysis is based on the fact that if 100% of energy is being inserted into any energy requiring unit, the amount of 70% will be effectively used for the intended purpose, whilst 30% are being lost due to inefficiencies and deficits within the production and processing infrastructure. It was established that approximately **70%** of energy is being applied and productively used within the production process, as **100%** is set as energy input and only **30%** could be measured as being available at the end of the production process. This leads to the conclusion that there is the potential for **30% off-heat recovery** and utilisation.

The exergy analysis, based on this principle, established a 3**0% loss**. But, as every production process is different and works with different parameters, no "one-size-fits-all" percentile rule of exergy, energy/exergy destruction or heat loss during production could be established. In

2010, the (US) EERE established a suitable determination process to that effect, which will be discussed in more detail further on in Chapter 3, section 3.7. Although Moran and Sciubba (1994) defined some core principles of exergy analysis, the practical application has, in fact, been utilised since the beginning of the industrial revolution (Brodyanski, Sorin and Le Goff, 1994).

Establishing exergenetic principles means utilising, monitoring and analysing two systems at different states whenever they are set in direct communication with each other, so that these have the opportunity to come into some state of equilibrium. Given that one of the two systems is an adequately idealized system with set parameters called "the environment" and the other is an "idea or system of interest", exergy is defined as the maximum *theoretical* shaft work (or electrical work) obtainable as the systems interact to equilibrium. Meaning: heat transfer only occurs in direct interaction with the environment. Brodyanski, Sorin and Le Goff (1994) established very clearly, that in order to achieve reliable and replicable data via exergy analysis, one needs to pay attention to the *thermodynamic* base of the concept of *energy efficiency* within *energetics* and *energotechnologies*. The authors found, that if the coefficient of energy transformation (CET) and the coefficient of exergy efficiency (CEE) are given, exergy analysis will provide reliable and replicable data, providing the researcher with results showing internal and external exergy losses.

Furthermore, by carrying out exergy analysis, the concept of *'transit exergy'*, as displayed in Figure 13, and its relationship with the CEE of systems and their parameters becomes clear (Brodyanski, Sorin and Le Goff, 1994; Waugh *et al.*, 2013; Siefert, Narburgh and Chen, 2016, 2016; Brockett, 2017; Li *et al.*, 2022). The linear flow of energy introduced, the efficacy of usage within the individual system section, and relevant resulting losses have been investigated throughout, using the data provided by a coal-fired power plant. Figure 3-14 will demonstrate an IGCC-CCS Baseline Model:

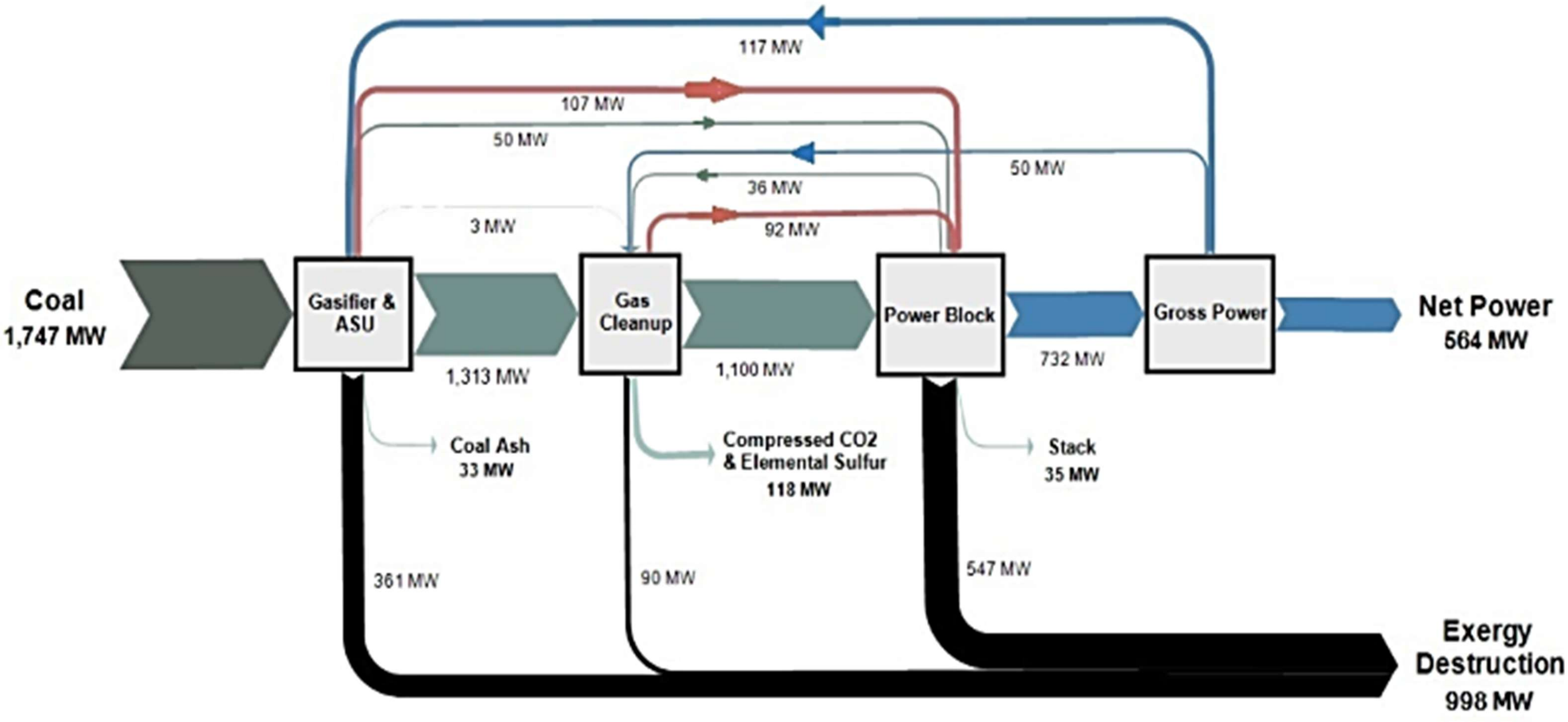


Figure 3-14: IGCC-CCS Baseline Model - Exergy flow diagram Power Plant Configurations with CO_2 Capture (Brodyanski, Sorin and Le Goff, 1994)

For steel production, this is an additional element to consider – meaning: researching energy *consumption*. This entails establishing if exergy loss can be minimised or harvested, or if the energy required for the steel production process can be reduced (Johansson and Söderström, 2011; Waugh *et al.*, 2013; Tata Steel Europe, 2020, 2023, 2024; Schmitz *et al.*, 2021; USEPA, 2023), as a proportion can be harvested from the production processes within. Therefore, this core principle is one of the elements of the Bio-Steel cycle, where heat emitted during the production process is being harvested and used elsewhere.
The individual industrial processes need to be investigated for their harvestable energy and heat losses, to be re-invested in the circular production process, and possibly even for external uses. There are plenty of opportunities for avoiding CO_2 emissions and decarbonising manufacturing, by harvesting energy, capturing and reutilising heat and off-gases within the steel manufacturing industry, from mining through to finish machining, which is explained in some detail in Chapter 4: The Bio Steel Cycle.

More detailed information can be found in Appendix 7: Energy, exergy and entropy.

3.8 Decarbonisation of the steel industry and selected case studies

3.8.1 Introduction - Energy consumption and emission-mitigation of emerging iron and steelmaking processes

The steelmaking process was thoroughly investigated by Conejo, Birat and Dutta (2020), and their starting point was the blast furnace, as steel is mainly produced via the blast furnace/basic oxygen furnace route (BF/BOF). Ca. 70% is produced by integrated BF/BOF-route plants and 30% by the EAF (electric arc furnace) route (71.5 and 28.0%, respectively in 2017), although companies worldwide are searching for solutions to decarbonise steelmaking and increasing the amount of electric arc furnaces in steel production (Leadit, 2023; Lempriere, 2024). The blast furnace is commonly a vertical shaft furnace, producing liquid metals by the reaction of air being added under pressure into the bottom of the furnace to a mixture of metallic ore, coke, and flux (lime) fed into the top section. Continued immediate combustion is maintained by the continuous addition of air under pressure. The blast furnace source of energy and reducing agent is the injected coke and coal. One ton of coke production requires 1.2–1.6 tonnes of coal (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). Preheating coal before coke-making reduces coal consumption and increases coke oven productivity (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). The production of Coke Oven Gas (COG) is about 300–360 m^3/ton coke (eia , 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). COG has a low calorific value (6–8 GJ/ton of coke) and contains heavy hydrocarbons like tar, which are subsequently removed to minimize downstream disturbances (eia, 1994; Benetto *et al.* 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). The blast furnace can be seen as a highly efficient thermal reactor, considering all the processes taking place within. It operates with two counter-current streams: descending solids and ascending gases and effectively operates as a heat exchanger. It needs to be mentioned that the blast furnace produces its own reducing gas, CO (carbon monoxide. Reduction reactions of iron oxide by CO produce

$CO_2.C_{(s)} + CO_{2(g)} = 2CO_{(g)}Fe_3O_{4(s)} + 4CO_{(g)} = 3Fe_{(s)} + 4CO_{2(g)0\text{-}/*870}$ Equation 3-1

(eia , 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021).

The blast furnace generates about 70% of the total amount of CO_2 in the integrated mill and most of the CO will be burned downstream into CO_2 (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). The blast furnace top gas contains approximately 25% of CO_2 (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). A medium-sized blast furnace with a production rate of 4500 tonnes/day produces about 1600 Nm^3/ton of off-gas (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). To reduce the consumption of chemical energy in the BF one should decrease the amount of fuel. There are several approaches to decreasing the consumption of coke, but there are two sustainable options: (i) recycle the off-gas and (ii) use biomass to replace coal injection (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). The consumption of coke in a modern BF is of the order of 300–350 kg/ton of hot metal and including PCI the total is about 500 kg/ton of hot metal (eia, 1994; Benetto *et al.*, 2004; Yi *et al.*, 2018; Yang *et al.*, 2021). The decarbonisation projects which could potentially have a signification impact on the way steel is being produced in the future are listed, as follows in Table 3-4.

Following these elaborations, one of the identified pathways to decarbonise the steel industry is to improve existing production processes. The following Table 3-5 will give a brief overview of the technologies currently either available at TRL9 or close.

3.8.2 Carbon capture, utilisation and storage

Carbon dioxide (CO_2) is being emitted by respiratory function of most living creatures, and as most plants require CO_2 to grow (NASA, 2023), it is a fascinating working symbiosis to behold. The natural carbon emissions cycle has been perfectly designed by nature, but humans have caused the production of CO_2 emissions to increase beyond the requirements of living things for this – initially – naturally occurring gas to life-threatening levels. One of the results is the climate crisis, as our planet is heating up to unprecedented temperature levels, which are incompatible with human habitation. Over the last 20 years, climate change and its effects on the global population, the natural world and our way of using up finite resources at an accelerating rate has been investigated and researched by a range of countries and numerous specialists and in the respective fields. The researchers aim was to establish a viable, economically and ecologically sound circular economic concept which could support the efforts of carbon capture and storage to avert the worst effects of climate change. In 2015, the European Commission (COM) issued a milestone guidance paper, an EU action plan for circular economic process, which is quite similar to the United States Environmental Protection Agency (USEPA, 2023), identifying the sources of and potential ways to reduce GHG emissions.

Table 3-4: A Selection of decarbonisation projects and endeavours

Project name	***Description***	***Reference***
The ULCOS PROJECTS - ULCOS/ULCOS-BF	The Ultra-Low CO_2 steelmaking (ULCOS) program: ULCOS is a project series involving 48 companies in the European Union and to drastically decrease CO_2 emissions, of the order of at least 50% over the whole steel mill. Phase I, with a budget larger than 50 million euros, started in 2004 and Phase II in 2010. ULCOS eventually proposed several breakthrough technologies: Top Gas Recycling Blast Furnace (TGRBF) or ULCOS-BF, ULCORED, ULCOWIN and ULCOLYSIS.	(European Commission Horizon 2020, 2019; COM (European Commission), 2015 a) (COM (European Commission), 2018, 2023b,2023c; European Commission, 2024) (Conejo, Birat and Dutta, 2020)
ULCORED	ULCORED is being described as a technology based on iron ore direct reduction, which produces DRI (direct reduced iron) in a shaft furnace. Hereby natural gas (NG) or gas obtained by gasification of coal, and off-gas is recycled into the furnace after CO_2 has been captured. This is directed into a concentrated stream and stored permanently. The main objective of the ULCORED process was to achieve a significant reduction in natural gas consumption as a fossil fuel. It was achieved by using partial oxidation (POx) of NG. In tandem with carbon capture and storage (CCS), ULCORED has the potential to reduce 70 % of CO_2 emissions, compared with the standard BF route. At its core, CO_2 scrubbing minimises greenhouse gas (GHG) emissions and maintains to reduce energy consumption at the same time. Therefore, ULCORED needs to be seen as an engineered combination of natural gas oxidisation and carbon capture.	(Conejo, Birat and Dutta, 2020) (Satyendra, 2019)
ULCOWIN	ULCOWIN and Siderwin are engineering processes which aim to produce iron by electrolysis at low temperature and are researching to develop a radically new steel production process without CO_2 emissions, based on electrolysis technology. It follows an initial project launched in the early 2000s, one of whose missions was to lay the foundations for electrolytic steel production at the laboratory stage. The carbon is replaced by electricity and, requires neither agglomeration nor coke. The operation of the blast furnace could be entirely electric, with oxygen being the only off-gas emitted. With no need to treat the hot metal, the adjustment to grade – say C35 - with the addition of carbon, would be performed during the melting of iron metal plates via electrolysis. One of the key benefits of this process is the easily implementable incorporation of renewable energy technologies into the process.	(Quader et al., 2016) (ArcelorMittal, 2023b)
ULCOLYSIS	With ULCOLYSIS an electrolysis-based process is being described which operates at liquid steel temperature, where molten iron oxide (iron ore = Fe_2O_3) is transformed into liquid metal and oxygen during an electrolytic smelting process. This method can be applied with other oxides, too.	(Birat, 2010; Conejo, Birat and Dutta, 2020)
HISARNA	HISARNA, a smelting technology resulting from a collaboration between ULCOS/European Commission, Tata Steel and Rio Tinto. To reach the 50%+ GHG emission reduction target, all of the afore mentioned technologies except for electrolysis can be associated with Carbon Capture and Storage (CCS). Smelting processes in general eliminate two steps: coking and pelletising of iron ores. HISARNA slightly pre-reduces iron ore fines and melts them in a cyclone by using pure oxygen, while most of the reduction and coal gasification takes place in the smelter (similar to the HIsmelt technology (Rio Tinto)). Coal powder is injected into the smelter. Encouraging pilot plant tests results demonstrated 20% fewer CO_2 emissions in comparison to the conventional BF operation. A higher percentage of CO_2 avoidance was achieved when CCUS of off-gas was integrated (Birat, 2010). An additional 10-20% of CO_2 emissions savings was thought to be attributed to the elimination of the requirement for coking and pelletising.	(Jones, 2011; Tata Steel Europe, 2020, 2023, 2023a, 2024; COM (European Commission), 2023a,b,c)
NER-300/400	The European Commission is involved in the NER-400 program, similar to the previous NER-300 program which was centred on low-carbon technologies, but this did not lead to any CCS project. In the NER-400 endeavours, TGRBF CO_2 is separated from the top gas. The blast furnace uses pure oxygen instead of air at the tuyeres, which generates a (mostly) nitrogen-free gas. With this concept, using 600 m3/ton of reducing gases can decrease the amount of fuel to 190–200 kg/ton maintaining a Pulverized Carbon Injection (PCI) rate of 170–180 kg/ton. Model calculations of energy consumption in the TGR-BF are 20–25% lower than the conventional Blast furnace. In a downsized oxygen BF, maximum shear stresses can be 20–30% lower compared to a conventional BF of the same output, thus making it in principle possible to charge coke with lower mechanical strength. Another innovation would be replacing PCI (powdered	(Birat, 2010; Cañete, 2014; Ariyama *et al.*, 2016; Suopajärvi *et al.*, 2018; Conejo, Birat and Dutta, 2020)

	coal injection) with powdered biomass, particularly charcoal. Replacement of PCI with heavy oil or natural gas is also possible but it does not contribute to reducing CO_2. Coal might be replaced by charcoal to a large extent. High-quality charcoal with a carbon content higher than coal can be produced by controlling pyrolysis temperature and using a wood-based feedstock. Furthermore, charcoal has lower concentrations of sulphur and acid oxides in addition to higher concentrations of basic oxides.	
AIST MOE / COURSE 50	In addition to ULCOS, AIST in the United States sponsored two projects, one related to the extraction of metals by electrolysis at high temperatures and another to hydrogen flash smelting. The concept of Molten Oxide Electrolytes (MOE) involves the melting of metal oxide and then the electrolytic separation of metal and oxygen. This process can contribute to decreasing GHG if lean electricity is employed and is somewhat similar to the ULCOLYSIS process. In Japan, there is a large National project called COURSE 50 supported by NEDO which was launched in 2007. One of its many dimensions is to introduce hydrogen in the Blast furnace to reinforce the reduction of iron ore.	(Conejo, Birat and Dutta, 2020; Gao *et al.*, 2022)
COREX	The only commercially successful smelting reduction process today is COREX. The process uses pellets and coal but generates even more CO_2 than the BF. Direct ironmaking from iron ore without coke and pelletizing presents important technical challenges. Among them are the higher concentrations of both sulphur and iron oxide in the metal (COREX slag has an unusual FeO content compared to a BF slag) as well as higher concentrations of CO and CO_2. These require higher rates of desulphurization, control of foaming slags and improved utilisation of coal particles to decrease the carbon footprint. Actual energy consumption by smelting processes can only refer to the COREX process since it is the only commercial one. Primary consumption of energy of COREX is higher in comparison to the BF, of the order 16 GJ/ton. In order to make it competitive, this process requires recycling the top off-gas in another plant like the DRI process or BF process.	(Manning and Fruehan, 2001; Li and Zhu, 2014; J. Li *et al.*, 2022)
EAF process improvement	A large number of innovations have drastically changed the shape, size and role of the EAF, and some of the innovations include: the development of the ladle furnace, redefining the EAF role as a melting unit; the development of UHP transformers achieving higher melting rates; foamy slag practice to operate with longer arcs and therefore higher energy density; continuous scrap preheating and charging; higher oxygen injection rates to increase the amount of pig iron in the metallic charge and to supply fossil energy (coal) in addition to electricity; optimisation of the hot heel practice; eccentric bottom tapping, improved post-combustion; oxy-fuel burners; hot charge of direct reduced iron (DRI); use of pre-heated metal, to name a few. Electrical energy consumption in the EAF varies depending on the metallic charge: the highest values range from 550 to 700 kWh/ton, when the metallic charge is Direct Reduced Iron (DRI) and decrease to 300–450 kWh/ton when the metallic charge is scrap. The lower values are achieved using both chemical energy (derived from oxygen injection) and scrap preheating technologies.	(Teng *et al.*, 2016; Singh and Jaison, 2020; Kirschen, Hay and Echterhof, 2021; Singh *et al.*, 2022)
Continuous casting / thin slab casting	Until the 1950s, ingot casting was the main technology in operation to produce steel. Whilst the amount of ingot casting decreased, continuous casting (CC) incrementally increased in volume and eventually largely replaced ingot casting. Currently, it is estimated that more than 96% of steel is produced by CC. Using this technology also reduced the volume of metal containing ores, and from 1.45 to 1.27 tonnes of liquid steel to produce 1 t of cold sheet. Continuous casting pours liquid steel into a turn dish and then into an oscillating mould. Thin Slab Casting (TSC) is a more recent version of CC; the post-cast-processing is almost the same, as some hot rolling is still required. The casting speed is increased in TSC in comparison with CC. During Near-Net-Shape Casting (NNSC), the resulting product exits the production line with a thickness of a few millimetres, and the majority of downstream processes (reheating, hot rolling, scarfing, pickling and annealing) become unnecessary. In CC, a typical slab thickness is 250 mm, whilst in thin slab casting the thickness is reduced to ca. 50–65 mm, and in NNSC 2–20 mm. In addition to higher productivity, and lower investment, the steel quality of NNSC products is free from oscillation marks observed in the material after CC. The simplified processing of NNSC has a ca. 80% lower energy consumption than conventional CC. The resulting emissions are reduced by ca. 60%, and currently estimated to be 170 kg CO_2/ton hot strip produced using NNSC.	(Thyssen Krupp, 2002; Luebering, 2009; Sosinsky *et al.*, 2009; Wänerholm, 2016; Conejo, Birat and Dutta, 2020; Guthrie and Isac, 2022)
CASTRIP® TSC / EUROSTRIP	The CASTRIP® facility at Nucor Steel's Crawfordsville started commercial operations in 2002, including a range of steel strips at thickness from 0.9 to 1.5 mm. EUROSTRIP ran a commercial facility in Krupp Thyssen Nirosta, following up on demonstrators in Isbergues, France, and Terni, Italy.	(Thyssen Krupp, 2002; Sosinsky *et al.*, 2009; Conejo, Birat and Dutta, 2020; Syre, 2023)

Athos	The Athos Project (Amsterdam-IJmuiden CO_2 Transport Hub and Offshore Storage) aims at developing a CO_2 transport and storage network in the North Sea Canal area to enable CCUS. Athos is besides Porthos in Rotterdam the second initiative in the Netherlands to build an infrastructure for CCUS. The Athos phase I ended on 20 Sep 2021 as a direct result of Tata Steel's decision to switch to hydrogen-based Direct Reduced Iron (DRI) steel-making technology. The Athos partners continue to engage with Tata Steel in phase II to assess potential support and to contribute to regional CO_2 reduction targets. In the North Sea Canal area, Athos is part of a broader package of initiatives to drive sustainable development in the region.	(The University of Edinburgh, 2023; Tata Steel Nederland, 2023)
Everest	The Everest (Enhancing Value by Emissions Reuse and Emission Storage) project consists of two phases: in the first phase, a carbon capture (from steelmaking process gases) facility has been installed. In phase two, the captured CO_2 is then delivered to the Athos (Amsterdam-IJmuiden CO_2 Transport Hub and Offshore Storage) infrastructure, aiming to convert the remaining gases into usable raw materials, with implementation in IJmuiden planned for 2027. The expected CO_2 savings results have been estimated for the first phase at approximately 3 million tonnes of CO_2 p.a. and phase two (reuse of process gases) approximately 4 million tonnes of CO_2 p. a.	(The University of Edinburgh, 2023; Tata Steel Nederland, 2023)
Hermes	The Tata Steel Hermes project is at its core the reduction of iron ore with H_2. It is estimated that enough supplies of green hydrogen and the steel production process technology to produce steel with hydrogen will be available by 2040. Tata Steel is collaborating with the chemical company Nouryon (at the port of Amsterdam) to develop the largest green hydrogen 100-megawatt renewable energy-powered water electrolysis facility in Europe (at Ijmuiden).	(The University of Edinburgh, 2023; Tata Steel Nederland, 2023)
Electrolysis	Siemens Energy are aiming to create the hydrogen economy of the future. They are working closely with partners from government, academia, and industry to create a sustainable and profitable hydrogen economy. The technologies in development embrace the whole hydrogen value chain: wind energy, infrastructure for power transmission, sea water electrolysis (similar to Tata Steel), in addition to hydrogen compression, transport, storage, and hydrogen-based power and heat generation.	(SIEMENS, 2022, 2023a; Tata Steel Nederland, 2023; Voestalpine, 2023)
Hydrogen EAF	Using hydrogen in the direct reduction – EAF route (DR-EAF) means reducing iron ore with hydrogen while in a solid state, to produce direct reduced iron (DRI) (sponge iron). This sponge iron is then fed into the EAF, where inserted electrodes are generating a current, which melts the sponge iron, and finally producing steel. However, some carbon is needed to produce steel, which is added in the form of pulverised coal or coal dust, biomethane or other biogenic carbon sources. The electrode energy consumption and added carbon equates to ±53 kg/CO_2 per tonne of steel, and where the electricity used is not from fully renewable energy sources, this carbon intensity adds to that figure. ArcelorMittal is developing a new, innovation project in Hamburg (Germany), the first industrial-scale production and process integration of Direct Reduced Iron (DRI) with 100% hydrogen as the reductant. The annual production capacity is estimated at 100,000 tonnes of steel.	(Bellona, 2021; ArcelorMittal, 2023a, no date)
GrInHy	The European Commissions GrInHy project (Green Industrial Hydrogen via Reversible High-Temperature Electrolysis) was carried out between 2016 and 2019. The technical and economic opportunities of high-temperature electrolysis (HT electrolysis) and the higher electrical system efficiency compared to low temperature electrolysis technologies led to establishing the following main objectives: • Delivering proof of achieving electrical efficiency of at least 80 % LHV • Increasing the scale of the SOEC core to a DC power input of 120 kW electricity • Producing a unit with a lifetime of ≥ 10,000 h with a degradation rate below 1 %/1,000 h; • Operation for ≥7,000 h whilst simultaneously adhering to the hydrogen quality standards of the steel industry. The electrical efficiency of 80 % has been largely achieved by operating the HT electrolyser in close proximity to the thermal-neutral operation point. The installation consisted of an optimized multi-stack module design with a total capacity of 120 kW electricity.	(Blume, 2021; COM (European Commission), 2022)
H2Future	Another project under the Horizon 2020 umbrella and managed by a cooperation of VERBUND, VOESTALPINE, and SIEMENS, a 26-month project of a 6MW electrolysis power plant was installed at the VOESTALPINE LINZ plant in Austria. Replicability of the experimental results at larger scales in EU27	(Voestalpine, 2023)

	for the steel industry is currently being studied and involves the technical, economic and environmental assessment of the experimental results utilising the CertifHY tools.	
HYBRIT	HYBRIT is a technology which is replacing CO_2 emissions with H_2O – water. Up to now, steelmaking involved coal to remove oxygen from iron ore, emitting copious amounts of CO_2 in the process. SSAB is set to revolutionise the industry with the innovative HYBRIT® technology, using hydrogen instead of coal in the ore reduction process, and emitting H_2O instead of CO_2.	(SSAB Svenskt Stål AB, 2022; SSAB, 2023)
Hydrogen direct reduction (HDR)	Similar to the HDR EAF process, direct reduction of iron ore using hydrogen has been piloted by a range of entities and the mechanisms and processes involved were clearly defined: direct reduction of iron is the chemical removal of O_2 from solid state iron ore. At present, the standard procedure to remove carbon from the iron used in the steelmaking process is chemically reduced from iron ore through the use of fossil fuel resources – natural gas or coke from coal, known as direct reduced ironmaking (DRI). The carbon in fossil fuels combines with the oxygen in the iron ore, initially without the addition of heat, producing metallic iron and a CO_2-rich process gas. Hydrogen and more specifically: green hydrogen, is seen globally as the clean energy source – evidenced by the fact that global industrial giants like Tata Steel, SSAB and ArcelorMittal are investing heavily in developing hydrogen plants with access to seawater, like in Ijmuiden (Tata Steel / Hermes).	(Rayner-Canham and Overton, 2010; Vogl, V., Åhman, M. and Nilsson, L.J., 2018; WSA World Steel Association, 2022, 2023a; Rice University, 2023)
Horizon 2020	Horizon 2020, the EU's flagship research and development funding programme, which was active from 2014 until 2020. It had a sizeable budget of ~€80 billion. Horizon 2020 has been succeeded by Horizon EuropeEN. Some of the afore mentioned projects have received funding from the Horizon 2020 finance provision, as declared. Horizon EuropeEN is the follow-on project after conclusion of Horizon 2020.	(COM (European Commission), 2015,2018,2019,2022,2023a,b,c
Horizon EuropeEN	Horizon EuropeEN is the follow-on project of Horizon 2020, and is a research and innovation funding programme, active until 2027, with a budget of €95.5 billion. The aims and objectives are tackling climate change, helping to achieve the UN's Sustainable Development Goals and boosting the EU's competitiveness and growth. Legal entities from within the EU and associated countries can participate.	(COM (European Commission), 2018, 2023b; European Commission, 2024)
HM Government 'The Ten Point Plan for a Green Industrial Revolution'	HM Government issued 'The Ten Point Plan for a Green Industrial Revolution' in 2020 covering the issue that most emissions are being produced through the burning of fossil fuels for electricity, heat, and transportation. The 6 sectors identified for being the most polluting are, as follows: • Electricity. • Transportation. • Industry. • Commercial/ Residential. • Agriculture. • Land Use/ Forestry. The efforts and plans currently in place amount to a total of achievable CO_2 reduction of 40.76%, with the potential to increase these efforts, based on the roadmap for further policies, to achieve a net-zero-carbon economy by 2050.	(HM Government UK, 2020)

Table 3-5: Some of the technologies currently either available at TRL9 or close

Post-combustion capture:		Athos	Captured carbon usage	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018;
		Everest	CCS: from BOG>former gas fields under the North Sea	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018;
		Geomimetic ®	CO_2 recycling (concrete, flue gases etc.)	Blue Planet (2021) Santos & Hanak 2022
	Short-mid term	DAC	Land trees (8.3t/ha/p.a.)3.8 t/tonne of steel	Zhou et al. 2021; FC 2021; Nix 2020; Suopajärvi 2018; Seethalakshmi 2016; Forestry Commission 2003
			Land shrubs, herbs	Zhou et al. 2021; FC 2021; Nix 2020; Suopajärvi 2018; Seethalakshmi 2016; Forestry Commission 2003
			Water plants	Zhou et al. 2021; FC 2021; Nix 2020; Suopajärvi 2018; Seethalakshmi 2016; Forestry Commission 2003
			Organisms (plancton)	Zhou et al. 2021; FC 2021; Nix 2020; Suopajärvi 2018; Seethalakshmi 2016; Forestry Commission 2003
		CEPS	Carbon enriched air 99% utilized in food production	Bao 2011, 2018; Farla et al. 1995
		Air-blown BF	MEA	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			MDEA	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Shift & Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
		TGRBF	MEA	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			VPSA	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
		Corex	MEA	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Shift & Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
	Long term	Air-blown BF	Shift membrane reactor + Selexol	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Selective carbon membrane	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
			Hydrate crystallization	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
		Adv. smelting red.	Purification only	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
		Mineral Carbonation	Two-tiered reaction tower	British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
		CCU Technology		British Steel 2022; Santos & Hanak 2022;TS 2019 2020; TSE2020;Toktarova et al. 2020;Chen 2018; Kuramochi2011/2018; Bataille et al. 2018
Pre-combustion process	Short term	HIsarna	Eliminates sintering, smelting reduction	TS 2019 2020; TSE 2020; EERE 2021;EIA 2022/2021; IEA 2021; WSA 2021; Kittipongvises 2017; EULA 2012
optimization		ReclaMet	Waste resource recovery	TS 2019 2020; TSE 2020
	Long term	Electrolysis	Direct water splitting; biomass>hydrogen	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
		Hydrogen EAF	Hyd. Direct reduction in EAF (H-DR/EAF)	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
		GrInHy	Electrolyser development	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
		H2Future	Electrolyzer development	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
		HYBRIT	Fossil fuel free primary steel prod.	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
		Hydrogen direct	HDR in BF/EAF/BOF; CO_2 from electricity used	EERE 2021; COM 2019; Mandova 2019; Vogl 2018
Research		reduction (HDR)		EERE 2021; COM 2019; Mandova 2019; Vogl 2018
Pre-combustion energy		Renewable energy technologies	Solar | Wind | Hydro | Geothermal	IPCC 2022; Santos & Hanak 2022; IRENA 2021; Mandova 2019; NREL 2019; Waisman et al. 2019; Bataille 2018
source replacement			Wind	IPCC 2022; Santos & Hanak 2022; IRENA 2021; Mandova 2019; NREL 2019; Waisman et al. 2019; Bataille 2018
			Hydro	IPCC 2022; Santos & Hanak 2022; IRENA 2021; Mandova 2019; NREL 2019; Waisman et al. 2019; Bataille 2018
			Geothermal	IPCC 2022; Santos & Hanak 2022; IRENA 2021; Mandova 2019; NREL 2019; Waisman et al. 2019; Bataille 2018
Pre-combustion energy		Industry 4.0	>Optimizing energy consumption in production	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
consumption optimization				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
			>Model based steel temperature adjustment	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
			> Hydrogen control in ladle operations	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
			> Hydrogen control in casting operations	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
			> Nitrogen control in ladle operations	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
			> Nitrogen control in casting operations	Jahani (2021); Franciosi 2020; Kuramochi 2018; Chen et al. 2018; Wei 2016; Babich & Senk 2015; Calvo & Domingo 2015
				Gupta 2014; Yang Raipalla & Holappa 2014; Copeland & Street 2013
Pre-combustion f. fuel repl.		Coal/Biochar	Biochar/Takachar	Takachar (2021);
Post-combustion capture:			Waste heat recovery	Franciosi 2020; Gupta 2014; Yang 2014; Worrell 2010

The opportunity for transition to minimising waste, and developing a resilient, sustainable, low carbon, resource efficient and competitive economic model must be taken seriously across Europe. As a side-effect, energy will be saved and also irreversible damages avoided, which are currently caused by using up resources at an unsustainable rate, as it exceeds the Earth's capacity for renewal – as far as climate and biodiversity, air, soil and water pollution are concerned. One of the key drivers to achieve the set objectives is a major initiative called “Horizon 2020”, the purpose of which is to fund innovative projects and targeted action in areas such as plastics, food waste, construction, (critical) raw materials, industrial and mining waste, consumption and public procurement.

One of the results of the EU countries’ efforts was the Paris Agreement, which was signed in 2016 by the member states of The United Nations (UN). It binds all signing countries to secure a sustainable global economic recovery and net-zero emissions future (not only zero CO_2 emissions – greenhouse gases (GHG) and other toxic emissions are also ringfenced within this agreement). One of the main goals is to limit global temperature rise to no more than 1.5 degrees Celsius, as achieving this would avert the worst ecological, financial and economic impacts of climate change.

HM Government issued ‘The Ten Point Plan for a Green Industrial Revolution’ in 2020, covering the issue that most emissions are being produced through the burning of fossil fuels for electricity, heat, and transportation. The 6 sectors identified for being the most polluting are, as follows:

- Electricity
- Transportation
- Industry
- Commercial/ Residential
- Agriculture
- Land Use/ Forestry

The efforts and plans currently in place amount to a total of achievable CO_2 reduction of 40.76%, with the potential to increase these efforts, based on the roadmap for further policies, to achieve a net-zero-carbon economy by 2050.

The European Environment Agency Report 03/2020 (EEA, 2020,2021) constitutes the official inventory submission of the European Union for 2020 under the UNFCCC (United Nations Framework Convention on Climate Change) (2015), as well as the Kyoto Protocol (KP) (UNFCCC, 2005), covering the years between 1990 and 2018. The European Union (EU), party to the UNFCCC, issues these reports on greenhouse gas (GHG) inventories annually, for emissions and removals within the area taking place within its territory. Due to the nature of this lag in reporting, the 2020 inventory report cannot yet reflect the effects which the COVID-19 pandemic might have had. Although the UK left the EU on February 1, 2020, EU law still applies until the end of the transition period. Moreover, key provisions of Regulation (EU) No 525/2013 ("Mechanism for Monitoring and Reporting GHG") and of Decision No 406/2009/EC ("Effort Sharing") apply to the United Kingdom also in respect of greenhouse gases emitted during 2019 and 2020. The EU, and its member states – including Iceland - agreed to a quantified emission reduction commitment, which will limit their average annual GHG emissions to 80 % of the sum of their base year emissions, which is reflected in the Doha Amendment (UNFCCC, 2012). GHG emissions decreased in the majority of sectors between 1990 and 2018, with the notable exception of transport, including international transport, refrigeration and air conditioning. Considering the aggregate level, the highest emission reductions were achieved in manufacturing industries, construction, electricity/heat production, iron/steel production and domestic combustion. Sausen and Schumann (2000) had already thoroughly investigated greenhouse gas (GHG) and – specifically – aviation CO_2 emissions, using data from the Global Carbon Project. Lee et al. (2021) went on to research issues revolving around these urgent matters and established how significant the impact of global aviation factually is in terms of CO_2 emissions produced, radiative forcing (RF) and effective radiative forcing (ERF) and its impact on climate change. The authors looked into both: radiative forcing and effective radiative forcing (and their effects on increasing the air temperature), with sums being calculated for the years 2000–2018. Allegedly, contrail cirrus (the condense clouds one can observe as an air signature of a plane's flight path), consisting of linear contrails and the cirrus cloudiness arising from them, yields the most significant warming ERF, closely followed by CO_2 and NO_x emissions. Interestingly, emissions of sulphate aerosol formation result in a negative (cooling) term.

In conclusion, the mean contrail cirrus ERF/RF ratio of 0.42 indicated that contrail cirrus is less effective in surface and atmospheric warming than other terms. It was established that by 2018, the net aviation ERF is +100.9 milliwatts (mW) m−2, meaning a 5–95% likelihood range (of 55, 145) with significant contributions from contrail cirrus (57.4 mW m−2), CO_2 (34.3 mW m−2) and also NO_x (17.5 mW m−2).

Ture (2007), also turning to the skies for solutions, researched the opportunities which lie within hydrogen production from solar energy, with hydrogen being a credible alternative to using fossil fuels in industrial applications. Effectively, CO_2 emissions were removed from hydrogen production, establishing that it is both economically and practically viable to produce hydrogen using solar energy - making hydrogen a renewable energy source.

House et al. (2011), along the same lines of thought, investigated the opportunities of economic and energetic analysis of capturing CO_2 from ambient air. In conclusion, they established that the total levelized cost of $80.-/MWh natural gas advanced combined cycle is the lowest total levelized energy cost, whereas with regards to the $/(t$CO_2$ avoided), hydropower is by far the most cost-efficient and bears the lowest risk for humans and the environment, at $748/t of CO_2 captured.

CIRAIG (International Reference Centre for the Life Cycle of Products, Processes and Services, 2015) and EMAF (Ellen MacArthur Foundation, 2019) carried out thorough critical literature reviews of concepts concerning circular economic processes, covering the following issues, presented in order of conceptual scale (from more to less encompassing):

- Sustainable Development
- Ecological Transition
- Green Economy
- Functional Economy
- Life Cycle Thinking
- Cradle-to-cradle thinking
- Shared Value
- Industrial Ecology
- Extended Producer Responsibility
- Eco design

The study of these concepts has led the researcher to develop the Bio-Steel-Cycle (Kiessling, Darabkhani and Soliman, 2022).

O'Callaghan (2018) wrote for the European Commission about 'green' hydrogen – produced utilising exclusively renewable energy technologies - as an alternative to fossil fuels. Possibly inspired by this, Sunny, Mac Dowell and Shah (2020) investigated the issue of what might be needed to deliver carbon-neutral heat using hydrogen and carbon capture and storage (CCS), which led to the discovery that it is entirely possible to produce hydrogen based on using renewable energy technologies. O'Callaghan (2018) found that, currently, around 20%

of all GHG emissions are produced by industries such as steel and cement – it is, therefore, vital to develop promising technologies and concepts in these areas. Siemens was referred to as claiming that '…Hydrogen and fuels derived … capable of reducing the CO_2 from fossil fuels … down to zero'.

O-Callaghan (2018) and Sunny, Mac Dowell, Shah (2020) referred to hydrogen technology as a concept based on generating energy exclusively utilising renewable energy technologies. To this effect, a thorough literature review has been carried out to determine the various possibilities of steelmaking process CAT, CCS and CCUS technologies, as demonstrated in the following Table 3-6.

3.8.3 Decarbonising the iron and steel industry

The current state of the decarbonisation of the iron and steel industry has been carefully reviewed, and key publications have been identified. Invaluable insights were provided with regards to decarbonisation of the iron and steel industry, "green" steel in particular and the mechanisms and processes necessary to achieve sustainable and carbon free iron and steel production. Setting the scene, Muslemani et al. (2021) worked on identifying the opportunities and challenges for decarbonizing steel production by creating markets for "green" steel products. Their in-depth investigation provides valuable insight into potential markets for green steel products and their manufacturers and to make the economic case for sustainable production. Arens, Åhman and Vogl (2021) researched which countries are factually prepared to "green" their coal-based steel industry with electricity and reviewed respective climate and energy policy. They subsequently published policy guidance by country for "green" steelmaking. One of the key papers to provide the technical insight into the vital components of sustainable steel is Wang (2022) and Wang et al.'s (2022) investigations of the opportunities for technology-driven decarbonisation and green steel for Australia. They carried out economic modeling of a green steel value chain with wider implications for the second and third-tier small to medium enterprises and heavy industry. Models, pathways, and roadmaps are guiding the industry on the path to decarbonisation, and therefore Bataille, Nilsson and Jotzo's (2021) study was considered a key paper. They provided some components for the BiSC (Bio Steel Cycle) model (Kiessling, Darabkhani and Soliman, 2022), when they looked at the iron and steel industry in a net-zero emissions world.

Table 3-6: Literature review of the steelmaking process, process improvement technologies, CAT, CCS and CCUS technologies

Author	Title	Description
British Steel, 2023	How we make steel	An overview of the steel making process in the UK
Santos and Hanak, 2022	Carbon capture for decarbonisation of energy-intensive industries: a comparative review of techno-economic feasibility of solid looping cycles	CCS of energy-intensive industries (steel, cement, paper, chemical..) techno-economic feasibility and implementation opportunities
EERE, 2021	Hydrogen Production: Natural Gas Reforming	Endothermic – heat dependent. Steam-methane reforming; high-temperature steam (700°C–1,000°C) is used to produce hydrogen from natural gas. Methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and some carbon dioxide.
EIA, 2023	Energy Outlook 2022 - Energy Outlook 2022 - Table 18. Energy-Related Carbon Dioxide Emissions ...	2022 Overview energy related CO_2 emissions by sector
EIA, 2021	Energy Outlook 2021 - Energy Outlook 2021 – Table 18. Energy-Related Carbon Dioxide Emissions ...	2021 Overview energy related CO_2 emissions by sector
FC, 2003	Forests, Carbon and Climate Change: the UK Contribution	UK tree cover and DAC
IEA, 2021	Data and Statistics	Global energy and fuel data
IETD, 2021	Basic Oxygen Furnace	Process data
IETD, 2021b	Electric Arc Furnace	Process data
Jahani et al., 2021	Application of Industry 4.0 in the Procurement Processes of Supply Chains: A Systematic Literature Review	I4.0 digitisation and CO_2 saving opportunities
Takachar (Keung), 2021	Takachar mobile units	Biochar units scalable and deployable internationally
WSA, 2021	December 2021 crude steel production and 2021 global crude steel production totals	World crude steel production for the 64 countries reporting to the World Steel Association was 158.7 million tonnes (Mt) in December 2021, a 3.0% decrease compared to December 2020
Ren et al. 2021	Vegetation uptake of mercury and impacts on global cycling	GHG vegetation uptake mechanism, vegetation cycling, and model representation of vegetation Hg (mercury) cycling
Franciosi et al., 2020	Integration of I4.0 technologies with maintenance processes: what are the effects on sustainable manufacturing?	Digitisation of manufacturing and possible CO_2 reducing effects
Liu et al., 2020	Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic	Global CO_2 emission development affected by Covid-19
Nix, 2020	John Nix Pocketbook – For Farm Management (50th edn)	Guidance book for agri- and agri-tech-businesses and management
Toktarova et al., 2020	Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study	Applicable to steel manufacture globally, providing real-time data on technology supporting transitioning to a low-carbon (steel) industry
TSE, 2020, 2024	Sustainability report	Fact Sheet EU sustainable and zero carbon steel manufacturing data
COM, 2019	BIONICO: A pilot plant for turning biomass directly into hydrogen'	Project within Horizon 2020 - BIOgas membrane reformer for decentralized hydrogen production
Waisman et al., 2019	A pathway design framework for national low greenhouse gas emission development strategies	Range of specialists in sustainability; Prof Fischedick/IPCC; Provided some key data to build the BiSC from
Griffin and Hammond, 2019	Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective	Opportunities and challenges to reducing industrial energy demand and (CO_2) emissions in the iron and steel sector are evaluated
Khakimov et al., 2019	Development of optimal modes and mathematical models of energy performance of electric steelmaking production	Development of the underlying mathematical formulae in energy performance of electric steel making

They identified new mitigation pathways, new supply chains, modeling needs and policy implications. Their mitigation pathways investigation towards the decarbonisation of steelmaking provided invaluable analysis and insight into supply chains and policy needs. Liu *et al.'s* (2022) work created a technological roadmap towards optimal decarbonisation development of China's iron and steel industry. They developed policy guidance exploring the deep decarbonisation pathways. Richardson-Barlow *et al.* (2022), identified policy and pricing barriers to steel industry decarbonisation during their case study of the UK iron and steel industry. They issued a guidance paper, exploring the decarbonisation pathways. One of the paths towards decarbonisation of the iron and steel industry is using hydrogen, particularly: hydrogen direct reduction. The discussion around H2 has gained more momentum again and Öhman, Karakaya and Urban (2022) researched the transition potential into a fossil-free steel sector and identified the necessary conditions for technology transfer to hydrogen-based steelmaking in Europe. Toktarova (2021) investigated the low-carbon steel industry interactions between the H2DR of steel and the electricity system via a Swedish case study. They created a cost-optimal design of the steel-making industry and electricity system with close to '0' CO_2 and were another key paper towards the creation of the BiSC model. Colla and Matino (2021) took a slightly different approach when they endeavoured to issue a guidance paper and overview of the state of the art, recent developments and future trends regarding hydrogen route for a green steelmaking process. In their opinion, steel production based on hydrogen is one of the key factors to improve the carbon footprint of the steel industry. A more global perspective was taken by Garcia-Herrero, Tagliapietra and Vorsatz (2021), within their development of hydrogen development strategies. They see hydrogen as a candidate to fully decarbonise European steelmaking global aviation and maritime transport. Grasa *et al.* (2022) investigated the blast furnace gas decarbonisation through calcium-assisted-mill off-gas hydrogen production. They took an experimental and modeling approach to the calcium-assisted steel-mill off-gas H2 production process (CASOH) in integrated steelmaking plants. Devlin and Yang (2022), however, focused more on regional issues when researching supply chain implications and their potential for decarbonising steel. Their focus was energy efficiency and green premium mitigation, green hydrogen-based iron ore reduction and renewable electricity-based steelmaking. Case studies, such as Turnbull's (2021) work concentrated on a highly granular model of China's coal production, transport and consumption system. Their work shows how its decarbonization and energy security plans will affect coal production and the effect of decarbonisation on coal imports. Griffin and Hammond (2021), however, cast the net wider with the focus on global transitions and investigation into making

UK steel production more environmentally benign whilst advancing decarbonisation of the iron and steel sector. Lu *et al.* (2022), also provided insight into China`s iron and steel industry decarbonisation options, based on a 3-dimensional analysis. Whereas Steenbrink (2022) focused on the impact of the Carbon Border Adjustment Mechanism. They conducted an economic and geopolitical assessment of the German-Chinese aluminium trade flows. Their paper provides a thorough assessment on how best to incentivise non-EU trade partners to adopt measures comparable to the EU's and - simultaneously - yielding revenue to reuse in accelerating decarbonisation of steelmaking. In terms of carbon avoidance, capture and utilisation, Kempken *et al.* (2021) identified possible decarbonisation barriers (Deliverable 1.5). The isolation of major barriers to the decarbonisation process of the EU iron and steel industry provides valuable insights into the reasons why the industry seems quite reluctant to decarbonise their existing production and facilities. Williams *et al.* (2021) conducted a case study, during which they focused on CO_2 capture and storage (CCS) and presented the results of focus group discussions in a Welsh steel-making community. The topic of decarbonisation of steel production by switching to renewable sources was welcomed during the local focus group discussions and showed widespread support in the community for the company's efforts in this direction. Tanzer, Blok and Ramírez (2021) went one step further by focusing their research on integration of biomass when they investigated the decarbonisation opportunities via BECCS: promising sectors, challenges, and techno-economic limits of negative emissions and BECCS in the iron and steel industry. Sarić, Dijkstra and van Delft (2021) considered CO_2 abatement in the steel industry through carbon recycling and electrification by means of advanced polymer membranes. For this, a conceptual process design and assessment were performed for a process that is a combination of carbon recycling and electrification of the steelmaking process. Wang (2022) focused more on energy-saving technologies and optimisation of energy use for a decarbonised iron and steel industry. A valuable guidance paper was issued where suitable decarbonisation technologies are categorised. A different approach was taken by Singh *et al.* (2022), as they researched the opportunities for decarbonisation of steel mill gases in an energy-neutral chemical looping process, providing the technical elements for carbon enrichment for plant stimulation (CEPS), which is based on flue stack gas scrubbing. In addition to CAT, CCUS and BECCS, waste recycling is a vital part of the decarbonisation process. Jacob, Sergeev and Müller (2022) provided a thorough review when they investigated the potential of valorisation of waste materials for high-temperature thermal storage. An overview of the decarbonisation process of both the electricity and steel making industry. Sun *et al.* (2022) seemed to have worked along the same lines and developed a concept for the decarbonisation of the iron and steel sector for a 2° C target, using inherent waste streams. Furthermore, other aspects of decarbonisation needed to be considered, as Antonazzo *et al.* (2021) pointed out: a key component of the transition process to decarbonisation is the need to meet green skills needs for a sustainable steel industry. They identified the skills required for a steel industry in transition to sustainability (as displayed in table 3-6). Zhiming *et al.* (2022) researched material-based decarbonisation implications and how lime quality affected metallurgical steel quality and the value in use of lime in the BOF steelmaking process. Garvey, Norman and Barrett (2022), however, focused on technology and material efficiency scenarios for net zero emissions in the UK steel sector. Their assessment included steel plant retrofitting and grid electricity decarbonisation. The review of publications with regards to decarbonisation has provided information for the path to decarbonise the iron and steel industry and technologies for the reduction of CO_2 emissions – in line with the Paris Agreement (UN, 2016), COP27 (UN, 2022) and the IPCC's recent (2023) report warnings and calls for action.

Among others, this data has provided the vital elements to build a model and strategy for decarbonisation of the iron and steel industry, in the short-term.

3.8.4 Discussion

With currently globally 59 projects underway concerned with decarbonisation of industrial processes, one would like to think that the decarbonisation and the net zero scenario should be easily achievable, in the short-term. However, with high CAPEX and long project timelines, the research for solutions is taking time.

3.8.5 Conclusions

Some milestones have been achieved, such as Germany committing to cut their CO_2 emission by 20% by 2020 (Wilke, 2023). As allegedly anthropogenic CO_2 emissions are yet to peak, unfortunately, this is just one country out of 195, and a lot more needs to be done, much faster (IPCC, 2023).

Chapter 4 will provide more insight into the technical solution and engineering opportunities of the Bio Steel Cycle.

Table 3-7: Decarbonisation efforts in the iron and steel industry

Title	*Remarks*	*Author*
From Australian iron ore to green steel: the opportunity for technology-driven decarbonisation	Green steel for Australia - economic modelling of a green steel value chain	Wang et al. (2022)
Technological roadmap towards optimal decarbonization development of China's iron and steel industry	Policy guidance exploring the deep decarbonisation pathways	Liu et al. (2022)
Blast Furnace Gas Decarbonisation Through Calcium Assisted Steel-Mill Off-Gas Hydrogen Production. Experimental and Modelling Approach	The calcium-assisted steel-mill off-gas H_2 production process (CASOH) in integrated steelmaking plants	Grasa et al. (2022)
Policy and pricing barriers to steel industry decarbonisation: A UK case study	Policy guidance exploring the decarbonisation pathways in the UK iron and steel industry	Richardson-Barlow et al. (2022)
Decarbonisation options of the iron and steelmaking industry based on a 3-dimensional analysis	Decarbonisation options - China`s iron and steel industry as a case study	Lu et al. (2022)
Energy saving technologies and optimisation of energy use for decarbonised iron and steel industry	Suitable decarbonisation technologies are categorised	Wang (2022)
Decarbonisation of steel mill gases in an energy-neutral chemical looping process	Strategy for carbon capture from steel mill gases	Singh et al. (2022)
Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation	Green hydrogen-based iron ore reduction and renewable electricity-based steel making	Devlin and Yang (2022)
Decarbonising the iron and steel sector for a 2° C target using inherent waste streams	Global steel demand and limitations of techno-economically feasible options for low-carbon steelmaking …	Sun (2022)
Impact of the Carbon Border Adjustment Mechanism: An economic and geopolitical assessment of the German-Chinese aluminium trade flows	Assessment on how incentivising non-EU trade partners to adopt measures comparable to the EU's; and yielding revenue to reuse in accelerating the decarbonisation of steelmaking	Steenbrink (2022)
Technology and material efficiency scenarios for net zero emissions in the UK steel sector	Assessment including steel plant retrofit and grid electricity decarbonisation	Garvey, Norman and Barrett (2022)
A highly granular model of China's coal production, transport and consumption system shows how its decarbonization and energy security plans will affect coal …	The effect of decarbonisation on coal imports	Gosens, Turnbull, Jotzo (2021)
Valorisation of waste materials for high-temperature thermal storage: a review	Decarbonisation of the energy system and decarbonisation of both the electricity and steelmaking industry	Jacob, Sergeev, Müller (2021)
Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe	Decarbonisation of steelmaking via hydrogen	Öhman, Karakaya, Urban (2021)
Value in the use of lime in the BOF steelmaking process	Lime quality and its impact on metallurgical steel quality	Zhiming et al. (2021)
The Low-Carbon Steel Industry-Interactions Between the Hydrogen Direct Reduction of Steel and the Electricity System	A case study in Sweden; cost-optimal design of the steel-making industry and electricity system with close to '0' CO_2	Toktarova (2021)
Editorial for the Special Issue: Overview, state of the art, recent developments and future trends regarding Hydrogen route for a green steelmaking process	Steel production based on hydrogen is one of the key factors to improve the green footprint of the steel industry	Colla and Matino (2021)
Industry in a net-zero emissions world: new mitigation pathways, new supply chains, modelling needs and policy implications	Mitigation pathways investigation towards decarbonisation of steelmaking; analysis of supply chains and policy needs	Bataille, Nilsson, Jotzo (2021)
Collection of possible decarbonisation barriers (Deliverable 1.5)	Identification of major barriers to the decarbonisation process of the EU iron and steel industry	Kempken et al. (2021)
Global Transitions	Investigation into making UK steel production more environmentally benign and advancing decarbonisation	Griffin and Hammond (2021)
Preparing for a just transition: meeting green skills needs for a sustainable steel industry	Identification of skills required for the steel industry in the transition to sustainability	Antonazzo et al. (2021)
Hydrogen development strategies: a global perspective.	Hydrogen is a candidate to fully decarbonise European steelmaking, global aviation and maritime transport	García-Herrero, Tagliapietra, Vorsatz (2021)
Which countries are prepared to green their coal-based steel industry with electricity? Reviewing climate and energy policy	Policy and guidance by country for "Green" steelmaking	Arens, Åhman, Vogl (2021)
Decarbonising steel production using CO_2 Capture and Storage (CCS): Results of focus group discussions in a Welsh steel-making community	Decarbonisation of steel production by switching to renewable sources – local focus group discussions	Williams et al. (2021)
Decarbonising industry via BECCS: promising sectors, challenges, and techno-economic limits of negative emissions	Decarbonisation of BECCS in the iron and steel industry	Tanzer, Blok, Ramirez (2021)
Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products	Investigation into potential markets for green steel products	Muslemani et al. (2021)
CO_2 Abatement in the Steel Industry through Carbon Recycle and Electrification by Means of Advanced Polymer Membranes	… For this, a conceptual process design and assessment were performed for a process that is a combination of carbon recycling and electrification of the steelmaking process… .	Sarić, Dijkstra, Van Delft (2021)

Chapter 4 The Engineering of the Bio Steel Cycle: The Solution

4.1 Introduction

The requirement to drastically reduce GHG emissions, and particularly: CO_2 emissions, has never been greater than today. The Kyoto Protocol, the Paris Agreement, and recent 2023 reports from the IPCC have clearly set out the impact which the highest ever recorded anthropogenic CO_2 emissions are having on our environment and climate.

The iron and steel industry is thought to be responsible for between 7% and 11% WSA (WSA World Steel Association, 2021a) of global industrial CO_2 emissions, although there are some scientist who are convinced that these could be significantly higher (Zhang, s. *et al.*, 2022; Morrow *et al.*, 2014; Hasanbeigi *et al*., 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Ren *et al.*, 2021; Swalec, 2021; Wang, C. *et al.*, 2022). As there is no global legal or practical framework currently in existence on how to measure CO_2 emissions, the definition of de facto emissions has proven to be very challenging.

The factual level of CO_2 emissions for every t of steel produced currently standing at more than 4.6t of CO_2 emissions (Kiessling, Darabkhani and Soliman, 2022), the onus is on industry to remedy the environmental damage caused in the past two centuries. The anthropogenic carbon emissions are at an all-time-high with reported ~65.6 Gt CO_2-equivalent in 2019 (IPCC, 2023). The 64 steel producing countries produced between January and December 2021 (WSA, 2022) 17Gt CO_2-equivalent of CO_2 emissions as a result of the current linear steel manufacturing.

The importance to significantly reduce GHGs and eliminating fossil fuel combustion and usage has never been greater, and fast, practical solutions - on a global scale - are needed. Already in 1912 it was recognised that coal consumption is an environmental hazard and incompatible with keeping global temperatures at a balanced level to sustain life. Industrial processes have for more than two hundred years polluted the air we breathe, and already in 1912 this was recognized in an Australian newspaper clip in The Rodney and Otamatea Times – Waitemata and Kaipaba Gazette (The Rodney and Otamatea Times, 1912). It is worth pointing out that in this mentioned article, merely the in-furnace-coal-combustion process is mentioned in connection with carbon emissions. CO_2 emissions from energy consumption, mining, pelletising, coking, sintering, steel smelting, casting, rolling, annealing, rolling, finish machining and surface treatment and related processes have not been considered at that time. But as these authors more than hundred years ago already established – possibly based on the carbon content of coal (78-95%) (IEA, 2023) and the release of CO_2 into the atmosphere by combustion, the factor to be 3.5 (7,000,000,000/CO_2 emissions / 2,000,000,000t of steel

= 3.5), resulting in 3.5t of CO_2 emissions in the blast furnace operations alone, by 1912. Although the steelmaking process has undergone significant improvements and the BOF operation has allegedly reduced the CO_2 emissions to between 3.2t and 1.6t/CO_2/t of steel produced (Worrell *et al.*, 2010; Li and Zhu, 2014; Griffin and Hammond, 2019; Toktarova *et al.*, 2020; Liu *et al.*, 2022; Suer, Ahrenhold and Traverso, 2022; Tian *et al.*, 2022), it begs the questions why this knowledge has not been used to establish the true CO_2 emissions over the past 2 centuries - including all necessary processes required to produce steel?

The objectives of this multi-disciplinary and multi-industry-overarching study are to identify the most efficient implementation opportunities of the chosen processes and technologies to reduce the current BF-BOF route 4.6t CO_2 emissions / t of steel produced to factual ‘0’, ordered in seven easy steps, from short-term to long-term solution implementation.

4.2 Motivation

The devastating effects of climate change, such as wildfires increasing in numbers and frequency, hurricanes, and earthquakes have sparked the desire and motivation for wanting to make a difference in the iron and steel industry. To date, there has been no publication stating the total CO_2 emissions for all process stages involved in the steelmaking process, from mining to finish machining.

The Bio-Steel cycle is aiming to work within the principles of the Circular (Tech-) Economy (Appendix II). Waste and CO_2 emission avoidance and reduction, and pollution reduction are the key elements of this model. This is an industry-overreaching, multi-disciplinary concept and systematic approach to steel manufacturing, considering all aspects along the production process and emphasising the need for production process improvement. This approach will benefit society, businesses and our environment, as well as reducing production cost in heavy industry. Based on the literature reviewed, a range of process components were researched and approaches to CCS were considered, such as a 3-phase-model (Toktarova *et al.*, 2020), the techno-economic- pathways-concept, where biomass (Wang *et al.*, 2019), hydrogen, and electrification of steel production were identified as possible factors to reduce CO_2 emissions – although they are largely making the case for electrification of steel production.

Reading inspiring publications by the Ellen McArthur Foundation (EMAF, 2019), the desire and motivation for wanting to make a difference was born. The core message and principles which (EMAF, 2019) have developed are the circular economy with the basis of three principles driven by design:

- Eliminate waste and pollution

- Circulate products and materials (at their highest value)
- Regenerate nature

Essentially underpinned by a societal transition to renewable energy, materials, and circular economic principles, a resilient system can be created which is positive for the environment. With habitat recreation and reversing biodiversity loss, it is much healthier for the planet's human and animal population alike. With the living conditions improved as a result of industrial production decarbonisation efforts, the effects of climate change such as habitat and harvest loss due to extended and prolonged wildfires and unseasonal flooding can be halted or even reversed. Additionally, it is beneficial for businesses, as usage of virgin material and its destructive extraction from natural sources can be reduced to a minimum – if not entirely avoided.

The developed concept "Bio Steel Cycle" and the "7 steps to net-zero CO_2 emissions steelmaking" has been published in November 2022, with this URL: https://www.mdpi.com/1996-1073/15/23/8880, and a copy of the published manuscript can be found in Appendix 5. For the benefit of the reader, it should be mentioned that in the published paper not the whole scale of the identified CO_2 emissions in the steelmaking process have been mentioned, but rather the BF-BOF-process-route had been focused on.

The publication of this work has attracted great interest. The author and supervisors were approached by Wiley's Publishers and asked to write a book with this theme and contents, detailing aspects surrounding the decarbonisation of the iron and steel industry. A book publication contract has subsequently been signed, and the publication of the finished manuscript is expected to be 2025.

4.3 Materials and Methods

The research which resulted in the development of the Bio Steel Cycle and strategy used global steel data and literature on sustainability, decarbonisation and CAT, CCS and CCUS technology. The main reason underpinning this choice and course of research is that, as suggested by the Steel Yearbook 2018/2019 (WSA, 2018/2019a), the global iron and steel industry is still heavily reliant on coal and is responsible for between 7% and 11% WSA (WSA World Steel Association, 2021a) of global industrial CO_2 emissions, with some scientists claiming that the share is much higher (Zhang, s. *et al.*, 2022; Morrow *et al.*, 2014; Hasanbeigi *et al.*, 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Ren *et al.*, 2021; Swalec, 2021; Wang, *et al.*, 2022). As there is no global legal or practical framework currently in existence on how to measure CO_2 emissions (i.e. from which data points to extract data), defined reporting structures and consequences of non-compliance, all these statements have to be viewed with caution. The literary sources used show to have used data sets accumulated and defined using a range of methods, with data and information partially provided voluntarily by industry. Without a clear framework and guidance on how, where, and when to measure CO_2 or GHG emissions, and defined recording and reporting structures, the definition of de facto emissions is quite a challenge. China is currently deemed to be responsible for 50% of global industrial CO_2 and GHG emissions, due to their reliance on coal for energy generation (Ren et al, 2021).

The impact of different technologies (Toktarova *et al.*, 2020) on the processes at all stages in the steelmaking process (Griffin and Hammond, 2019), and iron and steel manufacturing (WSA, 2022b) and related databases and corresponding literature were investigated. Additionally, literature with regards to CAT, CCS and CCUS and circular economic economy, sustainability and decarbonisation of the steel industry were categorised for ease of implementation, from easy to more challenging and depending on duration. An Excel database was used for data collection, modeling and key calculations. The parameters were defined as t of CO_2 per t of steel produced, although further parameters for future research are being allowed. The research works with metric tonnes only. Additionally, engineering simulation software has been used, such as Simul8 and Aspen Plus V11. The Simul8 and Aspen Plus V11 models are being adjusted continuously to meet the different applications of carbon avoidance, carbon saving, and carbon utilisation technologies.

4.4 The Bio Steel Cycle components and principles

4.4.1 Introduction

In order to prove the first hypothesis, the most likely implementable scenarios have been considered and simulated using standard mathematical principles, MS Excel calculations and process engineering software. The resulting reports are encouraging as they are providing strong evidence for technical viability of the principles of the Bio Steel Cycle model and that it can possibly be applicable to most heavy industries: such as cement, chemical, glass, paper, and transport. It includes using renewable energy technologies, avoiding CO_2 emissions by incorporating process improvement technologies, recycling waste and by-products and capturing post-combustion emissions where possible (IRENA, 2012, 2021; Bataille *et al.*, 2018; Mandova *et al.*, 2018, 2019; NREL, 2019; Waisman *et al.*, 219; IPCC, 2022a), as displayed in Figure 4-1.

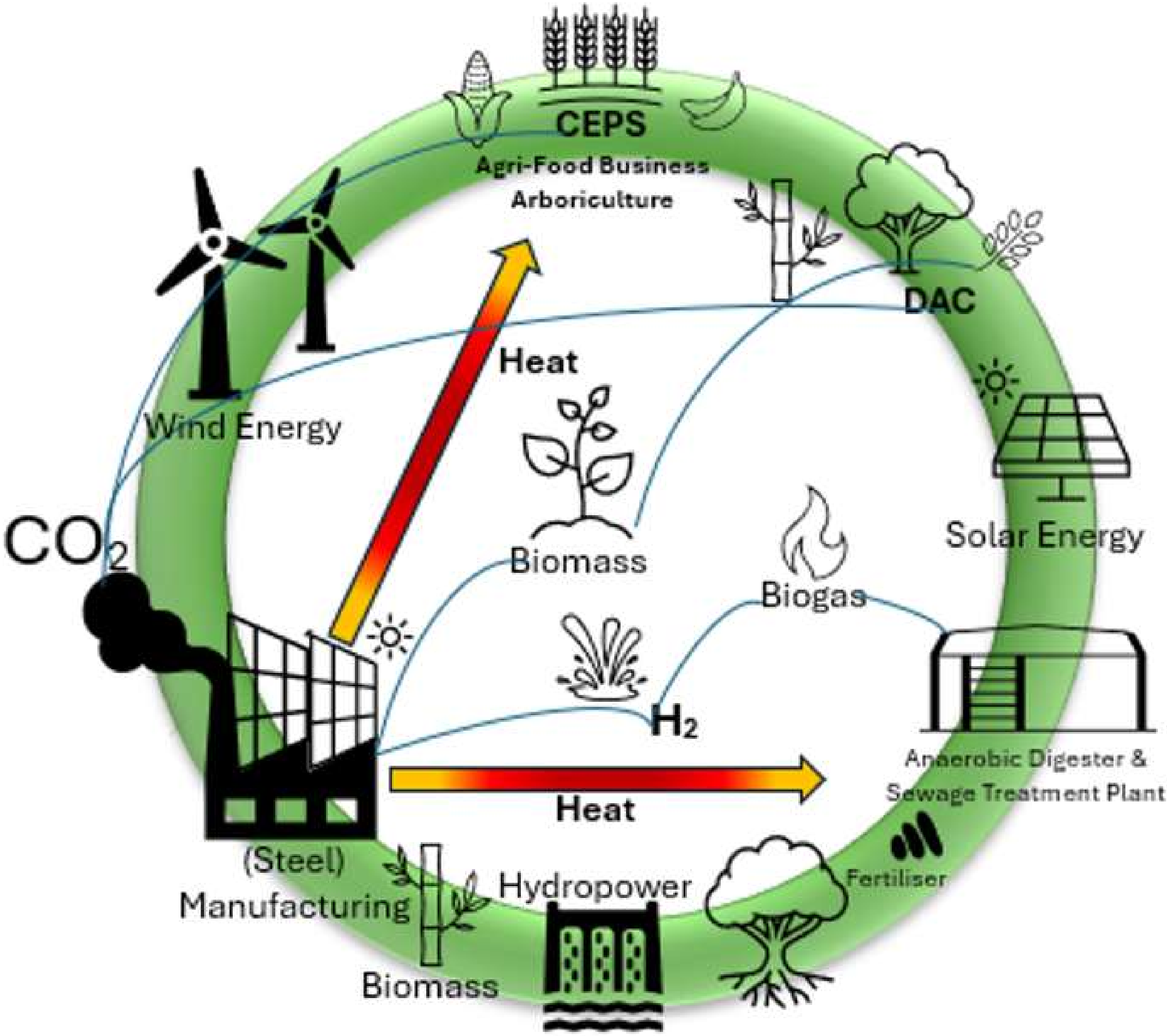


Figure 4-1: The Bio Steel Cycle (BiSC) and cyclical resource utilisation flow

It needs to be pointed out, that every production site is different, and the BiSC model and strategy need to be implemented with the site parameters in mind. The BiSC is not a universally applicable solution, but rather a toolkit to provide some sort of guidance what is theoretically possible overall, but every site requires specific assessment and evaluation. The implementation of the BiSC model and strategy depends entirely on the site geography, geology, energy infrastructure, proximity to residential dwellings and existing level of integration into the local overall infrastructure. Every industrial/production site is unique and requires assessment of the site parameters and evaluation of the best sustainable approach, incorporating a mix of renewable energy technology as most suitable for the site conditions (solar (thermal/PV), wind, hydro (i.e. Wales) and hydrogen, geothermal, and anaerobic digestion/biogas. Analyses of the technical and economical long-term potential of novel steel production technologies CAT, CCS and CCUS in the UK (2019; ONS Office for National Statistics, 2019), Germany (Vogl, Åhman and Nilsson, 2018) and beyond used techno-economic models to model three research-stage (Benetto *et al.*, 2004; Zakkour and Cook, 2010; Morrow *et al.*, 2014; Chen *et al.*, 2018; Griffin and Hammond, 2019; Mandova *et al.*, 2019; Toktarova *et al.*, 2020; Bhaskar *et al.*, 2022), ore-based steelmaking routes versus BF-BOF-route (Ananthanarayanan *et al.*, 2014; Yang, Raipala and Holappa, 2014; Babich and Senk, 2015; Wang, *et al.*, 2022). It was concluded, that in comparison, the BF with CCS1 (BFCCS) (Zakkour and Cook, 2010; Vogl, Åhman and Nilsson, 2018; Cumicheo, Mac Dowell and Shah, 2019; Tanzer, Blok and Ramírez, 2021; Williams *et al.*, 2021), hydrogen direct reduction (H-DR) (COM, 2019; Colla and Matino, 2021; Garcia-Herrero, Tagliapietra and Vorsatz, 2021; Grasa *et al.*, 2022; Öhman, Karakaya and Urban, 2022), and iron ore electrolysis (EW) (COM, 2022; Galitskaya and Zhdaneev, 2022; ArcelorMittal, 2023b), energy and raw material efficiency is significantly higher for H-DR and EW (Babich and Senk, 2015; Vogl, Åhman and Nilsson, 2018; COM, 2019; Tata Steel Europe, 2020, 2024), and the 80%-reduction-target by 2050 (UN, 2016) was thought to be perfectly achievable in the scenario, as per Tata Steel Europe's vision map 2050 (Tata Steel Europe, 2020, 2023, 2023a, 2024). It was found that there are a sufficient number of viable CAT, CCS and CCUS technologies (appendix 2), methods and strategies at TRL7-9 available for immediate BiSC implementation and achieving short- to medium term significant reduction of CO_2 emissions in steelmaking. The urgency for sufficient prioritisation throughout all industries and political willingness cannot be emphasised enough (UN, 2016) – the need to create a viable commercial environment, due to the required high capital investment (Worrell *et al.*, 2010; IRENA, 2012; Li and Zhu, 2014; Toktarova *et al.*, 2020; IETD, 2021a, 2021b; Sendi *et al.*, 2022; IEA, 2021a,c) and a significant vulnerability to electricity price fluctuation. Figure 4-2 will demonstrate how the BiSC technology can be implemented, in the short term:

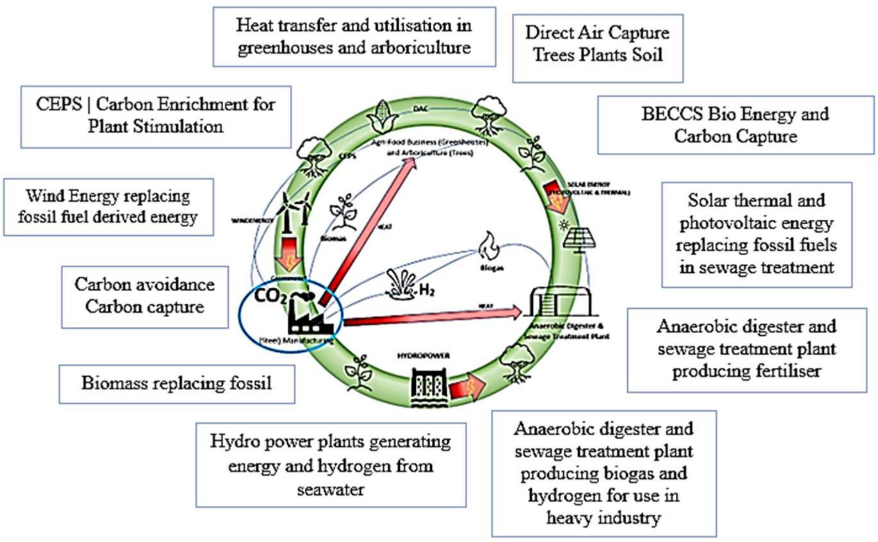


Figure 4-2 : BiSC with the implementation mechanisms involved

4.4.2 Materials and Methods

There are currently 65 (per February 2025) global decarbonisation projects underway, as displayed in Appendix 6: Green Steel Tracker. Some of these projects have given impetus to create the Bio Steel Cycle (BiSC) and its components, to create a truly circular model with a feasible strategy for change and implementation. These individual projects are mostly at TRL 6-9 and have therefore already undergone extensive scrutiny, as far as economic and technical / engineering aspects are concerned. Therefore, the individual processes and systems were utilised as building blocks to create the model of a truly circular steel production cycle, with minimal to zero CO_2 emissions. As the listed project managements are quite reluctant to release in-situ data and are only releasing information into the public domain for PR purposes, a different mechanism to prove the concept and the engineering implementation viability had to be found. In this case, process simulation software packages (Aspen, Inosim and Simul8) have been instrumental in building a process and case and proving the hypothesis that it is possible to reduce the CO_2 emissions in steel production to almost '0' and achieve higher energy independence at the same time.

4.4.3 Biomass utilisation

Innovative technologies such as Hisarna (Jones, 2011) and GrynHy (Blume, 2021; COM, 2022) and hydrogen direct reduction (HDR) have CO_2 saving potential in their own right, as explained in more detail, as follows. Removing coal as primary energy source or using (green) hydrogen (essentially biomass) direct reduction, an immediate 30% CO_2 emissions reduction is possible (Benetto *et al.*, 2004; Worrell *et al.*, 2010; Kittipongvises, 2017; Chen *et al.*, 2018; Suopajärvi *et al.*, 2018; Wilkerson, 2018; Liu *et al.*, 2020; Liu *et al.*, 2022; Toktarova *et al.*, 2020) and therefore, replacing coal with green hydrogen or other biomass would reduce the CO_2 emissions from steel making potentially by the same percentage. According to Siemens (2022), a 50% carbon emissions reduction is immediately possible via utilisation of green hydrogen direct reduction.

4.4.4 CO_2 avoidance with production process improvement

The conventional linear steel manufacturing process, including all processes such as coal, iron ore and limestone extraction, crushing, pelletising, sintering, smelting, casting, rolling, and finish machining have been investigated and resulted in establishing that the BF/BOF-route alone produces ~4.6t of CO_2 emissions, which are one of the undesired by-products of every metric t of steel produced. The results to date of research into the CO_2 emissions at the various stages of the steelmaking process and related sub-processes have been established, and the findings of the BF/BOF-route are displayed in Appendix

5. CO_2 emissions as a direct result of steel manufacture increased by 1.6% or 8.7 Gt CO_2 in 2020, although in the Net-Zero-Emissions-by-2050 scenario, industry emissions are estimated to decrease by 2.3% annually at 6.9 Gt CO_2 by 2030 – despite expected industrial production growth (IEA, 2021a,c). Improved material and energy efficiency, the increased utilisation of renewable energy technologies, and development and deployment of low-carbon process routes (including CCS and hydrogen) are all considered to have an emission-reduction-effect of individually between 12 and 30% (Appendix 2). Fossil-fuel derived energy generation, and combustion of fossil fuels for transport - including aviation - are the two biggest sources of CO_2 emissions - worldwide (Mandova *et al.*, 2019; Toktarova *et al.*, 2020; eia, 2021, 2021b, 2021c, 2023a, 2023b, 2023c; IEA, 2021b, 2023b; IPCC, 2021, 2021a; IRENA, 2021). Steel production is in close third place, followed by cement production and chemical and glass industry.

One possible solution to combat CO_2 emissions in the steel industry is the Bio-Steel Cycle (BiSC) as a model, based on circular tech economic principles. Steel scrap is considered a resource, and similar to recycling waste and by-products, is an integral part of the circular production process. Off-gases (CO_2 and other GHG) are being captured and reutilised, and alongside implementation of steelmaking process improvements, furnace heat capture and utilisation, CAT, CCS, and CCUS technologies and processes, and multi-disciplinary external components, are closing the circle (Bataille *et al.*, 2018; Mandova *et al.*, 2019; NREL, 2019; Waisman *et al.*, 2019; Bataille, Nilsson and Jotzo, 2021; IRENA, 2021; IPCC, 2022; Santos and Hanak, 2022). Technologies such as ReclaMet (Waste resource recovery, post-combustion) (Tata Steel Europe, 2020, 2023, 2024), electrolysis projects i.e. GrInHy and H2Future (Blume, 2021; COM, 2022) (direct water splitting: biomass>hydrogen, pre-combustion) all have an impact in the magnitude of between 12% and 25%, although further research is required to establish not only the most effective technology in terms of environmental impact, but also which technology can be deployed the fastest and the most cost-efficient.

4.4.5 CO_2 capture mechanisms

The standard steel production (SSP) process in combination with the currently operational newly developed technologies can achieve a reduction of more than 50% (Voestalpine, 2023) with successive implementation to less than 8 metric tonnes per ton of steel produced. By incorporating the BiSC components of CAT, CCS and CCUS into existing steel production sites, an almost 100% CO_2 emission reduction can be achieved, immediately.

The post-combustion capture of CO_2 (CCS) and other GHGs and the exploration of carbon scrubbing of flue gases have been explored. There are several possible technologies and processes to be considered for post-combustion carbon capture:

- mechanical capture
- compression and dehydration
- membrane installation
- guiding off-gas through troughs of physical solvents/solid sorbents (such as Zeolite13X)
  and chemical solvents
- as well as utilising metal-/organic frameworks

have been considered) (Bao *et al.*, 2018; Bataille *et al.*, 2018; Griffin and Hammond, 2019; Mandova *et al.*, 2019; Williams *et al.*, 2021; Lu *et al.*, 2022; Singh *et al.*, 2022). Suitable literature (Appendix 1) was thoroughly investigated with regards to applied and innovative steelmaking procedures, CAT, CCS and CCUS processes (Appendix 2), and improved management systems such as I4.0 (Franciosi *et al.*, 2020; Jahani *et al.*, 2021).

The key components within the Bio Steel Cycle are based on a circular production process and are functioning in an interactive manner. The basis for this system is the BF/BOF route and involves the afore mentioned CAT, CCS and CCUS and process improvements where possible.

4.4.6 CO_2 and off-heat utilisation in food production

Food production - in greenhouses - anaerobic digestion, and sewage treatment plants require a stable ambient temperature throughout the year, which requires a conventional source of heating. Re-using heat from the steelmaking process, the expenditure of installing heating systems and using fuel and energy is simply not required, as the air has already been heated. Although the installation of a suitable infrastructure would have to be considered, the economical case has to be further investigated, and the financial viability – cost of ducts and pipework against the installation of a heating and cooling system including energy requirements - needs to be solid to make a case for re-utilising flue-stack off-heat. The flue-stack heat can be as high as 1650°C and would have to cool down, i.e. via travelling through adequately sized pipework, ducts and possibly turbines (which in their own right would possibly be able to generate electricity, via convection, baffle systems or plate-heat-exchangers). The energy saved on heating food production facilities is deserving of further investigation, as this will effectively contribute to achieving net-zero carbon emissions in steel production. Additionally, incorporating the CEPS (Carbon Enrichment for Plant Stimulation) (Bao *et al.*, 2018) process into the BiSC based circular steelmaking process, involves CCUS by means of driving CO_2-enriched flue-stack off-gas from combustion processes into CEPS units. Subsequently, this at almost 100% carbon enriched air, is then directed into greenhouses to stimulate plant growth The chosen CEPS model is deemed scalable and has the capacity to provide 85 tonnes of CO_2 p.a. in its current configuration: concentrating CO_2 from ambient air at 400 ppm into an enriched product stream at 1000 ppm CO_2. Locating the source of CO_2, i.e., flue gases from production in steel, cement or energy production and greenhouses in close proximity to each other eliminates costs associated with filtering, deactivation, compression, transportation, handling, distribution and storage entirely. Every successfully installed CEPS unit/greenhouse infrastructure is effectively a CO_2 sequestration station and the economic feasibility is based on 1 kWh = 3600 kWs = 3.6 MJ (Universität Leipzig, 2021), costs between £0.11 – £0.21/kWh and 17.8kJ/mol CO_2 = 17.8kJ/44g CO_2 (eia, 2021) for pure CO_2 versus 8.5kJ/mol CO_2 = 8.5kJ/44g CO_2 for enriched, 1000ppm CO_2, costing effectively between \$15 and \$309/t CO_2. The efficiency, technical and economic viability are making the case for temperature swing absorption/desorption flue gas carbon capture.

4.4.7 CO_2 utilisation in the building industry

A further key component of the BiSC is the Geomimetic® process (Blue Planet, 2021), as these units are effectively recycling facilities for the recycling of reclaimed concrete and the reutilisation of CO_2, filters, dust, sludge and slack from (steel) production. These units have the capacity to reduce post-combustion CO_2 emission to effectively zero and should be on site of any (steel) production plant. The workings of the Geomimetic® process (Blue Planet, 2023) are in its essence carbon utilisation and sequestration processes at the same time, as these recycle CO_2 from flue gases and recycled concrete into synthetic limestone and aggregate in cement production, with the potential of absorbing 100% of the CO_2 emissions produced. This is a technique suitable to be applied in any industrial production setting: energy, steel, concrete, chemical industry, glass industry, paper and transport, to name a few.

4.4.8 DAC and agricultural waste for anaerobic digestion

In the spirit of innovative, multi-disciplinary approaches to solving contemporary CO_2 emission issues, the positive effects of DAC (Direct Air Capture) (Bastin *et al.*, 2019; Sheil *et al.*, 2019; Dönges, 2023; Nix, 2023; WEF, 2023), reforestation and utilisation of newly created woodlands for carbon capture cannot be emphasised enough. As one of the critical components of the BiSC, arboriculture for DAC would even be a profitable side-line (Nix, 2020, 2023) for steel producers, as illustrated in the following Figure 4-3:

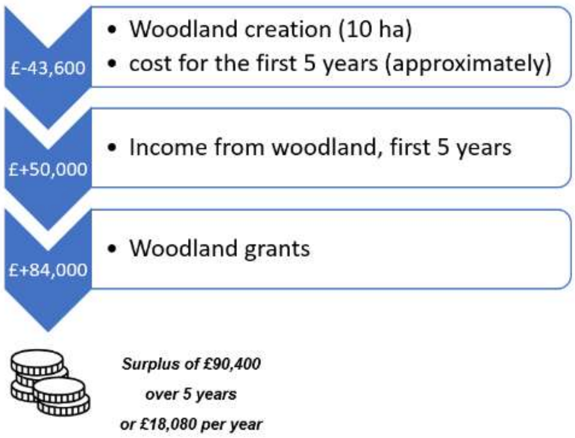


Figure 4-3: Woodland creation graph

Trees and vegetation as natural carbon sinks (FC, 2003; Bastin *et al.*, 2019; Sheil *et al.*, 2019; Dönges, 2023; Nix, 2020,2023) would ideally be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC). Whilst at the same time, the plant matter could feed the anaerobic digester, biochar plants or directly used at selected quality in iron and steelmaking as readily available biomass. In this respect, bamboo beats deciduous native plants with its carbon sequestration capacities: on average, one hectare of bamboo stand absorbs ~17 tonnes of carbon per year. (Seethalakshmi, Jijeesh and Balagopalan, 2016). Native deciduous and non-deciduous trees have a carbon sequestration capacity of on average 9t of CO_2/ha of tree plantation (FC, 2003; Yi *et al.*, 2018; Nix, 2020, 2023). Planting a sufficient number of trees should be considered in the planning for the updating of existing steel production plants and for any new development in order to meet the UK governments zero emissions targets. The UK tree cover stands at 13% (3.25 million hectares), which is the lowest in the Northern hemisphere. In comparison, forests and wooded land cover over 182 million hectares in the EU, which is about 42% of the EU's total land area. This equates to 0.36 hectares of forest per capita in the EU in comparison(EUROSTAT, 2023). Woodlands not only capture post-combustion CO_2 and create biomass for anaerobic digestion, but they also may create recreation and employment opportunities and additional sources of commercial activity. Additionally, they offer a low-cost opportunity for carbon-offsetting, which could be seen as a commercial opportunity in itself.

4.4.9 Anaerobic digestion, sewage treatment and hydrogen from biogas

The anaerobic digester and sewage treatment facility are vital components within in the BiSC and would be ideally integrated into the steel mill or quite possibly be independent businesses in their own right, conveniently located on site of the steel production facility. These units would be able to accommodate debris from nearby woodland management and additional biomass from surrounding residential and commercial entities. Steelmaking by-products, such as brown water, can be treated at the sewage treatment facility. The cleared sewage can subsequently be utilised to fertilise the food production units. The anaerobic digestion process in itself produces biogas, which can be used in steel production, but it also provides the base for extraction of hydrogen. The green hydrogen produced at or nearby the anaerobic digestion facility can then be used in (steel) production within the hydrogen direct reduction (HDR) process. As this has been derived from biogas as a result of anaerobic digestions, this can therefore be considered green hydrogen. Hydrogen direct reduction (HDR) has been piloted over recent years and has shown to have great CO_2 avoidance potential, and green hydrogen technologies are currently developed by a number of significant industry leaders, such as Mannesmann Salzgitter, in cooperation with the European Commission and Tata Steel (Blume, 2021; COM, 2022). Green HDR (hydrogen direct reduction or iron ore) in blast furnace and electric arc furnace application is considered as having a significant impact on reducing CO_2 emissions in steel manufacturing, as this process uses 3.48 MWh of electricity per ton of steel product and emits only 2.8% of blast furnace CO_2. However, as the prices of fossil-fuel derived energy have increased significantly, it is imperative to replace fossil-fuel derived energy with renewable energy technologies and biomass (IRENA, 2012, 2012a, 2021; Toktarova *et al.*, 2020).

4.4.10 Renewable energy technologies utilisation

Renewable energy technologies are one of the key components within the Bio Steel Cycle, as CO_2 emissions in steelmaking can be reduced by more than 30% (IRENA, 2012; Bataille *et al.*, 2018; Chen *et al.*, 2018; Albanito *et al.*, 2019; Bataille, Nilsson and Jotzo, 2021; Tanzer, Blok and Ramírez, 2021; Toktarova, 2021), if commercial entities in iron and steel production (Bataille *et al.*, 2018; Waisman *et al.*, 2019) were to simply switch their energy provider (Mandova *et al.*, 2019; NREL, 2019) to those which supply energy which was derived using 100% renewable energy technology and producing their own energy by retrofitting their plants with renewable energy technologies (wind, solar PV). The same applies to greenhouses, as there is a vast amount of roof space available, which has to date not been utilised. The static requirements would obviously have to be considered, but as the cost of solar energy and solar PV has decreased significantly over recent years (Dastoor, 2021) to less than £3/m^2, it can be considered an unmissable opportunity.

To increase energy efficiency makes economic sense, too: it is possible to use fewer natural resources whilst simultaneously achieving the same economic output and – at the same time - reducing the environmental impact and – as an added bonus – saving money and generating their own energy (Wilke, 2017).

Energy productivity is assessed on the basis of final energy consumption rather than primary energy consumption. This enhances the validity of the indicator because losses in the energy supply system through energy conversion and transport do not appear in the balance. Final energy consumption includes electricity as well as heat, therefore, weather conditions and stockpiling of fuels influence the indicator.

4.5 The 7 steps to net-zero carbon emission steel manufacturing

4.5.1 Introduction

The newly introduced concept "Bio Steel Cycle" (BiSC) (Kiessling, Darabkhani and Soliman, 2022) provided the elements with which a net-zero carbon emissions steel production can be made a reality, in the short- term. In the following, Figure 4-3 will demonstrate the steps, built on the components within the BiSC, which should be taken with the aim to net-zero carbon emission BF/BOF steel production.

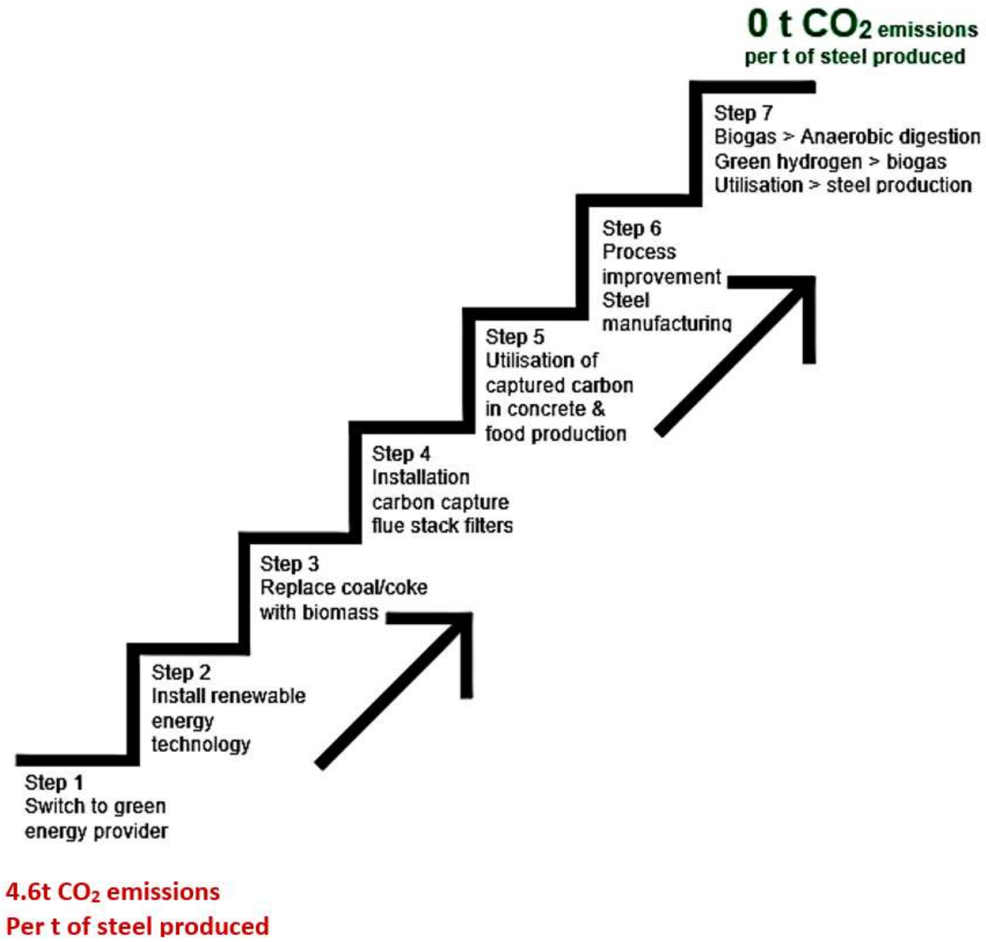


Figure 4-4: The seven steps to achieving net-zero carbon emissions steel production

The steps 1-7 were introduced based on the level of ease of implementation and from short-term to long-term project duration, starting with step one by switching energy providers and arriving at step seven with producing biogas as a result of full implementation of all elements of the Bio Steel Cycle (BiSC), splitting green hydrogen from this biogas and using thus gained hydrogen in steel manufacturing for hydrogen direct reduction (HDR). These steps are illustrated in Figure 4-4:

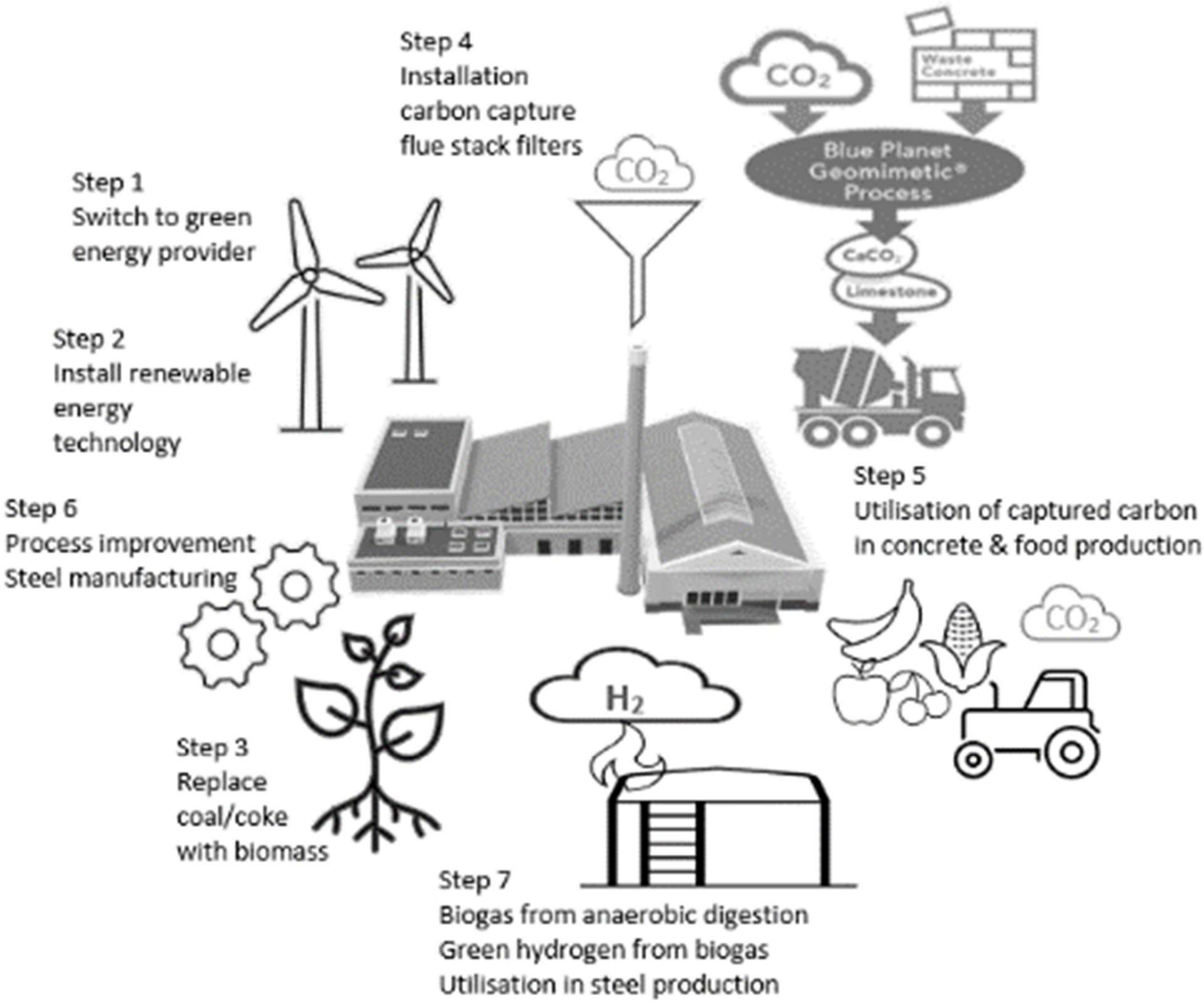


Figure 4-5: The seven steps to net-zero steel production

The steps 1-7 have been ordered by ease of implementation but are not "set in stone" as far as their order is concerned. One could argue that i.e. it might be easier to install flue stack filters than replacing coal/coke with biomass, as the production parameters to do so would require extensive testing and adjusting, to achieve the same quality steel as using coal/coke. However, the provision and usage of CO_2 filters in developed countries is scarce, to say the least, so the usage of biomass was set before the installation of flue stack filters. Or that the installation of flue stack filters is easier than installing renewable energy technologies. But in order to install filters, the off-gas contents, temperature and volume would have to be assessed first, in order to determine the best fit filter for this purpose. Therefore, the order has been set in the current fashion and is based on the afore mentioned assumptions which determined the ease of implementation.

4.5.2 Switching to green energy provider

Step 1 – Switching to green energy provider is probably the easiest to achieve. Any steel producer will just have to make an informed choice to switch their energy contract to an energy provider who produces energy solely relying on renewable energy technologies, and not – as it has been up to now – the one who agrees the best deal, regardless of the consequences for the environment.

There are a range of energy providers, which claim to produce energy exclusively based on renewable energy technologies. In the following Table 4-2, a list of providers available at the time of writing – although the industry is changing at a very fast pace (also in Appendix 4, for ease of use).

Table 4-1 : Energy providers deriving their energy from sustainable sources

Energy provider	*UK Headquarters address*	*Renewable sources*	*Green electricity*	*Green gas*	*Carbon offsetting*
(Octopus Energy, 2023)	UK House, 5th floor, 164-182 Oxford Street, London, W1D 1NN https://octopus.energy/	Anaerobic digestion, solar, wind, hydro	100%	0%	Yes
(Green Energy UK, 2023)	Green Energy (UK) plc Black Swan House, 23 Baldock Street Ware, Herts, SG12 9DH https://www.greenenergyuk.com	Hydro, solar, wind	100%	100%	No
(OUTFOX the market, 2023)	16 North Mills, Frog Island, Leicester, Leicestershire, LE3 5DL https://www.outfoxthemarket.co.uk/	Wind	100%	0%	No
(Ecotricity, 2023)	Lion House, Rowcroft, Stroud, Gloucestershire, GL5 3BY https://www.ecotricity.co.uk/our-green-energy/green-electricity	Wind (98%), solar (0.12%) and hydro (0.7%)	100%	Yes	Yes
(OVO Energy, 2023)	1 Rivergate Temple Quay Bristol BS1 6ED https://www.ovoenergy.com/	Anaerobic digestion 49%, solar 32%, wind 18%, hydro 1%	100%	15%	Yes
(Good Energy UK, 2023)	Monkton Park Offices, Monkton Park Chippenham SN15 1GH https://www.goodenergy.co.uk/	49.41% = Wind. 32.71% = Bio generation. 13.60% = Solar. 4.28% = Hydro	100%	No	Yes
(SSE Energy Solutions, 2023)	Inveralmond House, 200 Dunkeld Road, Perth PH1 3AQ https://www.sseenergysolutions.co.uk/business-energy/our-renewable-electricity	Hydro plants and wind farms	100%	No	Yes

4.5.3 Installing renewable energy technologies

Step 2 - Installing renewable energy technology. The installation of renewable energy technology requires surveying of existing steel plants, regarding static performance of buildings, ground parameters and structures in situ. Selection of the most suitable product from a range of technologies and producers is the most time-consuming step after surveying the locations.

Solar

Toktarova *et al.*(2020) identified a 30% CO_2 emissions savings potential by replacing fossil-fuel derived electricity with renewable energy derived. Most well-maintained industrial structures can be deemed suitable to accommodate the installation of the mature technology solar energy panels, either as solar thermal (hot water production) or photovoltaic panels (PV) (generating electricity). There are such a very wide range of solar and PV systems available, that it would be beyond the scope of this paper to list these in their entirety. It may suffice at this point to mention that there are suitable systems available for every type of setting, from on-roof, over to in-roof and wall-covering solar panels and even foils (Dastoor, 2021), which can be retrofitted to provide a reliable source of energy all year round. Even windows may consist of solar panels, as the newest known development are semi-transparent solar-cells. Researchers at the University of Michigan have developed a technique to manufacture highly efficient, semi-transparent solar cells at scale, which use micron-scale electrical connections between individual cells which constitute the solar modules (Malewar, 2022).

Wind

Wind energy pylons are – besides solar – another effective way to produce electricity from a natural source (wind). This technology is mature and widely used, Again, there are a wide range of products on the market and the site parameters will determine which system would be suitable for the location in question.

Hydro

At sites where solar or wind energy systems are unsuitable, open- (Figure 4-5) and closed-loop hydro energy systems might have their place to provide energy for industrial processes. Open-source hydro systems might be the precursor for hydrogen energy generation. In the US this technology is widely used, where creating closed-loop systems using pairs of existing or artificial lakes or reservoirs instead of rivers would avoid the need for new dams. There are currently projects underway (Blakers *et al.*, 2021), where in Bell County, Kentucky, for example, an old coal strip mine is being re-used. As Wales in the UK has a vast array of similar former mining locations, it should be practical to install these. Figure 4-6 shows an overview of an open-loop hydro-power system.

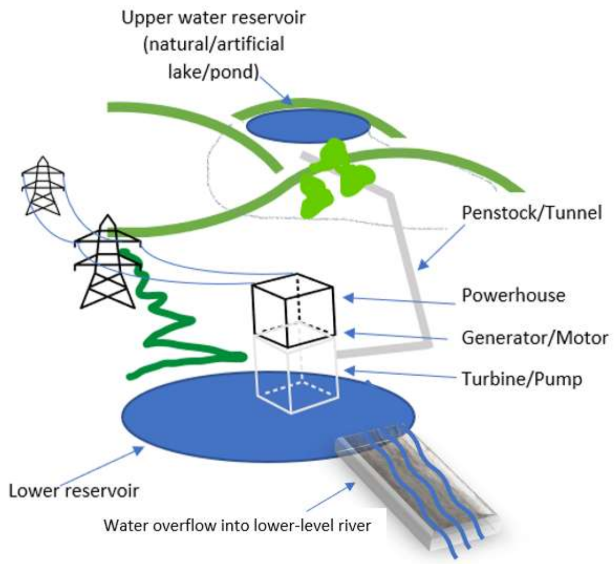


Figure 4-6: Pumped-storage hydropower (open flow)

4.5.4 *Replacing coal/coke with biomass*

Step 3 - Replacing coal and coke with biomass. Coal and energy derived from combustion of fossil fuels are the biggest emitters of CO_2 emissions, as identified by Wilke (2017), NREL (2019) and Toktarova (2021) during their investigations, and they established that replacing coal with biomass in steel production would quite easily achieve a 30% reduction in carbon emissions, which is the reason why renewable energy technologies and replacing coal and coke with biomass are cornerstones in the Bio Steel Cycle. Replacing pre-combustion fossil fuels with biomass (Vogl, Åhman, and Nilsson, 2018; Wilkerson, 2018; Albanito *et al.*, 2019; COM, 2019; Cumicheo, Mac Dowell and Shah, 2019; Mandova *et al.*, 2019; Wang *et al.*, 2019; Toktarova *et al.*, 2020; EERE, 2021; Tanzer, Blok and Ramírez, 2021) and operating (green) hydrogen direct reduction (HDR) (Blume, 2021; EERE, 2021; Garcia-Herrero, Tagliapietra and Vorsatz, 2021; Bhaskar *et al.*, 2022; COM, 2022; Öhman, Karakaya and Urban, 2022) as well as capturing post-combustion CO_2 emissions with the Geomimetic ® process (Blue Planet, 2023) are efforts which have the potential to reduce the CO_2 emissions in steel production to almost '0'. There is considerable outreach into other industries, such as the application of the Geomimetic ® process (Blue Planet, 2023), which produces aggregates from CO_2 emissions and recycled concrete to producing new concrete and utilisation of BOF slacks for road building.

4.5.5 *Installation of carbon capture flue stack filters*

Step 4 – Installation of carbon capture flue stack filters (See also: Section 5.6 MCDA). These technologies are wide ranging, and every production site has their own parameters and challenges to overcome. Thorough surveying of the sites and greenhouse gas emission (GHG) points need to be identified, and depending on the situation, a suitable GHG capturing system can be installed.

4.5.6 Utilisation of captured carbon in food production and the building industry

Step 5 - Utilisation of captured carbon in concrete and food production. Blue Planet (2023) are using the so-called Geomimetic® process, where recycled concrete and captured carbon are being reformed to make new concrete and aggregate. In combination with manufacturing post combustion flue stack carbon capture, the utilisation of the thus captured carbon and subsequent utilisation in making new concrete (carbon sequestration). This process has the capability to reduce the carbon emissions from steel production by almost 100%. CEPS (Carbon enrichment for plant stimulation) is the ideal growth enhancer for most known plants. To utilise the captured off-gas CO_2 and to direct this to greenhouses in close proximity could be the best use of a by-product now. This system has been tried and tested and enhanced food production significantly.

It has been established that for the majority of land-grown crops the CO_2 saturation point will be reached at about 1,000–1,300 ppm in perfect growing conditions. Generally, 800–1,000 ppm is recommended for raising tomatoes, cucumbers and peppers seedlings as well as for lettuce production (Ministry of Agriculture, Food and Rural Affairs Canada, 2023).

4.5.7 Process improvements in steel manufacturing

Step 6 - Process improvement in steel manufacturing, as per Table 2. Greater material and energy efficiency, and deployment of low-carbon process routes are all critical. The steel production process has been thoroughly investigated in every aspect from mining to recycling and it can be said that there is currently a global effort underway for developing more environmentally-friendly and resource-saving technologies in steel production, such as TGRBF (top gas recycling blast furnace operation, coal mine methane recovery) (Aylen, 1980; Kuramochi *et al.*, 2011, 2018; Bataille *et al.*, 2018; Chen *et al.*, 2018b; Toktarova *et al.*, 2020; Bataille, Nilsson and Jotzo, 2021; Santos and Hanak, 2022; Tata Steel Europe, 2023) and HISARNA (Jones, 2011; Tata Steel Europe, 2020, 2023; Tata Steel Nederland, 2023), which eliminates the need for the sintering process entirely. HISARNA, implemented individually, has the potential to reduce CO_2 emissions from steel production by at least 30%.

4.5.8 Utilisation of biogas and hydrogen from anaerobic digestion

Step 7 - Biogas from anaerobic digestion - Green hydrogen from biogas - Utilisation in steel production. Trees are natural carbon sinks (FC, 2003; Nix, 2020, 2023), and ideally woodlands would be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC) – while simultaneously, the trees would provide some of the material for producing biochar and organic matter to be fed into the anaerobic digester, alongside agricultural businesses.

Planting a sufficient number of trees (FC, 2003; Nix, 2020, 2023) and both anaerobic digester and biochar plants (Wilkerson, 2018; COM, 2019; Wang *et al.*, 2019) are vital components within the Bio Steel Cycle and instrumental to meet the UK governments zero emissions target. They should be considered in the planning for the updating of existing steel production plants and for any new steel plant development or refurbishment. As the UK tree cover stands at 13.2% per 2020 (3.2 million ha, 66.65m people = 0.048 ha per capita) (Forest Research, 2023), it is fair to say that this is the lowest percentage in the Northern hemisphere. EU forests and wooded land cover over 182 million hectares (42%) of the EU's total land area. Biochar (Keung, 2021) can easily be used as a direct replacement for coke or coal. Biogas and biomass also as alternative to commercial gases and fossil fuels (Mosayeb-Nezhad *et al.*, 2019; Nezhad, *et al.*, 2019; IRENA, 2021; Toktarova, 2021; Kabeyi, 2022), as their properties allow for 1:1 replacement. Using biochar instead of coke in (steel) production could reduce the CO_2 emissions by 30% (Mandova *et al.*, 2018; Wilkerson, 2018; Wang *et al.*, 2019).

Additionally, "green" hydrogen extraction from biogas, naturally produced by anaerobic digestion, offers additional carbon avoidance opportunities. Hydrogen direct reduction (HDR) has been piloted over recent years and has shown to have great CO_2 avoidance potential (Green hydrogen technologies are currently developed by a number of significant industry leaders (O'Callaghan, 2018; COM, 2019; Sunny, Mac Dowell and Shah, 2020; Blume, 2021; Bhaskar *et al.*, 2022), some examples of which can be found in the project list in Appendix 6. Green hydrogen implies hydrogen production using energy from renewable resources only, which is where the Bio Steel Cycle comes to full circle: biomass from trees used for DAC is converted to biogas in the anaerobic digester, which produces biogas. The hydrogen is then extracted from the biogas, using renewable energy technologies exclusively.

4.5.9 Results and findings

The results of this study are the identified levels of CO_2 emissions during the BF/BOF route in steelmaking, as per Table 4-3:

Table 4-2: CO_2 emissions of the BF/BOF route

Step in production	CO_2	Author

	- t/t product -	
Blast Furnace Smelting	2.388	Li and Zhu, 2014; Ferreira and Leite, 2015; Griffin and Hammond, 2019; Griffin and Hammond, 2021; Liu *et al.*, 2022
Modern Basic Oxygen Furnace	2.218	Worrell *et al.*, 2010; Li and Zhu, 2014; Griffin and Hammond, 2021; Garvey, Norman and Barrett, 2022; Liu *et al.*, 2022; Li *et al.*, 2022
Total ∑	4.606t	CO_2/t steel produced using BF/BOF route

******SEC = Specific Energy Consumption*

The sum total of identified levels of CO_2 emissions at ~4.61/CO_2/t steel along the linear steelmaking BF/BOF route is the result of thorough investigation and research into every process step, to date.

The individual seven steps towards ”0” carbon steel production have a different effect, based on the way they are being implemented, either individually or in sequence (successive), as displayed in 4-4:

Table 4-3: Individual/successive implementation of the seven steps to 0-carbon-steel

Implementation			
	Individual SSP * CO_2	**% Reduction CO_2**	**Successive SSP * CO_2**
BF/BOF-Route	4.61	-	4.61
Step 1	3.23	-30%	3.23
Step 2	3.23	-30%	2.26
Step 3	3.23	-30%	1.58
Step 4	2.31	-50%	0.79
Step 5	0.00	-100%	0.00
Step 6	3.23	-30%	0.00
Step 7	3.23	-30%	0.00

(* Standard Steel Production)

Notably, during the sequential implementation of the seven steps to ”0” carbon steel production—already with step 5, -100% carbon reduction has been achieved.

Figure 4-7 will demonstrate the effects of individual and successive implementation of the steps 1-7 on the linear BF/BOF-route of steelmaking:

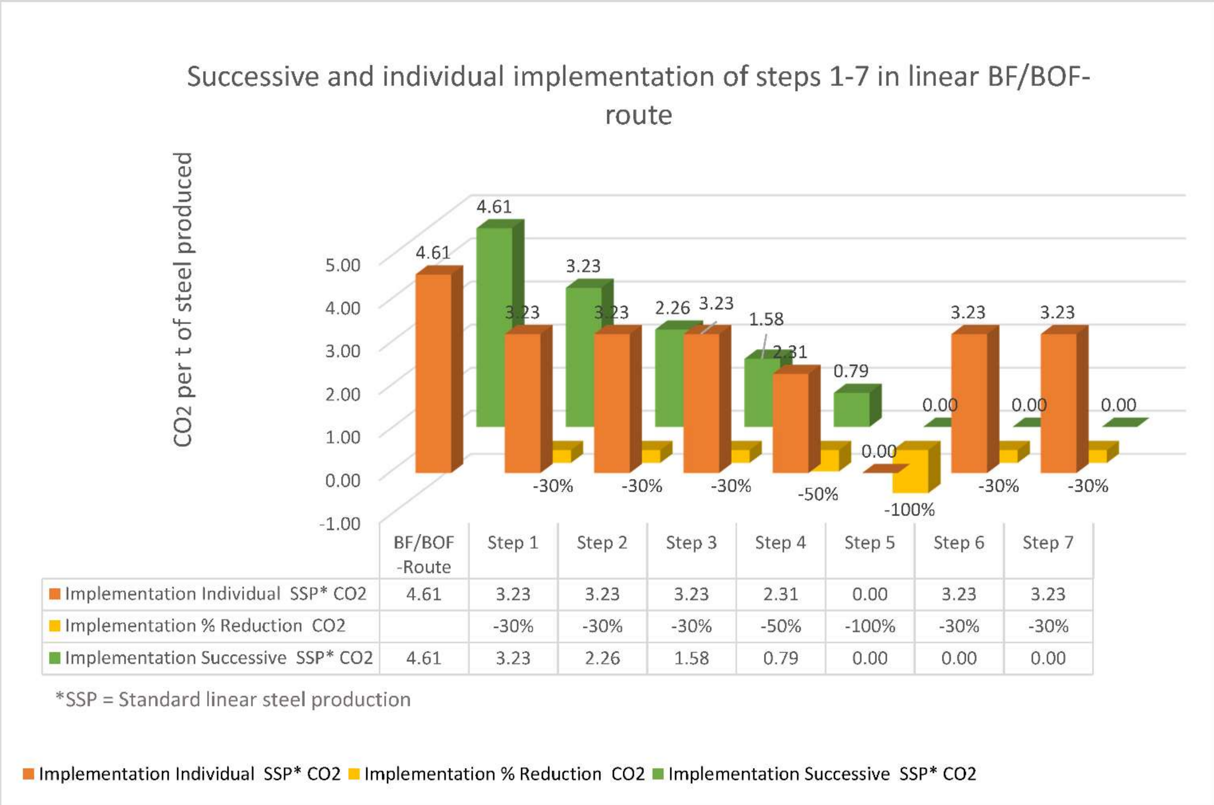


Figure 4-7: Individual and successive implementation of Steps 1–7.

This would logically render Steps 6 and 7 obsolete, with successive implementation, but the technical application of flue-stack scrubbing technology, processes or material is quite challenging, and the efficiency is dependent on site factors and the quality of the installation, as well as the execution.

4.5.10 Discussion

The 7 steps to net zero carbon emissions steel production can be followed through from one to seven or implemented individually. The ease of implementation is consistent with the order of the respective steps and can be chosen as appropriate. For best efficiency, the system should be implemented in its entirety.

The industrialisation processes have for more than 200 years caused significant damage to the natural environment. Although the current UK government seems to have abandoned their commitments to reducing carbon emissions in the UK and are instead issuing licences for natural gas exploration (Shell, 2022) and new coal mines (BBC British Broadcasting, 2022), private industry seems to have understood the severity of the climate crisis we find ourselves in. In 2018, Tata Steel announced a partnership with chemicals company Nourvon with the aim of producing hydrogen and oxygen at Tata Steel Europe B.V.'s Ijmuiden plant in the Netherlands (Tata Steel Nederland, 2023). Using water electrolysis, this effort is part of the company's drive to be a carbon-neutral steel manufacturer by 2050. As they are using electricity generated by using renewable energy technologies, the plant is set to save up to 350,000 t/p.a. of CO_2. The aim is to use the hydrogen as a reductant in the direct reduced iron steelmaking process (Tata Steel Nederland, 2023). Tata Steel have requested financial support to the tune of GBP1.5bn to fund its transition to greener production from the UK government for investing in sustainable technologies at their Port Talbot (Wales/UK) plant, which employs more than 4000 people at present (Tata Steel, 2023). With the 2020 UK Government "UK Green Industrial Revolution" paper still fresh in everyone's mind (HM Government UK, 2020), this might possibly come to pass.

Previous aforementioned studies have focused on the assessment of policy needs, skills needs, supply-chain pressures on a regional and global scale, and the requirement for models, strategies, and guidance papers, and investigated the technical solutions for the decarbonisation of the iron and steel industry. This paper is the first of its kind to (a) assess sustainability guidelines, (b) assess technical progress and viability of technical and process solutions for CAT and CCUS, (c) identify the factual CO_2 emissions of the BF/BOF route of steelmaking, and (d) offer a multi-disciplinary model and strategy to achieve factual "0" carbon emissions steel manufacturing in one research report.

The individual or successive implementation of the detailed BiSC components, accompanied by steel production process improvements and following the "7 steps to net-zero carbon emissions steel production" strategy is quite possibly the mechanism which is set to achieve between 50% and 100% CO_2 emissions reduction, immediately. The authors' work on the decarbonisation of the steel industry and further investigation of the CO_2 emissions along the whole steelmaking process, starting with coal and iron ore extraction, are currently under way.

4.5.11 Conclusions

The Bio Steel Cycle model and strategy could be seen as the engineering solution to the urgent issue of CO_2 emissions reduction requirements. The technology to avoid and reduce CO_2 emissions is available – all it takes now is the willingness in industry and governments to implement emissions reduction technologies and the provision of political frameworks and monetary incentives. One could argue that heavy industries have taken the natural environment for granted and have taken all the profits with total disregard for the consequences, for all of us, and the onus is therefore on them to remedy the wrongs they have committed. However, now is not the time for splitting hairs – now is the time for

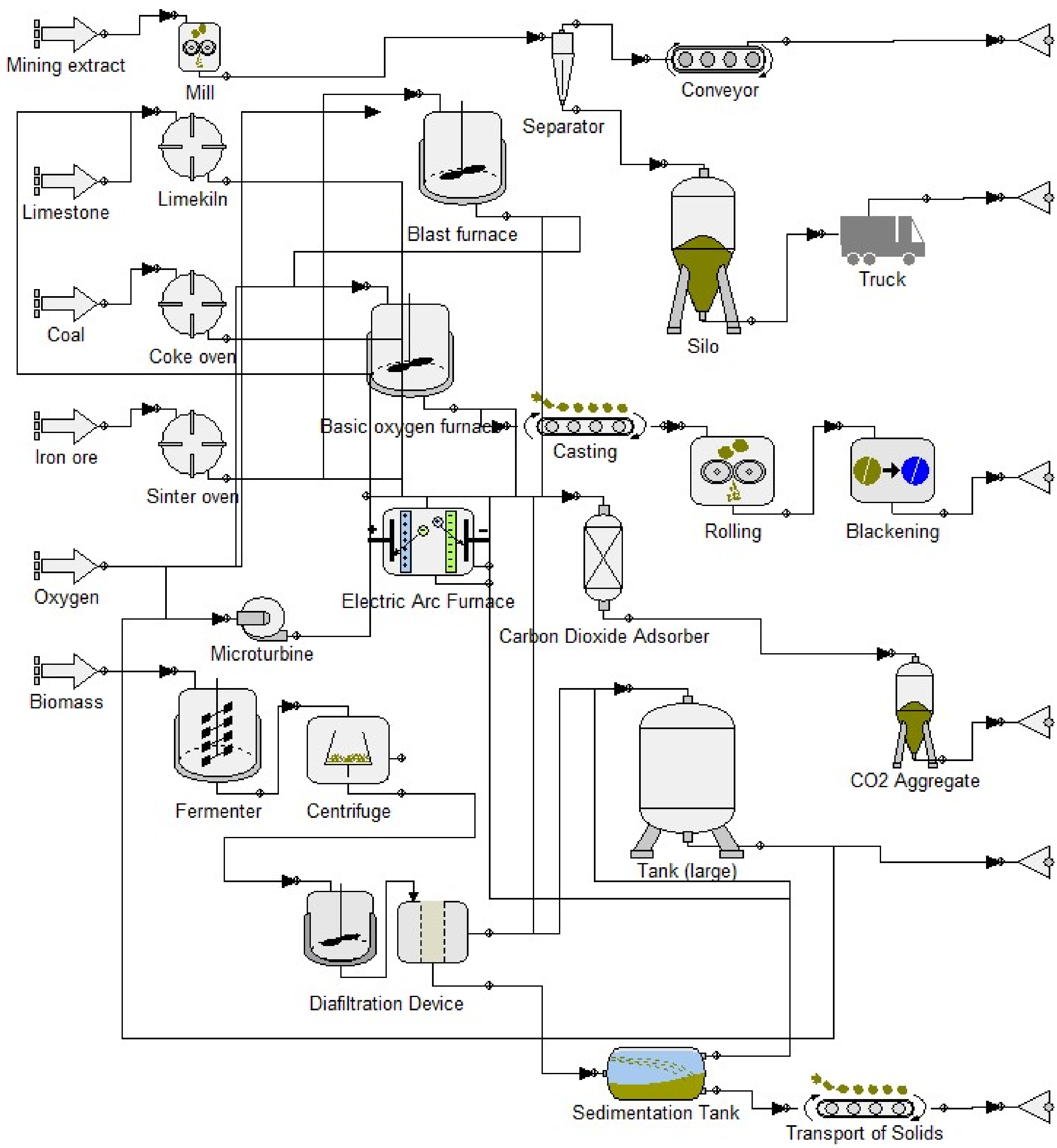
fast and effective action. CO_2 emissions and greenhouse gas emissions on the whole need to be drastically reduced, to ensure our planet will be a habitable place for generations to come.
The Bio Steel Cycle implementation can deliver this, in the short-term. Other industries could utilise this system, without much need for adaptation. The 7 steps to net-zero carbon emissions steel production and the Bio Steel Cycle components have been thoroughly researched throughout, and the model is providing a feasible strategy to reach net-zero carbon emissions steel production in the short- to medium-term. The individual steps to take for reaching net-zero and factual zero carbon emission steel production are technically possible and practically implementable in the short-term. Industry leaders have already recognised that the current linear steel production process is detrimental for our environment, and they have taken already considerable action by investing in R and D into production process improvement and infrastructure improvement towards sustainable and carbon-neutral steel production. The governments in the respective countries might be inclined within their "green" agendas to award green loans at favourable terms to enable businesses to reach their sustainability goals sooner rather than later. Legal frameworks require adaptation to accommodate an attractive solution for businesses – in the form of tax incentives and subsidies, possibly re-directed from nuclear and fossil fuel subsidies – and to apportion a set percentage of gross profits to drastically change their business models to sustainable, circular production processes. Despite global pressures, making steel – even in the UK – is still a very attractive business and it can be done sustainably.

4.6 Engineering aspects of process simulations

4.6.1 Introduction

As previously mentioned, industry leaders are keeping their process data close, and the alternative to obtaining empirical data from process improvement trials is to run these processes on simulation software packages. For the purpose of this study, three software applications from Aspen, Simul8 and INOSIM have been used to determine the feasibility of the Bio Steel Cycle model, concept and strategy. The focus of the trials were the engineering aspects which could be replicated using either one of the afore mentioned software applications, which are similar in that they work on the principle of required mass balance (quantity input must be equal to output). As each one has different features, parameters to consider and pathways for data processing, they were equally frequently used to compile the different process trials and finally to compare the results. It was not the subject of this study to build digital twins for the different processes involved in producing steel, merely the engineering aspects of the proposed Bio Steel Cycle were integrated into known process pathways and the results compared with research findings and analysis. Figure 4-8 will display one layout of the steelmaking process, including components such as CO_2 capture (Carbon Dioxide Absorber), biogas production (fermenter route) and biogas utilisation (microturbine) in steelmaking:

Figure 4-8: Whole process steelmaking incl. extraction and CCUS in INOSIM



In Figure 4-7, some of the BiSC components have been integrated into a process simulation in

INOSIM, such as CCUS and anaerobic digestion. Special attention was focused on anaerobic digestion and biogas production, as INOSIM seems to be, to date, the only software with fermentation components available.

4.6.2 Resource extraction

Resource extraction (mining) operations have been in place for thousands of years and the earliest evidence of mining and quarrying in England occurs during the Early Neolithic period, ~4000 BCE – so, more than 6000 years ago (Historic England, 2018). The processing of mining extract used for steelmaking (Ferreira and Leite, 2015; McKinsey and Company, 2021), specifically iron ore, coal and limestone, each undergo similar production pathways at ambient temperature. The mined or quarried source needs to be crushed to a workable size, dust and solids need to be separated and solids and dust are either collected in silos and tanks or transported with conveyor belts to a production site in close proximity or transported via truck (Bogunovic *et al.*, 2009). Valuable data of surface mining (quarrying) has been provided for the compilation of source extraction simulations by Bogunovic *et al.* (2009) and Griffin and Hammond (2021), when they investigated coal mining, whereas Ferreira and Leite (2015) presented findings on iron ore mining. Figure 4-9 will display a sample layout of coal mining:

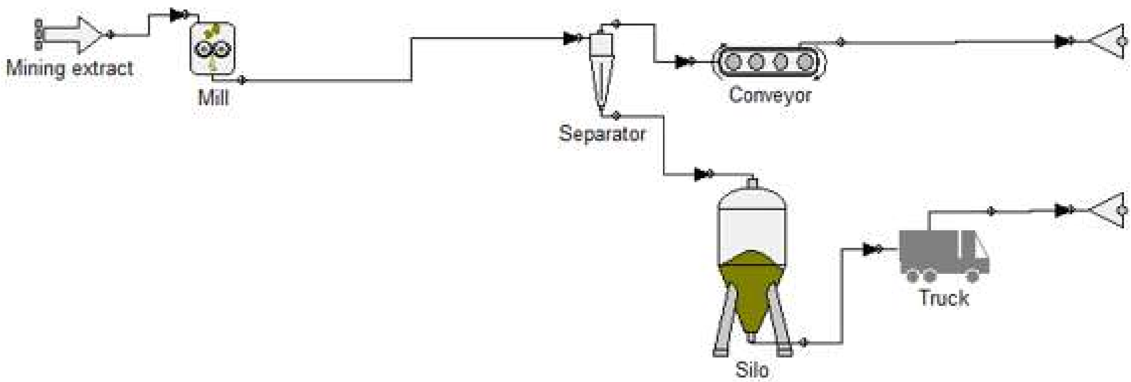


Figure 4-9: INOSIM simplified coal mining process layout

The basis for the process simulations was the BF-BOF route process, where a 330t capacity is assumed. Approximately 2t of coal need to be mined to have 1t of coke after coking the coal required to be used in the blast furnace. As simulation software works on mass balance, the actual coke quantity had to be used in the input streams: for sintering, 1650kg are needed and for the blast furnace 168015.25kg are required, at *169665.25kg*/169.67t in total. For the sintering process, *207405kg* of iron ore are needed and a total of *97367.91kg* or iron ore and iron oxide in the blast furnace. Lime and limestone is used at *106095kg* in sintering, *22153.62kg* for the blast furnace and *16500kg* of lime in the basic oxygen furnace. Therefore, a total of *144748.62kg* quantity of lime needs to be added as source in the input stream.

4.6.3 Primary resource transformation: coking and calcination

Coking of coal at between 1100°C and 2000°C and calcination of limestone to (burnt) lime at between 780°C and 1340°C required the same considerations as far as mass balance and input streams are concerned. Figure 4-10 shows the simplified coking and calcination route layout:

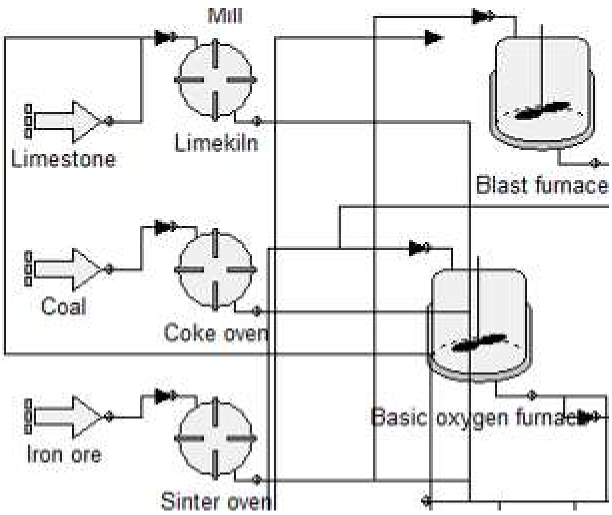


Figure 4-10: INOSIM Simplified coking and calcination operation within the steelmaking process

The average coke oven has a capacity of 36000kg and the lime kiln 50000kg. In order to achieve a mass balanced simulation, the afore mentioned quantities have to be used in the input streams (Riesbeck *et al.*, 2013; Li and Zhu, 2014; Shan, Liu and Guan, 2016; Chen *et al.*, 2018b): limestone *144748.62kg and 169665.25kg of coal.*

4.6.4 Secondary resource transformation: sintering

Within the sintering process, sinter is made by burning a mix of iron ore powder and fluxes (lime) at ~1300ºC to create an open-grained, consistent substance. The product sinter is then crushed and screened in a centrifuge to separate solids from dust, which at the same time cools the agglomerate (Fraunhofer Institute, 2009; Riesbeck *et al.*, 2013; Li and Zhu, 2014; Chen *et al.*, 2018b). The quantity of 97367.91kg iron ore and iron oxide (sinter) needs to be added to the input stream for the blast furnace.

4.6.5 *Blast furnace operation*

The blast furnace is the vessel where smelting of iron ore and fluxes takes place via the addition of 22864kg of 1000°C hot oxygen at 150psi via tuyeres (lances). A simplified layout can be seen in Figure 4-11:

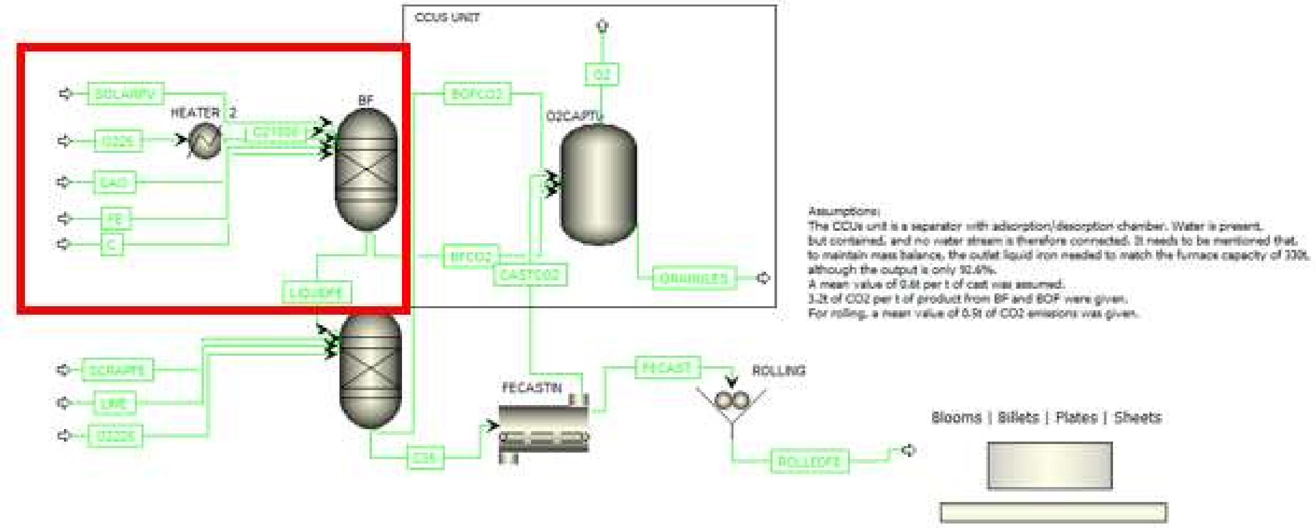


Figure 4-11: Aspen simplified layout of BF-BOF route steelmaking, BF section (red)

The injection of the hot oxygen into the charge causes a temperature rise to between 1700°C and 2000°C.The blast furnace product is essentially liquid iron, where a total of *97367.91kg* or iron ore and iron oxide, *22153.62kg* of lime and limestone and *169665.25kg* of coal/coke are used to produce molten iron. This is then transferred to the basic oxygen furnace.

4.6.6 *Basic Oxygen furnace operation*

Steel (C35 as an example) is the product of treating liquid iron from the blast furnace within the basic oxygen furnace with the injection of oxygen at ambient temperature at 220psi pressure. The chemical reaction of the liquid iron and flux (lime) with the oxygen causes the temperature to rise to between 1700°C and 2000°C. A simplified layout of this configuration can be seen in Figure 4-12.

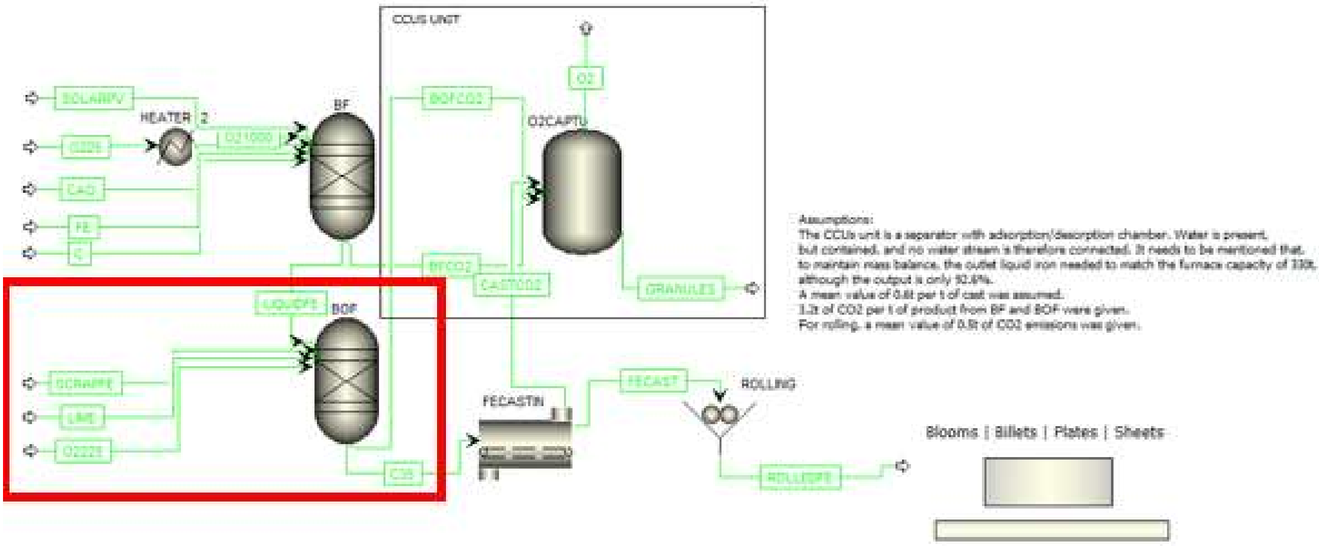


Figure 4- 12: Aspen simplified layout of BF-BOF route steelmaking, BOF section (red)

In the basic oxygen operation, no coal is required within the charge. The liquid steel is being cast after a 40-minute oxygen blow.

4.6.7 Casting, rolling and finishing

The liquid steel is transferred from the basic oxygen furnace by casting, typically by ladling. The liquid steel is effectively scooped into sections and forming into blooms and billets on a conveyor belt, where they can cool off down to 850°C on the journey through the factory. Displayed in Figure 4-13 is the sequence of casting, rolling and finishing:

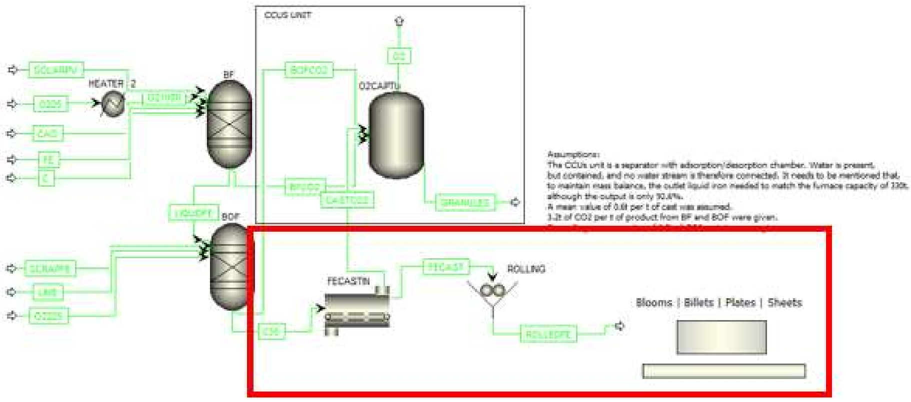


Figure 4-13: Aspen simplified layout of casting and finishing section (red)

After casting, the cast steel is then either hot or cold rolled and undergoes a set of finishing procedures, such as passivation (cleaning), electro plating, powder coating and blackening, depending on the customer's specifications.

4.6.8 CCUS

The off-gas emissions within the steelmaking process can be captured and the CO_2 separated to form aggregate (pellets) and oxygen. Additionally, the anaerobic digestion unit produces biogas and hydrogen, which can be reused in the steelmaking process – hydrogen as replacement for coal and biogas to operate microturbines. For this purpose, components had to be created displaying these processes in Aspen and INOSIM and corroborated in Simul8 processing. In the following, sections displaying these processes are shown in Figures 4-14 and 4-15:

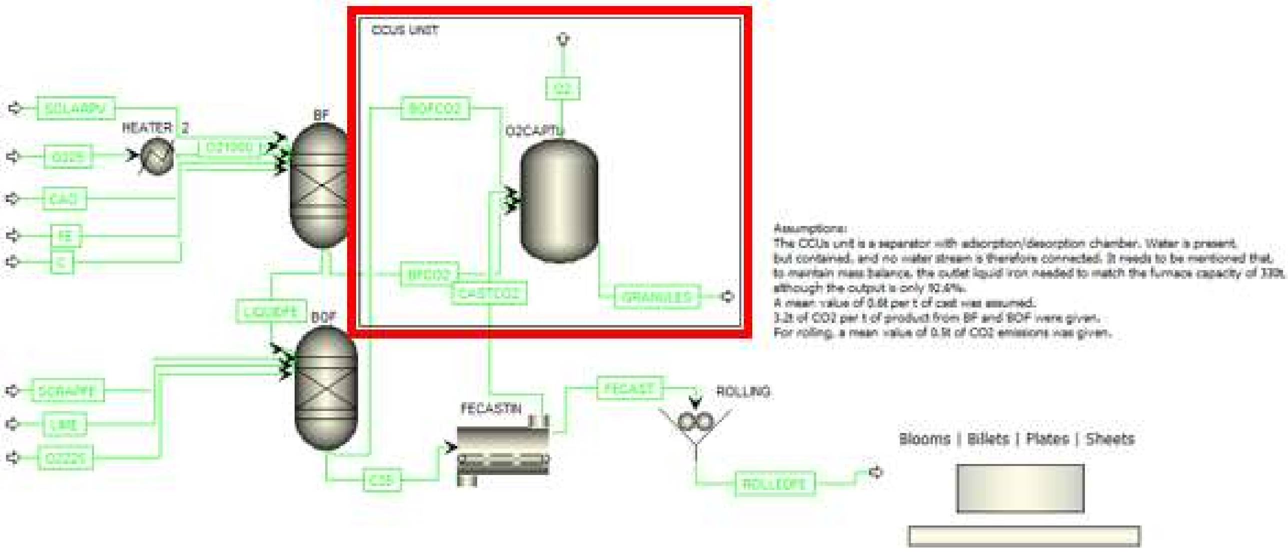


Figure 4-14: Aspen simplified layout of CCUS section (red)

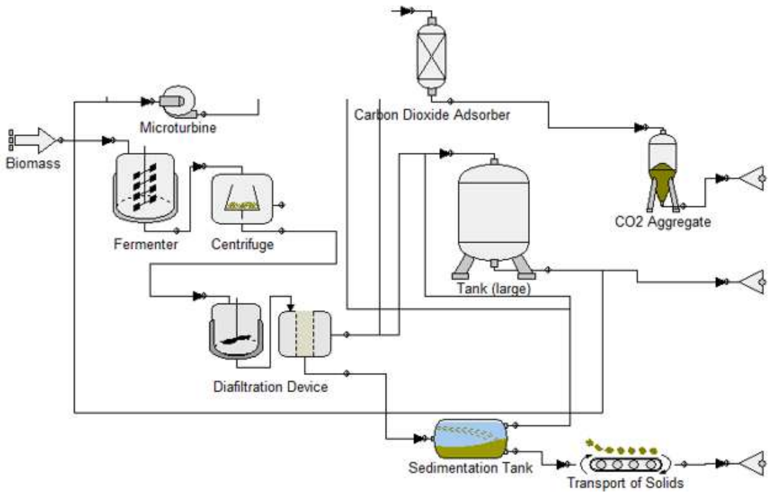


Figure 4-15: INOSIM simplified layout of CCUS section

The effects of switching to green energy providers, which causes a reduction in CO_2 emissions of 30%, and the installation of solar panels which causes a further reduction of 30% had to be incorporated into the simulations via CO_2 input streams, adhering to the achieved % reductions.

4.6.9 Results

The simulation results confirmed the findings from literature review, standard mathematical evaluation and analysis and MS Excel calculations. The details of which will be further discussed in Chapter 7.

4.7 Discussion

To establish the CO_2 emissions at the various stages in steelmaking were the driving force for compiling these process simulations in the various software applications. Engineering aspects needed to be established and parameters to be set and for this purpose, the capabilities of four different software solutions (MS Excel, Aspen, Simul8 and INOSIM) were compared. This resulted in the realisation that most process simulation software packages are mostly working with heat, work and material *flow* and are functioning on the principle of mass balance: quantities in the input streams at entry point need to be equal to quantities at the exit points. Therefore, the most feasible way to achieve mass balance was to be working *backwards* from the exit points. A blast furnace and basic oxygen furnace capacity of 330t or 330000kg were assumed. The input streams resources might be transformed during the individual process stages, but essentially, the mass stream balance requirement means that the amount of input requires to be equal the output stream.

4.8 Conclusions

It was therefore considered essential that all quantities were accurate at every stage, working backwards from the exit and output points. The determining factor for quantities and volumes were the blast furnace and basic oxygen furnace capacities, each standing at 330t or 330000kg (kg being the unit of measure in the software applications).

Having used all findings and parameters in the process simulations, it was established that arguably, the Bio Steel Cycle (BiSC) model and strategy could be seen as the engineering solution to the pressing issue of requiring to reduce CO_2 emissions - as fast as possible. A range of decarbonisation technologies at TRL 6-9 to avoid and reduce CO_2 emissions have been investigated and constitute some of the components within. The analysed engineering aspects have led to the conclusion that the proposed model and strategy are feasible, and implementation is technically possible, in the short-term. Not confined to the steel industry, but possibly applicable to most heavy industries and production processes. The strategy of the Bio Steel Cycle, detailed in the 7 steps to net zero carbon emissions steel production, are easily implementable, either subsequently or individually. The ease of implementation is consistent with the order of the respective steps and can be chosen as appropriate. For best efficiency, the system should be implemented in its entirety. Previous studies have focused individually on the exclusive investigation and assessment of either:

- policy needs
- skills needs
- supply-chain pressures on a regional and global scale
- and the requirement for models, strategies, and guidance papers
- and investigated the technical solutions for the decarbonisation of the iron and steel industry.

This study is the first of its kind to combine all of the aforementioned. Chapter 5 will provide more details on the opportunities for the Bio Steel Cycle implementation.

Chapter 5 Opportunities of the Bio Steel Cycle implementation

5.1 Introduction

Businesses' vulnerability to energy market price volatility and an upward trajectory of energy prices per unit of electricity and fuel have sent many economies to the brink of recession across geographical Europe. Drastic per-unit price increases, imposed upon consumers by energy producers have placed all industrial sectors and agricultural businesses under immense economic strain. Alongside the urgent need for decarbonisation of production in general and the steelmaking process in particular, achieving a higher level of energy independence across all sectors seems imperative. A multi-disciplinary approach with a proposed system of CO_2 emissions reduction technologies has the potential for short- to medium-term emissions reduction to zero in absolute terms. The figures stated here are the result of a thorough literature review, mathematical standard process and process simulations in suitable software applications. It was found that energy-saving and process improvement measures implementation (up to 60% efficiency increase), excess heat recovery (30% of energy can be saved), retrofitting renewable energy technology (60% implementation across production) and thus improved energy independence of 88% at the endpoint can be achieved, in the short-term. At least for the UK, there are incentives, grants, and subsidies available for commercial entities to make this a reality. Greater energy independence can be seen as a positive yet inevitable side effect of decarbonisation efforts, not only in the steel industry. This paper needs to be seen as having taken a multi-disciplinary approach to finding practical solutions for a contemporary issue. The volatility of the global energy market and recent price-hikes by energy producers have caused never-before-seen levels of profit for the energy companies, and untold pressures for businesses and the population in most developed economies. Numerous countries are on the brink of recession across geographical Europe at the time of writing, and energy price increases have made a strong case for the urgent need to achieve greater energy independence. This could be considered one of the foremost important contemporary endeavours. The iron and steel industry, along with heavy industry and petroleum refineries (IEA 2022), are by far the largest emitters of global industrial CO_2 emissions, due to their high energy demand. The industry is deemed responsible for between 7% and 11% WSA (WSA World Steel Association, 2021a) of global industrial CO_2 emissions, although there are some scientists who claim these could be significantly higher (Zhang, s. *et al.*, 2022; Morrow *et al.*, 2014; Hasanbeigi *et al.*, 2016; Hasanbeigi and Springer, 2019; Hasanbeigi, 2021, Hasanbeigi, 2022; Ren *et al.*, 2021; Swalec, 2021; Wang *et al.*, 2022), due non-existing recording and reporting structures, and the variability of established results. Although the definition of GHG or CO_2 emissions is quite challenging, China is seen as responsible for 50% of current global industrial GHG emissions (Ren et al, 2021) overall, due to their heavy reliance on coal. The increased use of coal in energy generation, due to oil and gas shortages, was found to be the main factor (IEA, 2023b) increasing global energy-related CO_2 emissions by over 2 billion tonnes, their largest ever rise in absolute terms.

5.2 Greater energy independence in steel production

This chapter will provide insights into this exciting opportunity, namely:

- Highlighting the opportunities for an 88% higher degree of energy independence in steel production
- Identifying the production stage CO_2 emission levels and their reduction to zero
- Establishing the application points of renewable energy technology and stages where achieving 30%, 60% and 88% energy independence is possible
- Evaluating some economic risks and opportunities of renewable energy technology installation

5.3 Material and Methods

Throughout this project, global data in connection with renewable energy technology implementation in different settings has been utilised (Nix, 2020; Caminiti *et al.*, 2021; Dastoor, 2021; IRENA, 2021b; El-Khozondar and El-Batta, 2022). Information on factual CO_2 emissions in steel production (Kiessling, Darabkhani and Soliman, 2022) and manufacturing (WSA World Steel Association, 2019, 2020, 2021b, 2021a, 2022) have been considered, as well as data from other industrial sectors (ECRA, 2009; WBCSD, 2017; EULA, 2012; Cañete, 2014; Mandova *et al.*, 2018; EEA, 2020,2021; Nix, 2020, 2023; COM, 2023b). The data was accumulated, analysed, and used for modeling using MS Excel and analysed by applying standard mathematical principles. For proof of concept, followed by steel production process simulations in Simul8, Aspen+ and INOSIM. The 7 Steps to Net-Zero CO_2 Emissions Steel Production (Kiessling, Darabkhani and Soliman, 2022) strategy is one guidance paper for the decarbonisation of the steelmaking process. Simultaneously, the practicalities of the strategy are making a higher degree of energy independence a reality, in the short-term. It could be achieved in seven easy-to-follow steps, even if only some sections are being applied:

Step 1: Switching to green energy provider
Step 2: Installing renewable energy technologies
Step 3: Replacing coal and coke with biomass (biochar)
Step 4: Installation of carbon capture flue stack filters
Step 5: Utilisation of CO_2 in food and concrete production
Step 6: Further process improvement in steel manufacturing
Step 7: Implementation of anaerobic digestion>biogas>green hydrogen

To visualise the opportunities of a) the circular steel production process, b) the implementation of renewable energy technology and c) achieving great energy independence, a comprehensive steel manufacturing overview has been compiled, as displayed in Figure 5-1. Conventional energy use and renewable energy implementation points have been incorporated for highlighting the simplicity of achieving a higher degree of energy independence, whilst simultaneously decarbonising the steelmaking process:

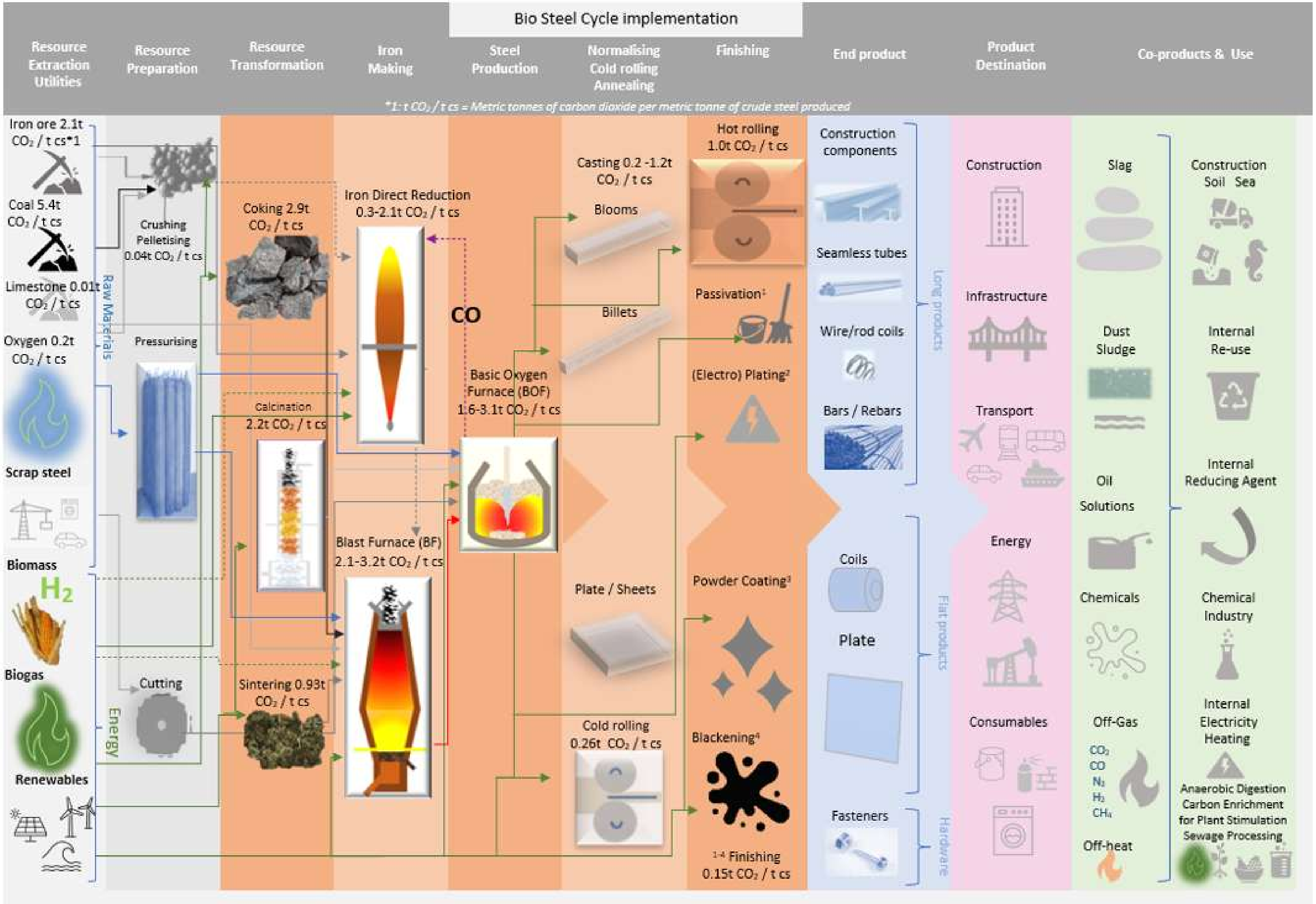


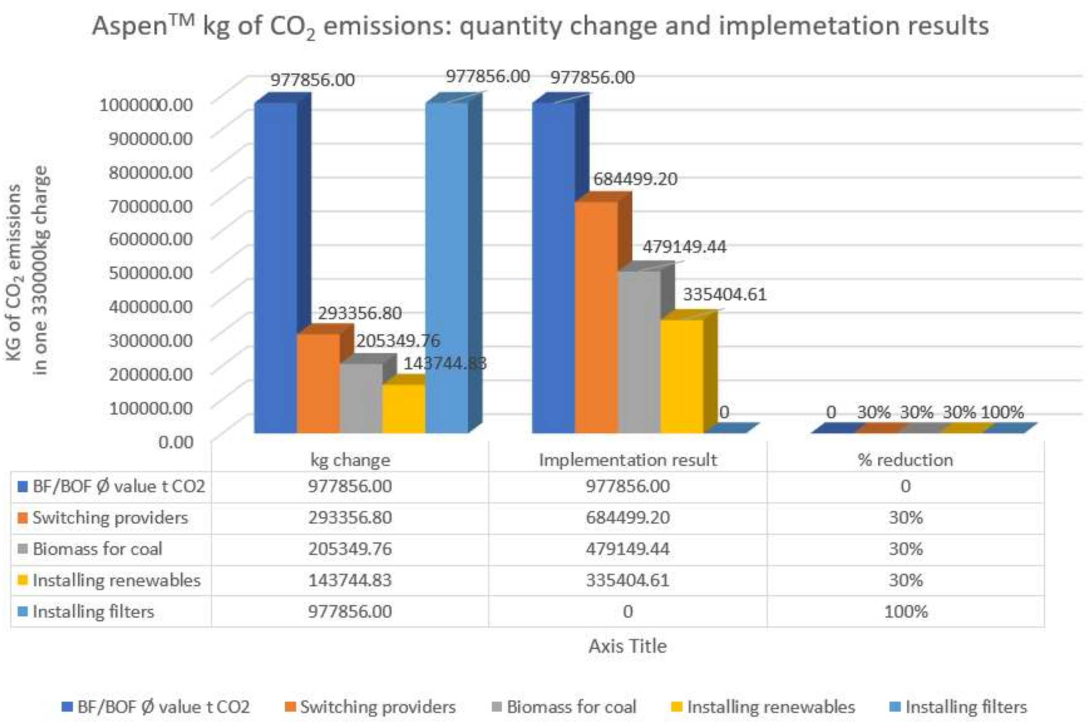
Figure 5-1: Steelmaking table flowchart with BiSC

As displayed in Figure 5-1, the same principle applies to the steel production process as far as off-heat is concerned. It was established that a total potential of 425PJ (1 PJ (Petajoule) = 31.6 million m³ of natural gas or 278 million kilowatt hours of electricity) of excess heat is readily available at a 95°C temperature, and 960PJ at approximately 25°C (Fleiter *et al.*, 2020). This amount is thought to represent between 4% and 9% of the total industrial final energy demand (based on 2015 data).

Capturing this excess heat means utilising energy potential we have already used in industry, thus reducing the amount of energy to be produced by the same amount. The benefits for agri-businesses utilising off-heat from production and CO_2 in carbon enrichment for plant stimulation are the subject of ongoing research (Fleiter *et al.*, 2020).

In detail process simulations to prove viability of the concept and the 1 hypothesis: stating that it is possible to reduce CO_2 emissions in steel production by at least 30% and achieve a higher degree of energy independence at the same time, have been carried out and the resulting reports and evaluations can be found in Chapter 6 and 7.

The BF-BOF route process simulations and thus confirmed possible CO_2 reductions in kg in relation to a 330000kg blast furnace vessel, based on the British Steel Scunthorpe site, are quite remarkable. The % reduction per stage in CO_2 emissions have been successively implemented and the results are displayed in Figure 5-2:



	kg change	Implementation result	% reduction
BF/BOF Ø value t CO2	977856.00	977856.00	0
Switching providers	293356.80	684499.20	30%
Biomass for coal	205349.76	479149.44	30%
Installing renewables	143744.83	335404.61	30%
Installing filters	977856.00	0	100%

Figure 5-2: CO_2 emissions reduction in BF in kg per charge, per 20-minute-blow

The simulations and resulting reports provided proof for the concept of the Bio Steel Cycle, insofar as with implementation of both, biomass and the Geomimetic process, the steel production CO_2 emissions could be reduced by 30% and to almost '0'. Therefore, proving the hypothesis that it is possible to produce steel without CO_2 emissions if the novel concept and strategy was being implemented. At the same time, an up to 88% higher degree of energy independence can be achieved, when renewable energy sources are being installed, which will be further elaborated on in the following text.

5.4 Heat loss recovery – energy and CO_2 saving protocols

5.4.1 Heat loss recovery

Already since the 1990s, scientists were convinced (Moran and Sciubba, 1994), that 30% of the heat energy entering any production process is: a) lost and b) could be recovered. The technology to do so has experienced a steep learning curve and is now commercially viable and available. Excess heat from any production or manufacturing process can be reused to supply any production site with heat and warm water, partly, due to the simplicity of the technology required.

The energy basis and flow have been investigated thoroughly, and an energy industry defining and telling report and graph was produced by Moran and Sciubba (1994). The theory of this exergy analysis is based on the fact that if 100% of energy is being inserted into any energy requiring unit, the amount of 70% will be effectively used for the intended purpose, whilst 30% are being lost due to inefficiencies and deficits within the production and processing infrastructure. In this case: insulation of the heat-bearing infrastructure (pipework). Via a connected network of pipes and lines, the energy or heat can be exported to nearby agri-businesses or transferred to neighbouring homes and industries through a district energy system.

5.4.2 Energy saving protocols

Excess heat is a hidden resource of energy, and it is all around us. Utilising excess heat means enabling almost 100% energy efficiency. According to the International Energy Agency, 2023b) it is apparent that energy demand is set to grow dramatically in the near future, due to population growth and rising lifestyle energy demands. Without urgent action to tackle the demand side of our lifestyle choices, and decarbonisation requirements of the climate crisis, by using every single unit of energy more efficiently, we will not get on track to meet global climate goals. Swalec (2021) stated, that global emissions of CO_2 – including land use and fossil CO_2 – will remain relatively high at 40.5Gt CO_2 in 2022, but still below their 2019 peak of 40.9Gt CO_2. According to the IEA (2023b), a global push for more efficient use of energy can reduce CO_2 emissions by an additional 5 gigatonnes per year by 2030, based on current energy demand.

5.4.3 CO_2 saving protocols

<u>The heat loss recovery constitutes already 30% of the required CO_2 reduction needed to meet the Net Zero by 2050 scenario</u> (UNFCCC, 2005; UN United Nations, 2016).

As far as energy security and greater energy independence are concerned, these energy savings are set to avoid having to produce almost 30 million barrels of oil - per day (three times Russia's average annual production, based on 2021 data), and 650 billion m^3 of natural gas per year – around four times of EU imports from Russia in 2021 (IEA, 2022b).

Although there has been a steady decline in overall electricity consumption in the iron and steel manufacturing sector (Figure 3), there is a substantial amount of electricity which could be saved and thus, the existing infrastructure is used more efficiently.

Most importantly, existing infrastructure can be easily retrofitted with technology to prevent heat loss and – at the same time – could be utilised to a) capture almost 100% of CO_2 emissions, use the captured CO_2 in ancillary industries, b) installing renewable energy resources (solar, wind, hydro) in suitable locations to increase the level of energy independence. What is being produced on-site, does not have to be imported somewhere else, at fluctuating prices (IEA, 2000, 2018, 2021b, 2023b; OECD, 2015).

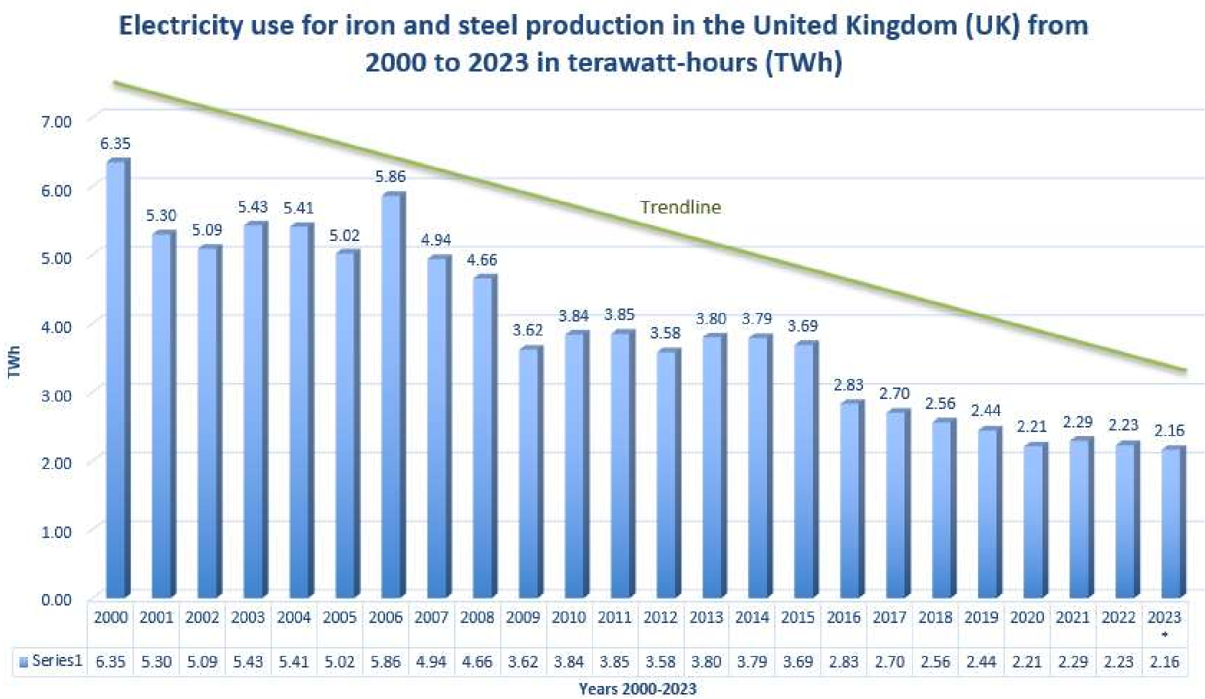


Figure 5-3: Electricity use for iron and steel production in the UK
from 2000 – 2023 (Statista, 2023)

As shown in Figure 5-4, the development of electricity usage in steelmaking has been on a downward trajectory since the year 2000, partly due to process and efficiency improvements across most industries:

In stark contrast, quite the opposite observation was made for global electricity consumption (IEA, 2000, 2018, 2021b, 2023b; OECD, 2015), as Figure 5-5 will demonstrate:

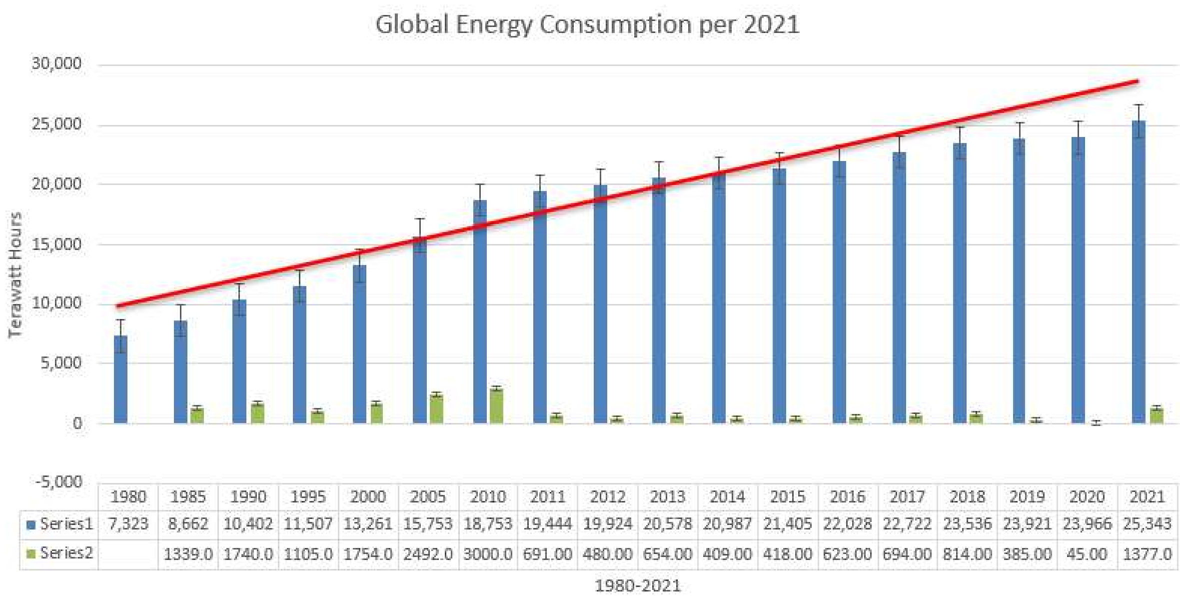


Figure 5-4: Global electricity consumption 1980-2021

Global electricity consumption has continuously increased during the last 50 years, arriving at estimated 25,300 terawatt-hours in 2021. Since 1980 and up to 2021, global electricity consumption has increased three-fold, and the global population increased by roughly 75 percent, simultaneously. In line with extended industrialisation and infrastructural improvement, these factors caused a three-fold increased electricity demand, with an upward trajectory prognosis, as of the end of 2021. Since the year 2000, China's gross development product (GDP) was recorded as developing a 16-fold increase, establishing China as the second-largest global economy, after the United States. The development of its billion-strong population and manufacturing industries has caused China to require increased levels of energy, more than any other country. Thus, it has become the largest consumer of electricity, worldwide. China and other BRIC countries (Brazil, Russia, India, China) are still vastly outpaced by developed economies with smaller population sizes, in terms of per capita electricity consumption. To place this in context: Iceland, with a population of less than half a million inhabitants, consumes the most electricity, per capita (per person) in the world, followed by Norway, Qatar, Canada, and the U.S. Contributing factors such as the existence of power-intensive industries, household sizes, living situations, appliance and efficiency standards, and access to alternative heating fuels have been identified as the determinants of the amount of electricity the average person requires, in the cited countries.

Therefore, given these developments and the looming climate catastrophe, greater energy efficiency, meaning partly excess heat recovery, poses a viable solution to the manifold current most urgent crises.

There is vast potential to simultaneously save energy by making existing infrastructure more efficient by reducing the energy/heat loss and therefore saving energy at the same percentage (30%). Means: this is 30% of the energy industry does not have to import and pay for from external sources. At the same time, 30% of CO_2 emissions for the energy not required, as saved, would not have to be produced.

Consequently, improving the existing infrastructure to prevent energy and heat loss would mean a more energy secure and more sustainable production cycle, in any industry, while achieving greater energy independence and reducing the greenhouse gas emissions linked to fossil fuel consumption, particularly of energy derived from fossil fuels.

5.5 Retrofitting renewable energy technologies on site

Renewable energy technologies are an economically viable alternative (Caminiti *et al.*, 2021) to combustion processes based on fossil fuels such as coal and gas to produce heat and energy (Cañete, 2014; EERE, 2021; COM, 2023b; Tata Steel Europe, 2023, 2024). Solar, wind, geothermal, hydropower and green hydrogen are well-established technical solutions (COM, 2019, 2022; EEA, 2020,2021; Blakers *et al.*, 2021; Caminiti *et al.*, 2021; Bhaskar *et al.*, 2022; Shubham *et al.*, 2023), which have already been successfully implemented in a range of countries and settings (Kuramochi *et al.*, 2011, 2018; Seethalakshmi, Jijeesh and Balagopalan, 2016; Kittipongvises, 2017; Chen *et al.*, 2018b; Toktarova *et al.*, 2020). Some countries and industries are supplying their entire energy needs via renewable energy solutions (Gielen *et al.*, 2019) - hence why this component is one of the cornerstones of the BiSC, as producing electricity and heating energy accounts for 36% of the UK's CO_2 emissions (ONS Office for National Statistics, 2019). Besides the emissions savings, using renewable energy technologies exclusively could provide greater independence to businesses across all sectors and increase the UK's energy self-sufficiency. The first step to greener production and greater energy independence on a fossil fuel base is the switch to an energy provider who is deriving their energy at 100% from renewable sources. Renewable technology is market ready – now the implementation is key. The choice and implementation of any of the renewable energy technologies are entirely dependent on the individual site parameters and need to be thoroughly assessed with regard to their suitability for the identified location, their potential ROI (return on investment), and viability with an outlook over and beyond the next 30 years. These need to include service and maintenance time and cost, the likelihood of repairs and the availability of suitable service providers to carry out said repairs, servicing and maintenance.

5.5.1 Solar Energy

Utilising existing buildings on industrial and production sites, suitable locations can easily be retrofitted with photovoltaic (PV) solar panels, producing energy from daylight and sunshine. These have the additional benefit of monetary grants (non-repayable), provided by the UK government, and government-backed loans and subsidies (OFGEM, 2023). The cost of manufacturing solar panels and wind turbines has plummeted dramatically in the past decade, making them affordable and often the cheapest form of electricity (IRENA, 2022). As an example, solar module prices fell by up to 93% between 2010 and 2020. During the same period, the global weighted-average cost of electricity (LCOE) for utility-scale solar PV projects fell by 85% (IRENA, 2022). There is a variety of renewable energy technologies at TRL9 available, but solar PV technology and onshore wind generation for independent energy production were established as the mainly utilised renewable energy technology in a competitive market (IRENA, 2022). The newest development in solar PV panels is the next-generation perovskite solar cells which allegedly can be manufactured at 50% cost of traditional silicon cells, at 50% greater efficiency, according to researchers from Nanjing University (China) (The Independent, 2023).

5.5.2 Wind Energy

The second largest dominant technology after solar energy is onshore wind energy (IRENA, 2022). Utilising the vast UK coastline, large offshore wind parks have been established, producing renewable energy reliably for some time now. Given that the UK is an island, technically, one could argue that it only makes logical sense that - since land in the UK is scarcer than water – that offshore wind park development should be given priority to onshore wind farms. There are currently four types of wind turbine energy generators (WTGs), which are 1) Direct current generators (DC), 2) Alternating current synchronous generators (AC), 3) AC asynchronous generators, and 4) Switched reluctance generators.

The actual wind turbine designs are manifold, and information on new interpretations of the basic principles and their expression of innovative designs are being published on an almost monthly basis. The newest development are vertical axis wind turbines, where contrary to the traditional "windmill" design, the blades are caged between two circular frames and mounted through the pillar, giving the turbine an almost mushroom-type shape (Shubham *et al.*, 2023). Due to the smaller dimension of the mounted multiple blades, this design is much more suitable in commercial or residential settings in comparison to traditional wind turbine designs, not only but mainly due to their much smaller size. Although it has become apparent that the number of blades not only increases efficiency, but also noise levels, the speed at which these technologies are developing gives hope that a solution will soon be found to combat these issues.

5.5.3 CHP units and turbines and biogas turbines

The same rapid development environment applies to combined heat and power (CHP) boilers and biogas turbines (Nezhad, *et al.*, 2019; Bazooyar, 2020; Kabeyi, 2022), as more energy efficient and less greenhouse gas emitting systems are becoming available. Harnessing the heat generated in steel manufacturing is one of the key elements of CHP units and could be considered as one of the components of the BiSC and the transformation of heavy industry towards decarbonisation and sustainability. To make the green industrial revolution happen, the UK government has created new energy efficiency schemes from 2022 to replace the current domestic and non-domestic renewable heat incentives (RHI) (OFGEM, 2023). There are a range of schemes accessible to businesses, such as finance and support from the Department for Business, Energy and Industrial Strategy and others, as displayed in Table 5-1:

Table 5-1: Grants and support for the implementation of renewables

No.	Scheme	Description	Author
1	England Woodland Creation Offer	Landowners, land managers and public bodies eligible to apply to the England Woodland Creation Offer (EWCO);support for woodland creation (>£10,000 per hectare)	FC, 2021
2	Greening Eden	The CBEN Partnership will complete the calculations using data provided by each company and site visits to provide practical and cost-effective advice on how to reduce emissions. These could range from no-cost changes in behaviour, low-cost actions, or capital investment projects (£400,000 grant fund).	CBEN, 2015
3	Green Heat Network Fund	Commercialisation and construction of new low and zero carbon (LZC) heat networks (including the supply of cooling) and retrofitting and expansion of existing heat networks. Funding supports the uptake of low-carbon technologies (heat pumps, solar and geothermal energy) as a central heating source. The GHNF is open to organisations in the public, private, and third sectors in England.	DBEI, 2022
4	Green Gas Support Scheme	Funding support for biomethane injection to the national grid.	OFGEM, 2023a
5	Clean Heat Grant	Upfront capital funding for households and businesses for the installation of sustainable heating technologies (heat pumps, biomass).	OFGEM, 2023b
6	Smart Export Guarantee (SEG)	The SEG funds for the low-carbon electricity exporters, feeding back to the National Grid. Anyone with an installation of one of the following technology types is eligible to apply: Solar photovoltaic (solar PV), Wind, Micro combined heat and power (micro-CHP), Hydro, Anaerobic digestion (AD) support and grants for SMEs to help them to reduce carbon emissions.	OFGEM, 2023c
7	SME Energy Efficiency Scheme (SMEES)	Guidance and funding for businesses looking to improve their energy efficiency.	DBEI, 2022a
8	Energy for Business	Support and grant funding for SMEs with projects to reduce carbon emissions or save energy.	DBEI, 2022b
9	HNIP	Heat Networks Investment Project (HNIP) government-backed funding	DBEI, 2022c
10	Low Carbon Dorset	Free support to help businesses in Dorset reduce their carbon emissions, improve energy efficiency and aid the development of new low carbon products	LowCarbonDorset 2023
11	Business Energy Efficiency Programme - West Midlands	Energy reviews and grants to help businesses in the West Midlands manage and reduce energy costs.	Worcestershire Council (no date)
12	Low Carbon Workspaces	Offers grants to implement energy efficiency measures, to save money and cut waste	Low Carbon Workspaces, 2023
13	Horizon Europe funding	Funding for research or innovation that's groundbreaking, improves European research standards or responds to challenges like climate change or food security.	COM, 2020
14	Coventry and Warwickshire Green Business Programme	Grants, free energy audits and low carbon product development support for businesses.	Carbon Copy, no date
15	DE-Carbonise Project	Derby and Derbyshire	Derby City Council, 2023

5.5.4 Hydro Power

Technology generating electricity using either biomass or hydro-turbines (water-based), hydrogen generating systems and anaerobic digestion (AD) systems (Nix, 2023) are also included in some of the schemes currently supported by the current UK governments' incentives to promote sustainable energy generation, as displayed in Table 5- 1. Currently, there are closed loop and open hydro power systems available. Given the volatility of UK river water levels and contamination with faeces released by water companies, closed-loop hydro power systems might be the technology of choice, where feasible.

5.5.5 Anaerobic Digestion

Projects containing components such as DAC (Direct Air Capture), re-directing heat and utilising anaerobic digesters (ADs) to produce biogas (methane and hydrogen), and producing energy on-site with turbines (Nezhad, *et al.*, 2019; Bazooyar, 2020; Kabeyi, 2022) can be directly linked to one of the incentives shown in Table 5-1, such as the 'Farming Investment Fund' and includes funding for agricultural businesses such as farmers, foresters, growers and agri-contractors with grants for investing in new technologies, equipment and infrastructure. The anaerobic digester has the ability to convert almost any organic (non-contaminated) matter into biogas and substrate, at relatively low running and maintenance cost, in relation to the initial installation outlay. ADs are an essential part of the BiSC in a drive to generate biogas and potentially hydrogen at a later stage, to be recirculated into the steelmaking process. These are also supported by the schemes in Table 5-1.

5.5.6 Geothermal Energy and ground-source heat pumps

Geothermal energy is an additional renewable energy source, working with heat-pump units in tandem with water-filled boreholes which is then naturally heated by the hot rock. The hot water produces vapour that can be used to drive turbines and create electricity. As (Milanović Pešić *et al.*, 2022) established, there are now some developed countries which are discovering the potential of geothermal energy (GTE) as an innovative and sustainable energy source. Having investigated the complex geological structure in Serbia, the authors found that it contains a considerable number of thermo-mineral springs and geothermal wells and the geothermal heat-flow-density ranges from 80-120 mW/m^2, above most European countries' average (60 mW/m^2). The conclusions were that a thorough geothermal heat-flow-density analysis requires to precede any potential suitability assessment, so that a cost-effectiveness calculation of using geothermal energy can be conducted. Sharmin *et al.* (2023)

compared geothermal energy with other renewable energy sources and concluded that geothermal energy produced by Enhanced Geothermal Systems (EGS) and Hybridized Geothermal Systems (HGS) for domestic and commercial use, as well as power generation in a variety of power plant setups, has the potential to significantly reduce harmful greenhouse gases. Karayel, Javani and Dincer (2022) went just the step further and investigated the geothermal energy potential for green hydrogen production in Turkey and found that the total hydrogen production potential of using geothermal resources is estimated to be ~560 kilo tonnes. Their work could potentially support planning and strategising purposes in endeavours to developing new energy policies and investing in renewable energy resources. Geothermal systems are also supported by the afore mentioned UK incentives.

Ground source heat pumps (GSHP) function in a similar sub-surface, yet slightly different way in that they operate with extracting heat via a system of antifreeze fluid-filled pipes buried underground from the earth's core and use the heat which has been stored at sub-surface levels at a maximum depth of 200 metres. This heat is created when the sun warms the earth, particularly during the hotter seasons, and it is still stored consistently during the colder seasons. Compared with the simplicity of solar or wind energy system installations, the installation of geothermal or GSHP systems seems quite challenging.

5.6 Multi-criteria decision analysis (MCDA) for BiSC (Bio Steel Cycle)

5.6.1 Introduction

The first exhaustive publication on MCDA (multi-criteria decisions analysis) were the pioneers Keeney, Raiffa and Rajala (1979), whose work is still the benchmark for creation of meaningful data to support decision making in a political or industrial context. They built their practice on decision theory: a) decision trees, b) modeling of uncertainty and c) the expected utility rule. The application of decision factor identification theory to accommodate multi-facetted future outcomes, Keeney and Raiffa created a theoretically sound multi-level integration model of the uncertainty associated with future events and the varied objectives those criteria might influence. There is also the technique for order of preference by similarity to ideal solution (TOPSIS) system, as another multi-criteria decision analysis method (ElMarkaby *et al.*, 2023), which was originally developed by Ching-Lai Hwang and Yoon (Hwang and Yoon, 1981). This was followed by publications of governmental guidelines (HM Government UK, 2009) which provided further guidance on practical application of MCDA.

5.6.2 Basics of MCDA for BiSC

The initial steps in multi-criteria analysis of technologies used in steel manufacturing and improved steelmaking processes described, as follows:

1. Context: a) Aims of the MCA. b) Identify decisions makers.
2. Identifying suitable projects.
3. Identifying a) objectives, b) criteria and c) value associated with the consequence of each option.
4. Describing the expected percentage reduction in CO_2 emissions, cost and time of installation and project lifetime.
5. Attributing weighting to each criterion relative to their importance to the decision-making process.
6. Combine calculated weights and scores for each of the options to determine an overall value.
7. Sensitivity analysis to variation in scores or weighting.
8. Examination and analysis of the derived results.

It should be emphasised that the application of MCDA is not limited to scenarios with the aim to determine only one single most appropriate option for implementation. Using the different steps of the MCDA process can be especially helpful when the requirement is to either short-list a set of options for further analysis, or if the aim is to compile a meaningful grouping of options. In order to determine the options, the value tree for objective determination needs to be established, as follows in Figure 5-6:

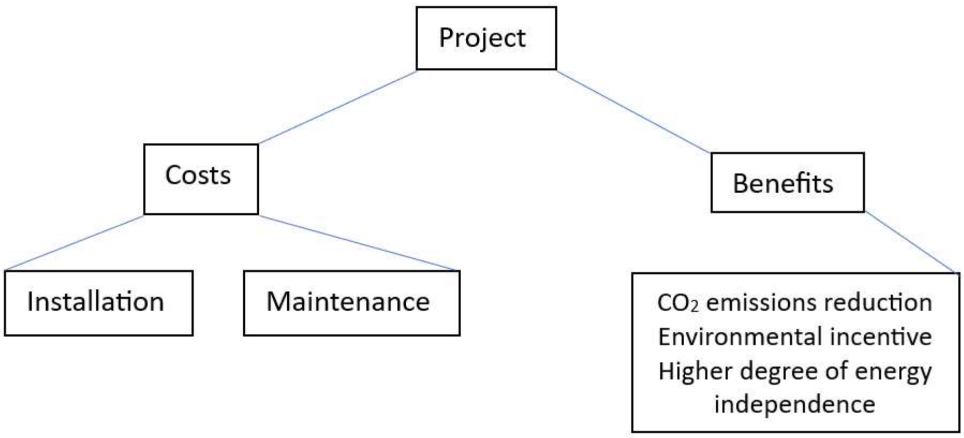


Figure 5-5: Value tree for objective determination

Based on the value tree for objectives in Figure 5- 6, and the afore mentioned initial steps, the categories most suitable for the current setting of CO_2 emissions reduction and decarbonisation of the steel industry are: TRL determination, percentage efficiency, installation cost, CO_2 reduction percentage, implementation project lifetime, and level of environmental intrusion (Keeney, Raiffa and Rajala, 1979). The steps for the MCDA in the efforts of decarbonising the steel industry were therefore defined and subsequently implemented accordingly. Having established the required steps to carry out a meaningful MCDA and having chosen the projects to analyse, a project duration and lifetime GANTT chart and performance matrix has been established, using MS Excel, in Tables 5-2 and 5-3:

Table 5-1 Table 5-2

Table 5-2: GANTT chart project duration and lifetime

					Implementation	Year	*1*												***2***	***3***
Step 1-7		Project or			Project	Month	1	2	3	4	5	6	7	8	9	10	11	12		
in BiSC	Technique	Process	Company	System / Performance	Lifetime															
1	Switching>Green energy	Energy Provider	See Appendix 4	100% renewable energy	1 day															
2	Installing renewables: Solar	Solar PV panels	C (Internal back conta	1kWh/ 4 panels=25667panels	2 years															
2	Installing renewables: Wind	Horizontal axis w. turbine	Norvento nED100	100 kW/£317,655.27x65	6 months															
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E53	800 kW/£807,581.80x8	6 months															
2	Installing renewables: Wind	Horizontal axis w. turbine	EWT DW61	1 MW/£981,368.75x6	6 months															
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E82	3 MW/£1,829,271.35x3	6 months															
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E126 EP3	3.5 MW/£2,458,302.00x2	6 months															
2	Installing renewables: Wind	Vertical axis wind turbine	Patriot Modular	70kW/£188,196.00/x92	6 months															
2	Installing renewables: Hydro	Small closed loop system	Helios Atlas	6.5MW	10 months															
3	Using biomass / green H_2	H_2ermes: H_2 from seawater	HyCC/Tata Steel	15,000t H_2/p.a.	2 years															
4	CO_2 filters installation	$CaCO_3$ based CO_2 absorber	Giammarco Vetrocoke	Hot potassium Carbonate (HPC) solution	1 month															
5	Utilisation captured CO_2	Geomimetic: CCUS in aggregate	Blue Planet	100% CCUS	1 month															
6	Process improvement	Hisarna; ironmaking by simultaenous iron ore reduction and scrap melting combined with biomass and limestone instead of lime	Tata Steel, Horizon 2020, Horizon Europe	3300t hot metal per day	3 years															
7	Anaerobic digestion>biogas utilisation in steelmaking	Biogas and H_2 from anaerobic digestion	Biogen	Biogas production	3 months															

Table 5-3: Performance matrix

Step 1-7 in BiSC	Technique	Project or Process	Company	System / Performance	TRL 6-9	% Efficiency	Installation Cost £	CO_2 Reduction Percentage	Implementation Project Lifetime	Level 1-5 Environmental Intrusion
1	Switching>Green energy	Energy Provider	See Appendix 4	100% renewable energy	√*	√	√	√	√	√
2	Installing renewables: Solar	Solar PV panels	C (Internal back conta	1kWh/ 4 panels=25667panels	√	√	√	√	√	√
2	Installing renewables: Wind	Horizontal axis w. turbine	Norvento nED100	100 kW/£317,655.27x65	√	√	√	√	√	√
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E53	800 kW/£807,581.80x8	√	√	√	√	√	√
2	Installing renewables: Wind	Horizontal axis w. turbine	EWT DW61	1 MW/£981,368.75x6	√	√	√	√	√	√
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E82	3 MW/£1,829,271.35x3	√	√	√	√	√	√
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E126 EP3	3.5 MW/£2,458,302.00x2	√	√	√	√	√	√
2	Installing renewables: Wind	Vertical axis wind turbine	Patriot Modular	70kW/£188,196.00/x92	√	√	√	√	√	√
2	Installing renewables: Hydro	Small closed loop system	Helios Atlas	6.5MW	√	√	√	√	√	√
3	Using biomass / green H_2	H_2ermes: H_2 from seawater	HyCC/Tata Steel	15,000t H_2/p.a.	√	√	√	√	√	√
4	CO_2 filters installation	$CaCO_3$ based CO_2 absorber	Giammarco Vetrocoke	Hot potassium Carbonate (HPC) solution	√	√	√	√	√	√
5	Utilisation captured CO_2	Geomimetic: CCUS in aggregate	Blue Planet	100% CCUS	√	√	√	√	√	√
6	Process improvement	Hisarna; ironmaking by simultaenous iron ore reduction and scrap melting combined with biomass and limestone instead of lime	Tata Steel, Horizon 2020, Horizon Europe	3300t hot metal per day	√	√	√	√	√	√
7	Anaerobic digestion>biogas utilisation in steelmaking	Biogas and H_2 from anaerobic digestion	Biogen	Biogas production	√	√	√	√	√	√

* the presence of a tick indicates the presence of data. Previous versions of this table eliminated incomplete data sets.

Having established a performance matrix, the scores for the projects need to be established.

This is the point where things become complicated: it is not normally possible to combine TRL determination, percentage efficiency, installation cost, CO_2 reduction percentage, implementation project lifetime, and level of environmental intrusion. However, with an MCDA it can be done. The core idea is to construct scales representing preferences for the consequences (i.e. from low to high or high to low), to weight the scales for their relative importance (share out of 100), and then to calculate weighted averages across the preference scales, to obtain a combined rating as a result. For the purpose of this exercise, relative preference scales will be illustrated. The base example image, as follows in Figure 5-7:

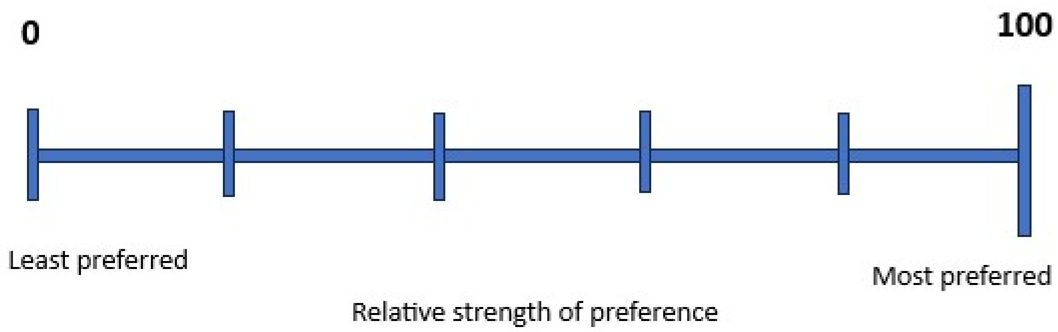


Figure 5-6: Relative strength of preference scales example

Relative strength preferences scales are anchored at their left ends by the least, valued at '0', and at their right ends by the most preferred options of a criterion, valued at '100'. It so follows that The most preferred option is assigned a preference score of 100, and the least preferred a score of 0, similar to a temperature °Celsius scale. Scores are assigned to all options, resulting in the numbers representing differences in strength of preference. It needs to be emphasised, that these are relative judgements, and a certain bias can be assumed, as is human nature. However, these can be seen as sound judgements, based on a solid foundation of researched facts and data sets. These scales contain values and weightings at set stages, which are demonstrated in the following Table 5-4. It needs to be emphasised that all weightings are subjective but based on the principle that most businesses' aim is to generate profit, and to maximise revenue at lowest possible cost in time and capital. Therefore, the weighting has been designed in accordance and with this principle in mind *(Spence and Rutherfoord, 2001; Jensen, 2002, 2002; Jarillo, 2003; Bini and Tusset, 2008; Murray and Hwang, 2011; George* et al.*, 2023; Smith, no date)*.

Table 5-4: Weighting of preferences and objectives

TRL determination / 16 points weighting	Percentage efficiency / 10 points weighting
Low>high	Low>high
6 = 4	0-25 = 3
7 = 8	26-50 = 5
8 = 12	51-75 = 8
9 = 16	76-100 = 10
Installation cost / 25 points weighting	CO_2 reduction percentage / 30 points weighting
High>low	Low>high
0-10m£ = 25	0-50 = 15
11-20m£ = 20	51-100 = 30
21-30m£ = 15	
31-40m£ = 10	
41-> = 5	
Implementation project lifetime 14 points weighting	Level of environmental intrusion / 5 points weighting
High>low	Low>high
1 day – 6 months = 14	Level 0 = 5
7 months – 2 years = 10	Level 1 = 4
2 years and longer = 6	Level 2 = 3
	Level 3 = 2
	Level 4 = 1
	Level 5 = 0

The overall weighted scores at each stage, for each objective, are then calculated, resulting in an overall score for each option by using the following formula (Keeney, Raiffa and Rajala, 1979):

$$\boldsymbol{S_i = \sum W_i W_i} \qquad \text{Equation 5-1}$$

Abbreviations in equation 5-1 explained: S_i = Score; $\sum$= sum of; W_i = Weighting

5.6.3 MCDA for BiSC

For every objective, the weighted scores were added: $S = W_1S_1 + W_2S_2 + W_3S_3 + W_4S_4 + W_5S_5 + W_6S_6$, resulting in the weighted scores on the right-hand side of the MCDA matrix in Table 5-5:

Table 5-5: : MCDA analysis Bio Steel Cycle implementation steps

Step 1-7 in BiSC	Technique	Project or Process	Company	System / Performance	TRL 6-9	S_1 Score	% Efficiency	S_2 Score	Installation Cost £	S_3 Score	CO_2 Reduction Percentage	S_4 Score	Implementation Project Lifetime months	S_5 Score	Level 1-5 Environmental Intrusion	S_5 Score	100 Best 0 Worst Score	Ranking By Score	**References**
1	Switching>Green energy	Energy Provider	See Appendix 4	100% renewable energy	9	16	100	10	£0.00	25	30	15	1	14	0	5	85	1	Appendix 4
2	Installing renewables: Solar	Solar PV panels	C (Internal back conta	1kWh/ 4 panels=25667panels	9	16	23	3	£51,334,000.00	5	30	15	24	10	0	5	54	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Horizontal axis w. turbine	Norvento nED100	100 kW/£317,655.27x65	9	16	40	5	£20,647,592.55	15	30	15	6	14	3	2	67	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E53	800 kW/£807,581.80x8	9	16	40	5	£6,460,654.40	25	30	15	6	14	3	2	77	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Horizontal axis w. turbine	EWT DW61	1 MW/£981,368.75x6	9	16	40	5	£5,888,212.50	25	30	15	6	14	3	2	77	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E82	3 MW/£1,829,271.35x3	9	16	40	5	£5,487,814.05	25	30	15	6	14	3	2	77	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E126 EP3	3.5 MW/£2,458,302.00x2	9	16	40	5	£4,916,604.00	25	30	15	6	14	3	2	77	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Wind	Vertical axis wind turbine	Patriot Modular	70kW/£188,196.00/x92	8	12	40	5	£17,314,032.00	20	30	15	6	14	3	2	68	2	Clean Energy Reviews, 2023; Renewable Energy Hub, 2023; Renewables First, 2023; Nix, 2023
2	Installing renewables: Hydro	Small closed loop system	Helios Atlas	6.5MW	8	12	80	10	£23,488,990.54	15	30	15	10	10	4	1	63	2	Helios Atlas, 2023; IRENA, 2012
3	Using biomass / green H_2	H_2ermes: H_2 from seawater	HyCC/Tata Steel	15,000t H_2/p.a.	7	8	80	10	£56,212,441.16	5	30	15	24	10	1	4	52	2	Tata Steel Europe, 2022; Shumkov, 2022
4	CO_2 filters installation	$CaCO_3$ based CO_2 absorber	Giammarco Vetrocoke	Hot potassium Carbonate (HPC) solution	9	16	99	10	£68,145.00	25	100	30	1	14	0	5	100	1	IEA, 2021b
5	Utilisation captured CO_2	Geomimetic: CCUS in aggregate	Blue Planet	100% CCUS	9	16	100	10	£0.00	25	100	30	1	14	0	5	100	1	Blue Planet, 2023
6	Process improvement	Hisarna; ironmaking by simultaenous iron ore reduction and scrap melting combined with biomass and limestone instead of lime	Tata Steel, Horizon 2020, Horizon Europe	3300t hot metal per day	6	4	80	10	£60,469,288.43	5	55	30	36	6	2	3	58	2	Tata Steel, 2020/2020a
7	Anaerobic digestion>biogas utilisation in steelmaking	Biogas and H_2 from anaerobic digestion	Biogen	Biogas production	9	16	90	10	£19,500,000.00	25	60	30	3	14	5	0	95	2	DEFRA, 2021; Nix, 2023
		Weighting			W_1		W_2		W_3		W_4		W_5		W_6				
					16	-	10	-	25	-	30	-	14	-	5	-	-		
					Low>high	-	Low>high	-	High>low	-	Low>high	-	High>low	-	High>low	-	-		

There are multiple factors and outcomes to consider, which require analysis of the results and possible effects on different scenarios. The weighting and scores have been attributed to the author's best knowledge and are not influenced by any bias.

5.6.4 MCDA sensitivity analysis to variation in scores or weighting

The scores and weighting were given thorough thought, and it was determined that the best approach was to establish weighting in line with this work's aims and objectives: establishing ways and means for decarbonisation of the iron and steel industry and achieving a higher degree of energy independence. In 21st century capitalist Britain, the negative effects of cost implications preventing implementation of decarbonisation technology have been colossal, at great cost to the natural environment.

But even before the IPCC (2021, 2022, 2023a, 2022a) have issued a stark warning, industry leaders have realised their responsibilities and have started globally 59 (per 2023) projects – and counting - with the aim to establish technologies which have the potential to decarbonise heavy industry, and not only the steel industry (Appendix 6).

Therefore, the weighting has been attributed, as follows:

As identifying suitable CO_2 reduction technologies is imperative, the weighting has been attributed to be 30 points out of 100, as this is the most crucial objective. The levels have been split into two categories, 0-50% CO_2 emissions reduction potential at 15, and 51-100% CO_2 emissions reduction potential at 30 points. Next in line are the installation cost, as the prevention of implementation of suitable decarbonisation technology due to high cost is one of the main factors preventing timely CO_2 emissions reduction in heavy industry. Cost of 0-10m£ have been weighted at 25 points, 11-20m£ at 20, 21-30m£ at 15, 31-40m£ at 10, and 41m£+ at 5 points. It is quite obviously crucial that the identified technology is available to industry, and therefore the technical readiness levels have been weighted at 16 points, with TRL 6 weighted at 4 points, TRL 7 at 8, TRL 8 at 12, and TRL 9 at 16. The project lifetime factor is feeding into the requirement for a higher degree of energy independence and has therefore been attributed 14 points. From fastest to slowest, the weighting has been determined to be for 1 day – 6 months at 14 points, 7 months – 2 years 10 points, and any project taking 2 years and longer from start to completion 6 points. The technology efficiency has been weighted at 10 points, with 0-25% efficiency at 3 points, 26-50% at 5, 51-75% at 8 and 76-100% at 10 points. As one of this work's driving factors is preventing further damage to our natural environment and halting or at best reversing environmental damage, the environmental intrusion of the chosen technology need to be taken into consideration, too. The least environmentally intrusive technology has been set at Level 0 with the highest score of 5 points, Level 1 at 4, Level 2 at 3, Level 3 at 2, Level 4 at 1, and Level 5 with a high impact factor at 0 points.

5.6.5 MCDA examination and analysis of the derived results

As cost and time as time is money seem to be the most crucial factors deciding upon the successful technology implementation, the initial installation cost have been plotted against the expected project lifetime. Figure 5-8 will demonstrate the relation:

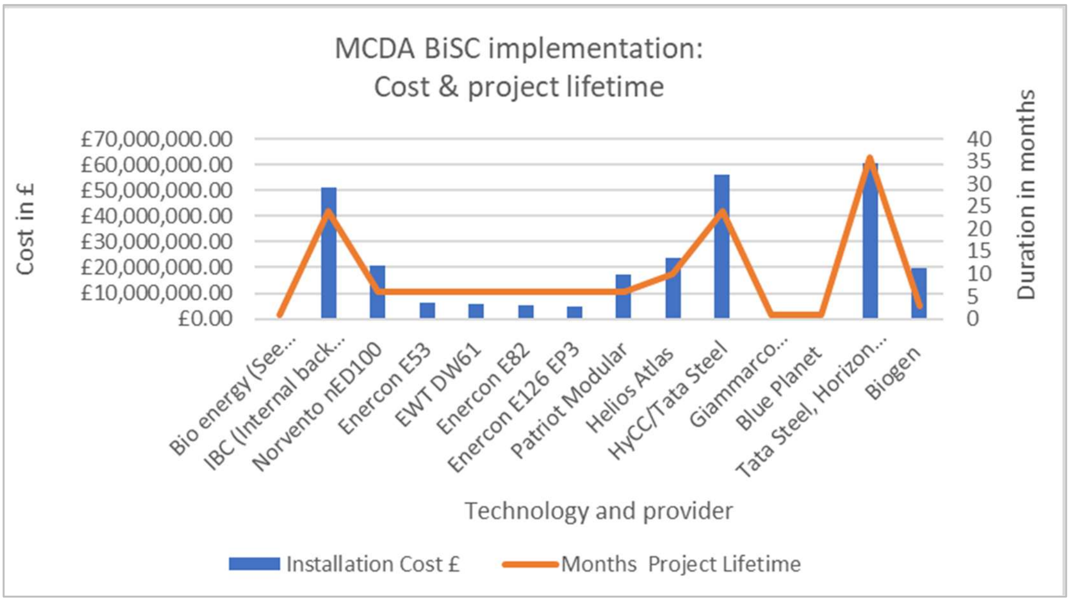


Figure 5-7: MCDA BiSC cost and project duration

Based on the graph and comparison of cost and project lifetime, the technologies standing out with relatively low cost and installation time are: Switching to a bio energy provider and wind energy for energy procurement, installing CO_2 filter mechanisms and using Blue Planet's Geomimetic© process for CCUS.

But this is not the only deciding factor, the technology efficiency also plays an important role, as displayed in Figure 5-9:

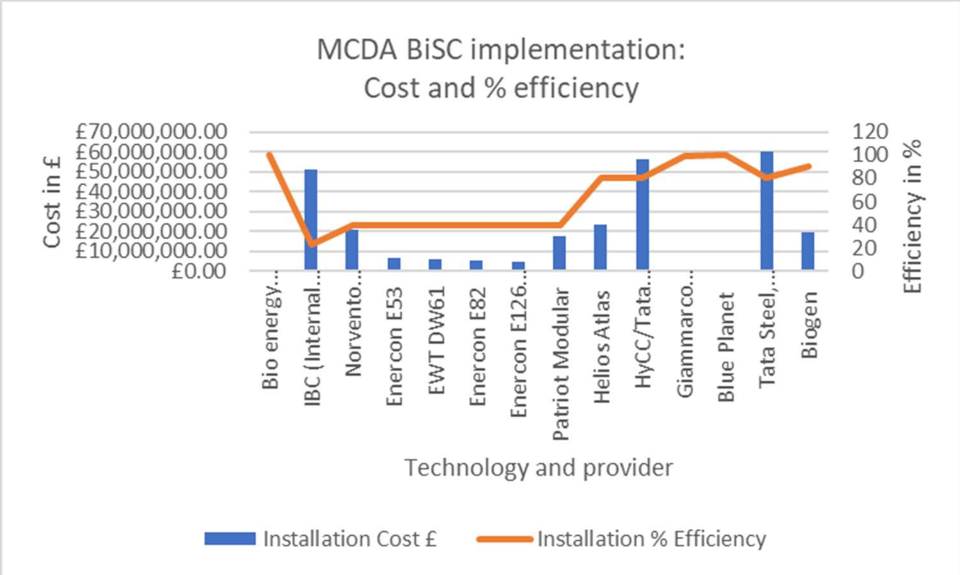


Figure 5-8: MCDA BiSC cost and % efficiency

Comparing cost and technology efficiency, the best choices from this viewpoint are: Switching to a bio energy provider and wind energy for energy procurement, installing CO_2 filter mechanisms, using Blue Planet's Geomimetic© process for CCUS and installing an anaerobic digester to produce biogas. As industry leaders have a responsibility for their company staff and stakeholders, the technological readiness levels (TRL) also play an important role. The following graph in Figure 5-10 will reveal the connection:

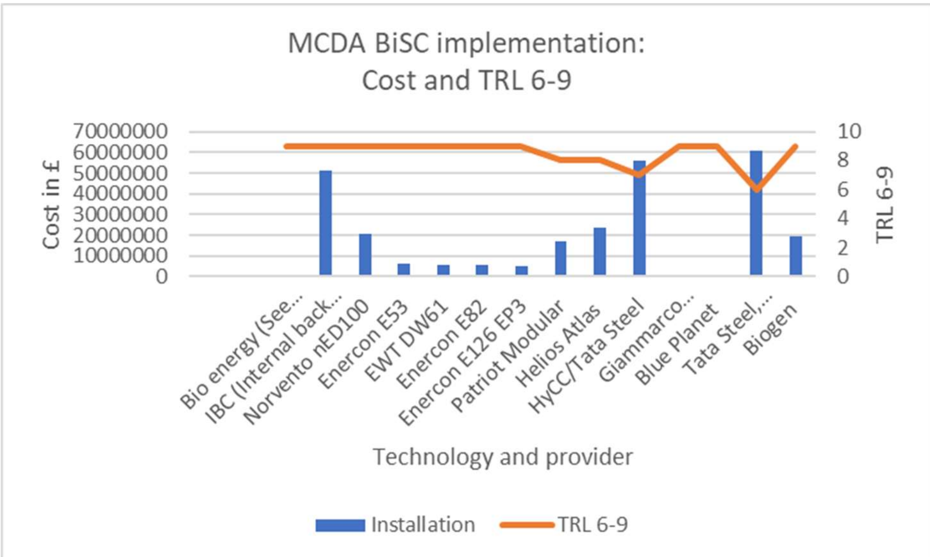


Figure 5-9: MCDA BiSC cost and TRL 6-9

The chosen technologies are at TRL 6-9 and each of the options is viable, taking into consideration company staff and stakeholder responsibilities. Tata Steel's Hisarna is at TRL 6, which means it is now ready to be used in an industrially relevant environment in the case of key enabling technologies. Alongside switching to green energy providers and CO_2 capture installations (100 points), HIsarna at an overall score of 80 points could be one of the implementation candidates to achieve net-zero CO_2 emissions steel production and higher energy independence, along CO_2 filter installation at 100 points, CCUS at 100 points and anaerobic digestion for the production of biogas and use in heavy industry at 95 points.

5.6.6 MCDA Conclusions and discussion

The MCDA analysis has provided in-depth detail for decisions makers, supporting the planning and implementation of suitable projects to achieve decarbonisation of the iron and steel industry and achieving a higher degree of energy independence. Saving on CO_2 emissions by switching to green energy providers now seems not only the easiest but also the most fiscally responsible course of action. Although solar PV panels are one of the easiest technologies to install, they are almost prohibitively costly – but the alternative as far as renewables is concerned, is readily available in form of wind turbine technology. These steps, combined with CO_2 filter installation, carbon utilisation as aggregates and anaerobic digester installation to produce biogas seem the most sensible paths to timely and efficient decarbonisation of the iron and steel industry and for achieving a higher degree of energy independence.

5.7 The Bio Steel Cycle implementation stages, support schemes and cost

The BiSC implementation of stage-relevant components with the aim to decarbonise the steelmaking process require significant up-front capital investment. The current retail price for one metric tonne of steel is currently, at time of writing in 08/202, at £1,000/ t cs, and the cost of producing 1 t of cs stands at £433.13. Gross profit margins are currently at 66.87%, despite the retail price drop from £1,645 in 04/2022 to £1,000 in 08/2023. Theoretically, this should provide steel manufacturers worldwide with the means to invest in the decarbonisation of the steelmaking process, similar to the EU, without affecting business operations or efficiency. Table 5-6 demonstrates how the BiSC component implementation can achieve an almost zero CO_2 emissions steel production process, whilst not financially impacting business performance, and additionally, can even provide an added source of income (DAC):

Table 5-6: BiSC implementation, financial support and cost

	10,000t/day x 360 days = annual capacity steel cs production per BF/BOF	*4.6t CO_2 / t cs via BF/BOF = p.a.*	*Cost of producing one t of cs via BF/BOF, in UK, in £, 08/2023*	*UK retail price per t of cs, in £, 08/2023*			
Baseline	3,600,000.00	16,560,000.00	**433.13**	**1,000.00**			
Stage BiSC	*Technology*	*Installation cost in £*	*Maintenance cost ~5% p.a., in £*	*Amortisation over 20 years, incl. maintenance p.a., in £*	*Potential UK/EU financial support scheme, no. as per table 5- 1*	*Theoretical UK/EU financial support scheme value in %/£*	*Added cost or -profit / t cs*
CO_2 capture post combustion	Filter insertion	68,145.00	3,407.25	3,577.61	2, 8, 12, 14, 15	100%	0.00
	CEPS \$35–300/T-CO_2 = mean £132/ t; daily capacity 10000t	132,000.00	6,600.00	6,930.00	2, 8, 12, 14, 15	100%	0.00
	DAC 10 ha, 5 years	43,600.00	2,180.00	2,289.00	1	10,000 per ha	-56,400.00
Installation renewable energy technologies	Wind	4,916,604.00	245,830.20	258,121.71	6, 7, 8, 11, 14.15	100%	0.00
	Solar	51,334,000.00	2,566,700.00	2,695,035.00	6, 7, 8, 11, 14.15	100%	0.00
	Hydro	23,488,990.54	1,174,449.53	1,233,172.00	6, 7, 8, 11, 14.15	100%	0.00
	Anaerobic Digestion	19,500,000.00	975,000.00	1,023,750.00	from 2 to 15	100%	0.00
Steel production process improvement	Hisarna	60,469,288.43	3,023,464.42	3,174,637.64	from 2 to 15	100%	0.00

**All information derived from table 5- 5 and resources therein*

The technology and financial support is available in developed countries to decarbonise heavy industry, particularly the steel industry, in the short-term. All that is required now is the willingness to immediate implementation.

5.8 Discussion

Implementation of sustainable and renewable energy components into any production cycle, such as direct air capture (DAC) to: a) capture off-gas carbon and b) produce biomass for the production of biogas in anaerobic digestion, carbon enrichment for plant stimulation (CEPS) (promoting growth in greenhouses for food production), anaerobic digestion (AD) to produce biogas and hydrogen, and capturing and utilising excess heat can individually make significant contributions to a higher degree of energy independence for the individual commercial entity. Figure 5-11 will provide more clarity by displaying the relevant percentage changes:

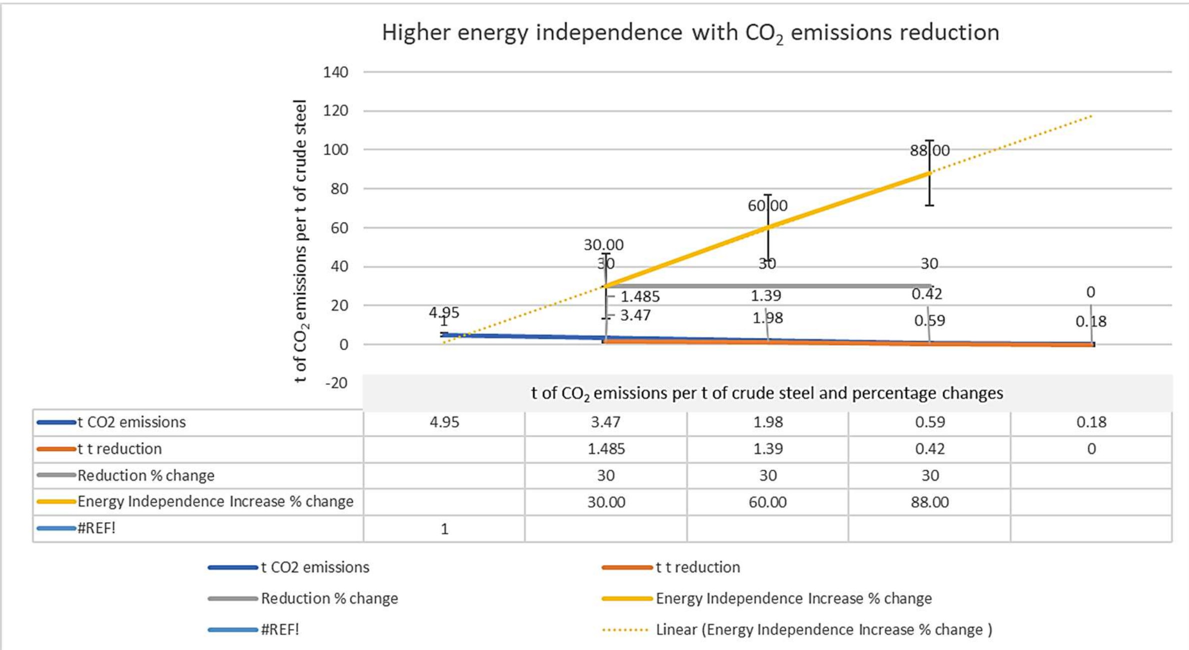


Figure 5-10: CO_2 emissions levels and reduction of the BF/BOF and BF/EAF route

The MS Excel extrapolations established how the different components of the "7 steps to net zero carbon emissions steelmaking"-strategy can be implemented and installed. Installing renewable energy technologies can not only help to reduce CO_2 emissions but will supply the production site with renewable energy, where 30% of energy does not have to be imported from third parties and paid for, bringing the reduction in CO_2 emissions down to -49%. At this point in production, where biomass has already replaced the use of coke, and renewable energy technologies (solar, solar PV, wind, hydro) have been installed, an additional 30% of energy can be saved, and thus does not have to be bought in, by using biogas, bringing the reduction in CO_2 emissions to -65.7% (Devlin and Yang, 2022). This will have been produced in the link-connected anaerobic digester, which produces biogas from connected agri-businesses. The negative percentage reduction in emissions means, in reverse, that at these points in the (steel) production process, a greater degree of energy independence can be achieved at 30%, 49% and 65.7% (Devlin and Yang, 2022; Kiessling, Darabkhani and Soliman, 2022). This implies that energy at the same percentage point levels is not required to be imported from external sources, as it is produced either on-site or link connected. Besides energy and heat saving, generating their own energy will inevitably lead to achieve a higher level of independence, at least by 30% and ideally, at 65.7%, there are savings to be had by not being forced to import and pay for energy from conventional suppliers, energy derived from renewable sources or not. We have been made painfully aware that private and business users of energy and fuel are at the mercy of corporate stakeholder interests and thus vulnerable to high price velocity. Retrofitting the existing industrial building infrastructure with renewable energy technology, with components of the "7 step to net zero carbon emissions steelmaking"-strategy, can support achieving: a) greater energy efficiency and independence, b) turbo-charge the decarbonisation of energy production, c) decarbonise steel and industrial production, and d) provide savings opportunities via excess heat recovery. Observing economic principles, it can be assumed that, overall, there is a third of cost involved, with two-thirds of savings over a 30-year-investment period. Additional, significant positive milestones can be reached, such as investment into a workforce with "green" skills, future-proofing the business against energy price hikes, besides the positive effects of greater energy independence, decarbonisation of production and rehabilitation of the natural world which has been disrupted beyond recognition by the Anthropocene. Figure 5-12 shows the current level of country policy guidance vs. actual requirements (UNEP, 2020).

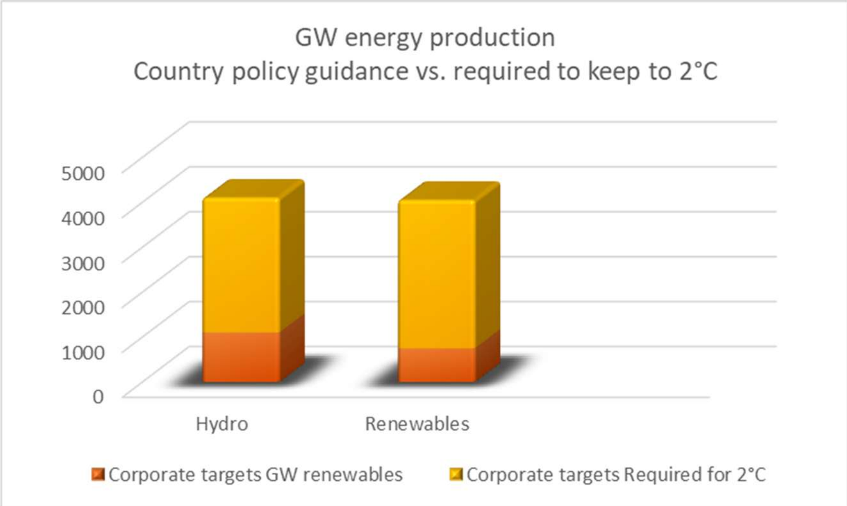


Figure 5-11: Country policy guidance versus renewables implementation required to keep the temperature rise below 2°C (Adapted from UNEP, 2020)

5.9 Conclusions

The legal landscape and country governmental guidance will have to change dramatically, in order to meet the targets, set by the Paris Agreement (UN, 2016) and COP15 (UNEP, 2022) and the dire warnings issued by the recent IPCC reports (IPCC, 2023b).

By improving their carbon capture and off-heat utilisation capabilities, and investing in renewable energy technology, businesses are:

a) supporting achieving the decarbonisation of production,
b) reaching a higher degree of energy independence,
c) achieving a higher level of asset efficiency,
d) training workforce in required 'green' skills,
e) reducing their energy costs and
f) creating a viable additional income stream for their present and future operations.

Not only will a higher degree of energy independence achieve an economic advantage in monetary terms, but any installation of renewable energy systems will also support limiting the global temperature rise to below 2°C and thus support avoiding climate disaster. The CO_2 emissions by industry sector were analysed (Chen *et al.*, 2018a; Mandova *et al.*, 2019; ONS Office for National Statistics, 2019; Jahani *et al.*, 2021) and besides the iron and steel industry, there are other industries which are CO_2 emitters, which are also generating copious amounts of off-heat, co-products and therewith resources, which could be harvested and used to power energy-dependent devices: transport, energy supply, business (incl. heavy industry), the residential sector, agriculture, and waste management.

Achieving a higher degree of energy independence is within reach of all sectors of society, made possible by technological progress and incentives and grants provided by the respective governments and countries, besides the UK. The opportunities are manifold; they merely require political willingness and implementation across all industries.

The research preceding the compilation of the current paper has provided answers which are reaching over into multiple other heavy industries, and additionally resulting in further opportunity for a range of research directions, which are listed, as follows:

1. The CO_2 captured in the iron and steel industry can be used in the building industry (concrete – Geomimetic ® process), agriculture (CEPS), food and drinks industry (CO_2 for beverages) and pharmaceutical applications.
2. Waste products from steel making, i.e. sludge and slag, can be used in infrastructural projects, such as road and bridge building.
3. Other GHG captured from post-combustion processes can be used in the chemical industry and be reused or recycled, eliminating the need for waste management.

The upgrading and retrofitting of existing and new steel plants and other industrial production sites provide an immense opportunity for further research, as there is a vast range of implementation points at active and abandoned production plants, not limited to:

1. Adding solar foil, panels, tiles and shingles to buildings and carparks structurally sound and capable of taking additional load
2. Adding a hydrogen transfer network for hydrogen direct reduction in steel production from a network of anaerobic digesters
3. Adding wind turbines on suitable on-shore brownfield sites which are not suitable for human habitation.
4. Further work is currently underway and will provide more detail on the more salient points of this paper.

Chapter 6 Process flowcharts and simulations in MS Excel, Aspen+V12.1, Simul8 and INOSIM

6.1 Introduction

Providing proof of concept and proving the viability of the proposed Bio Steel Cycle model and 7-steps-strategy is one of the elements of any desktop research, in lack of a physical testing site or laboratory. There are sophisticated software tools available, which are helpful in demonstrating processes and establishing chemical and metallurgical reaction outcomes. Although the process simulations only entail a proportion of 20% of the pentagonal research approach, they are an integral part of providing a widely accepted method of research result verification. The modeling process, such as the Bio Steel Cycle model and its implementation, follows a preconceived method, as described in the simplified diagram (Figure 6.1)

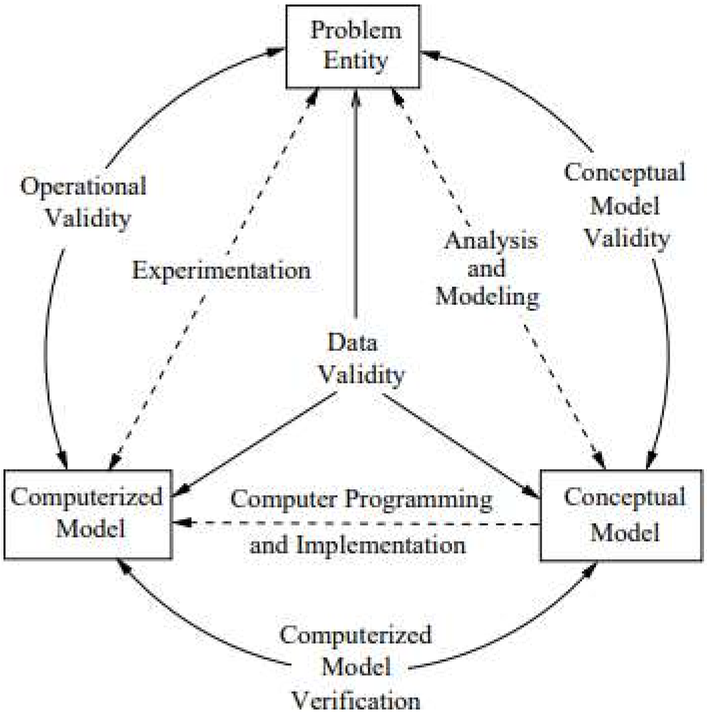


Figure 6-1: A diagram of the stages within the modeling process (Sargent, 1998)

For this purpose, and as a base to start the software simulations from, an MS Excel flowchart was constructed. This contains the quantities of material flow, which most process simulation software packages are based on, and the reaction formulae which are the conversion elements in the steelmaking process. It also provides a valuable tool to verify the results from the various simulations and subsequent reports on CO_2 emissions. The preliminary results of the literature review, statistical tests, mathematical standard calculations, MS Excel extrapolations and process simulations have been verified and validated with comparison against contemporary research, such as by data from the German government.

The German Government and their Environment Agency has issued helpful data and graphs to demonstrate the CO_2 avoided by using renewable energy technologies across the country. Special attention needs to be paid to the reduction in CO_2 emissions for electricity, as the steel manufacturing process at all stages uses a large quantity of electricity, derived from fossil fuel sources. Figure 6-2 will display a graph to this effect:

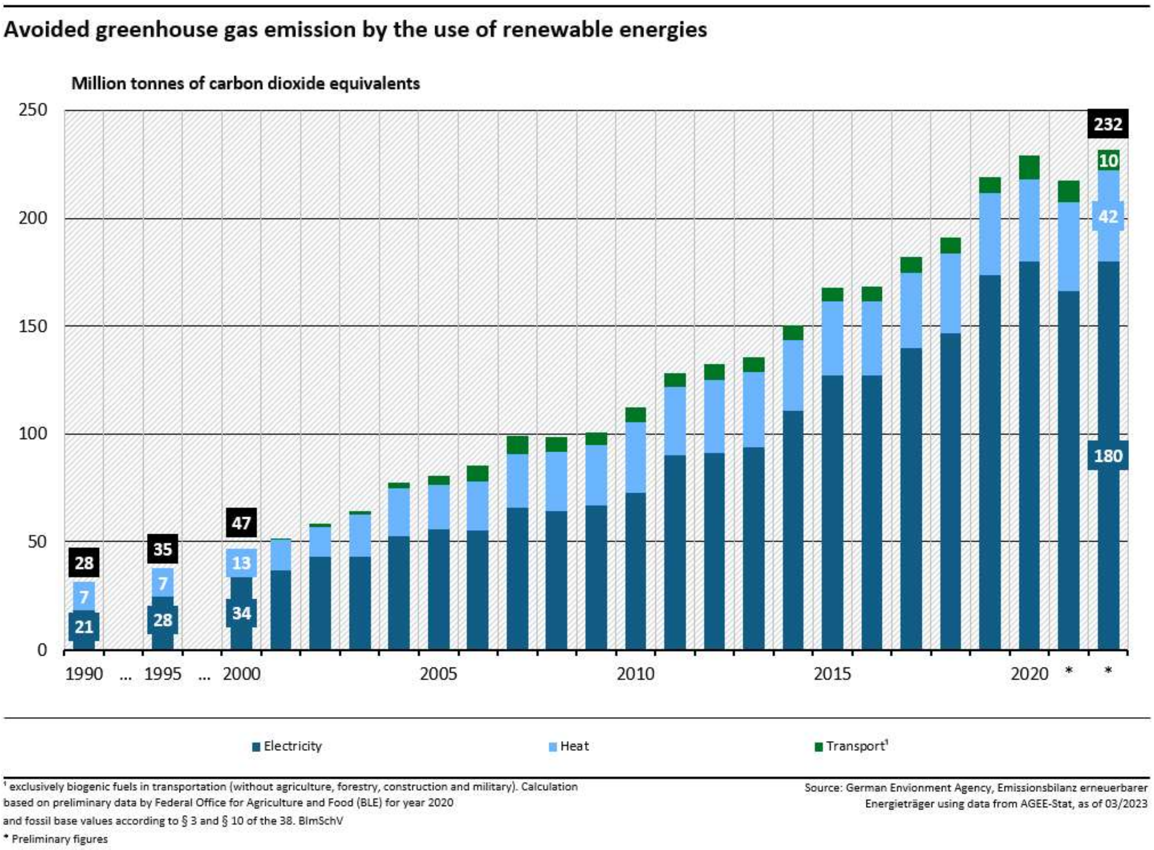


Figure 6-2: German Environment Agency Emissionsbilanz erneuerbarer Energieträger (Wilke, 2017)

The parameters for creating this graph can be found in Figure 6-3:

Hauptitel:	Vermiedene Treibhausgas-Emissionen durch die Nutzung erneuerbarer Energien
Main heading:	Avoided greenhouse gas emission by the use of renewable energies
Untertitel:	
Quelle:	Umweltbundesamt, Emissionsbilanz erneuerbarer Energieträger unter Verwendung von Daten der Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat), Stand 03/2023
Source:	German Envionment Agency, Emissionsbilanz erneuerbarer Energieträger using data from AGEE-Stat, as of 03/2023
Fußnote:	[1] ausschließlich biogene Kraftstoffe im Verkehr (ohne Land- und Forstwirtschaft, Baugewerbe sowie Militär), Berechnung basierend auf vorläufigen Daten der Bundesanstalt für Landwirtschaft und Ernährung (BLE) für das Jahr 2020
Fußnote:	und auf den fossilen Basiswerten gemäß § 3 und § 10 der 38. BImSchV
Fußnote:	* vorläufige Angaben
Footnote:	[1] exclusively biogenic fuels in transportation (without agriculture, forestry, construction and military). Calculation based on preliminary data by Federal Office for Agriculture and Food (BLE) for year 2020
	and fossil base values according to § 3 and § 10 of the 38. BImSchV
Footnote:	* Preliminary figures
Achsenbezeichnung 1:	Millionen Tonnen Kohlendioxid-Äquivalente
Name of axis 1:	Million tonnes of carbon dioxide equivalents

Figure 6-3: Parameters for the graph 6- 1 (Adapted from Wilke, 2017)

The use of renewables has increased dramatically in Germany over the last three decades. In 2022 alone, 232Mte were avoided by using renewable energy technologies, which constitutes saving more than eight times as much compared to the CO_2e emissions savings in 1990. The biggest proportion of these savings were attributed to electricity generation from renewable sources, accounting for almost 78% of the avoided emissions in 2021, whereas 18% were attributed to the heating sector and 4% came from the transport sector – using biofuels and electricity from renewables.

6.2 Process flowchart in MS Excel

In order to construct process simulations in the various software solutions, a flowchart needs to be compiled with the materials and quantities involved, including the formulae and equations which explain the chemical and metallurgical processes taking place at the different stages of the steelmaking process.

For this purpose, MS Excel was deemed to be the best suited to provide a framework for achieving this. Figure 6-4 will demonstrate the flow of material, quantities of the materials involved and results per implementation of the respective steps within the Bio Steel Cycle:

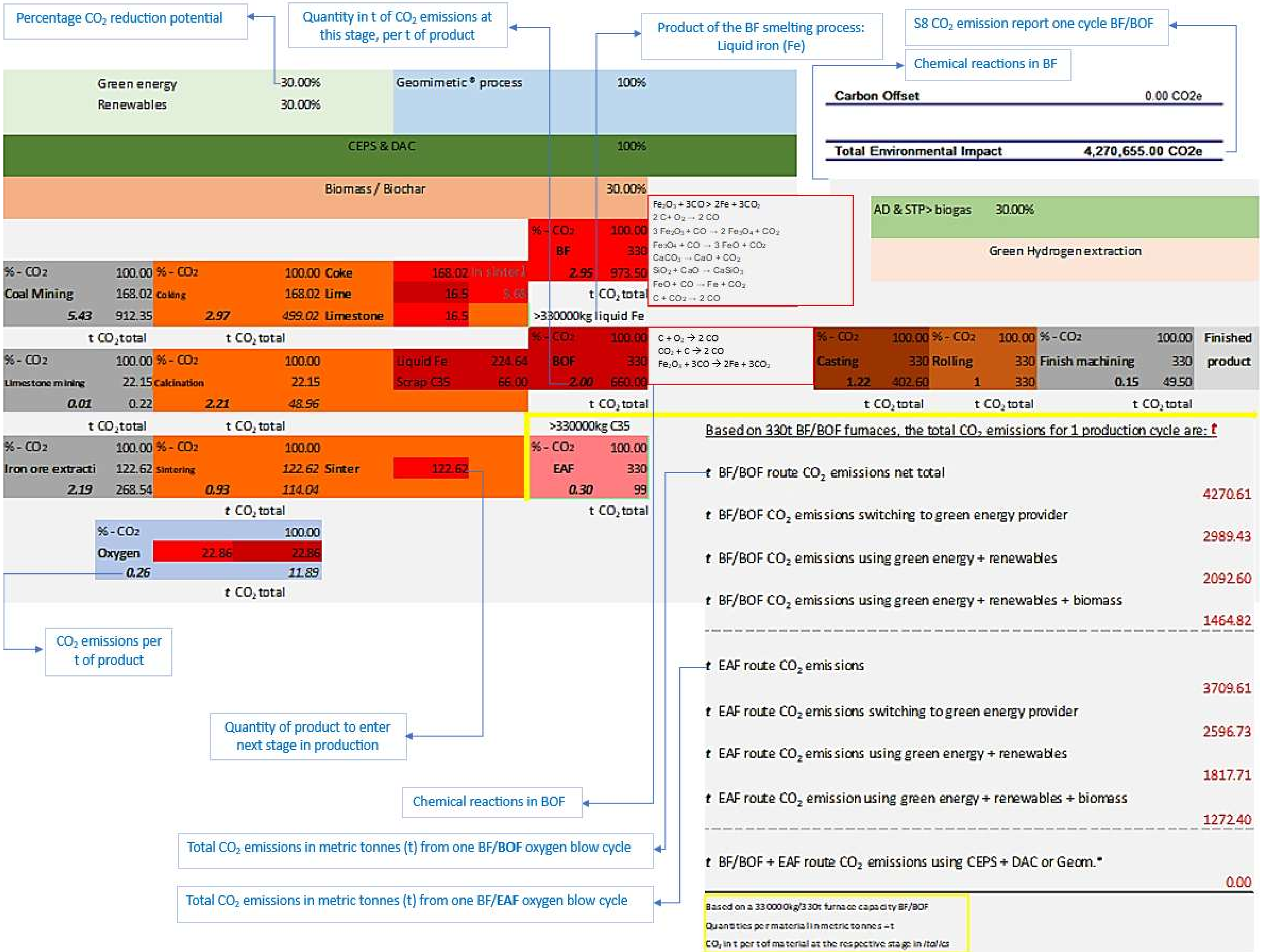


Figure 6-4: Flowchart steelmaking process with CO_2 emissions and explanations/comments

The quantities and values in Figure 6- 3 display the quantities of iron ore, limestone, lime, coke and 1000°C oxygen required to be sent to the blast furnace as the first furnace-based process. Following on, the product of the blast furnace, the liquid iron, is sent to the basic oxygen furnace, where the hot metal alongside lime, scrap steel and oxygen at 25°C is being converted to liquid steel. The results on the right-hand side of Figure 6.2.1 summarise the quantities of CO_2 emissions during the steelmaking process, including resource extraction, calcination, coking, sintering, pressurising oxygen, and through the BF/BOF-route to casting, rolling and finally, finish machining. The effects on the total emissions of all process stages leading to the production of steel have been summarised, as well as the effects of the BiSC components implementation.

The individual CO_2 emissions savings procedures have been applied with their percentage savings potential and the resulting reduced totals are shown, respectively.

6.3 Process simulations in Aspen+V12.1

A similar approach was taken to corroborate the results from the MS Excel extrapolations, the mathematical formulation and calculations, and Simul8 process by producing simulations in Aspen+V12.1. The calculations are set to work for a 330000gk/330t blast furnace, similar to the British Steel site in Scunthorpe, and for the operational year of 1 hr, to reflect the 40-minute average charge processing and discharge time. The setup parameters, as follows, in Figures 6-5, 6-6 and 6-7:

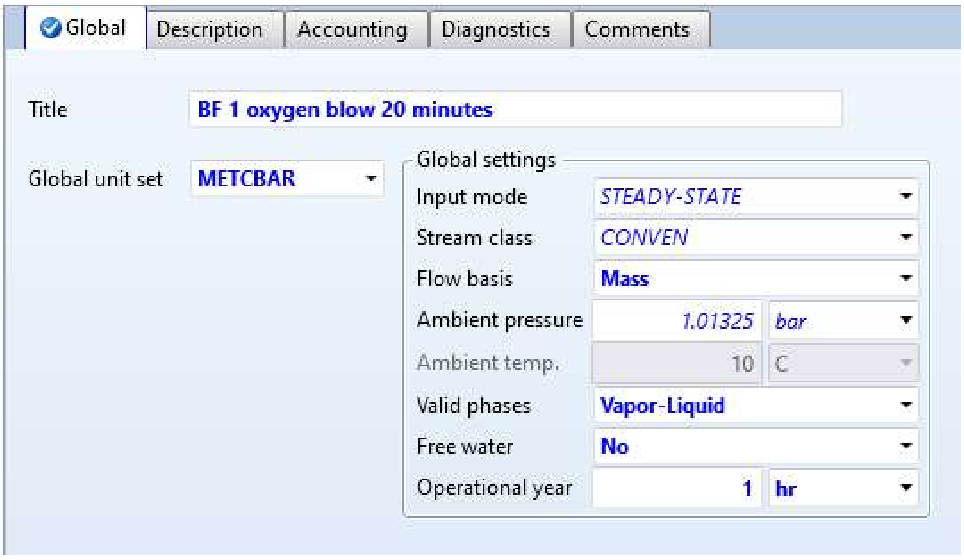


Figure 6-5: Setup parameters in Aspen

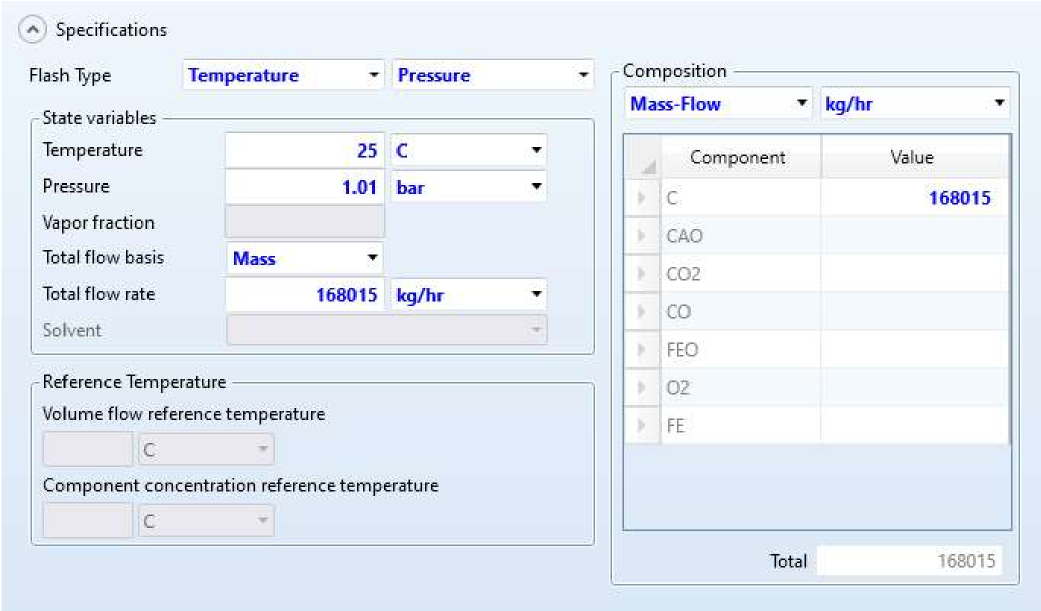


Figure 6-6: Material flow setup parameters in Aspen

with the example for coal/coke (chemical sign: C)

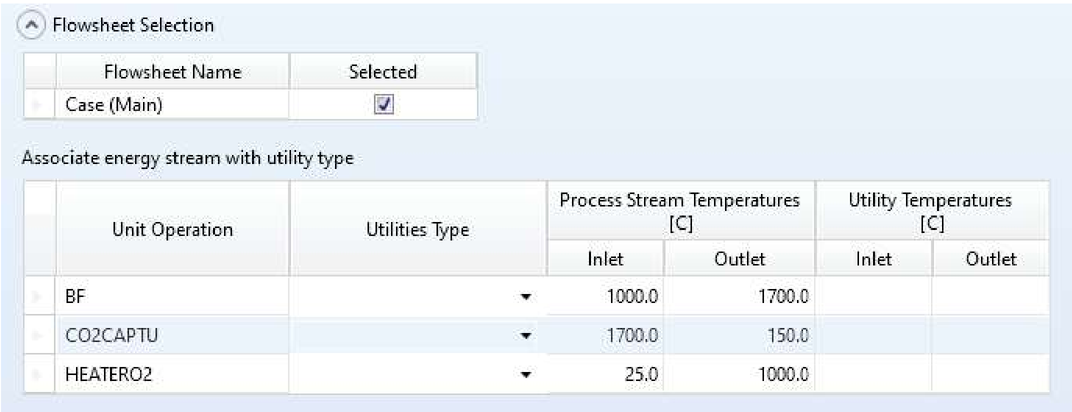


Figure 6-7: Input and outlet temperatures for the blast furnace configuration

Verifying the results of the preceding evaluations, computations and calculations, initially 977856kg of CO_2e flow for the blast furnace stage was reported by the Aspen system analysis, without any mitigating measures.

Leaning on the professional background experience in multi-metal manufacturing, it became clear very early during this research journey working with Aspen Plus and other simulation software (Simul8, Inosim), that there are limitations to what the simulation software solutions can deliver and that there are no set layouts for any production process, as every production site is different. For the development of a model suitable for decarbonisation of the steelmaking process, a basic steelmaking model (Wang *et al*., 2019) was used as a guideline. As an example: the temperatures required for making liquid iron (BF) or steel (BOF) are mainly achieved by inserting oxygen at high pressures: such as in the blast furnace, where Tuyères inject oxygen at 1000° Celsius. The reactions of the different material within the vessel upon injection of the heated oxygen under pressure are causing the temperature to rise. To achieve this in Aspen Plus, a heater requires to be switched before the inlet into the BF and BOF - which is in a production site situation mostly not the case. It became evident that, in order to implement the Bio Steel Cycle concept and strategy, the focus needed to be on material flow balance, where all input data and flow streams of material input and output, similar to Wang *et al.* (2019), would have to be installed. Ensuring material balance for the inlet and outlet streams proved to be imperative. The focus was then on the investigation of the BF/BOF outlets and results.

A reduction of ~30%, to 684499kg of CO_2e flow was reported when solar PV panels for energy generation on site were installed, as displayed in Figures 6-8 and 6-9:

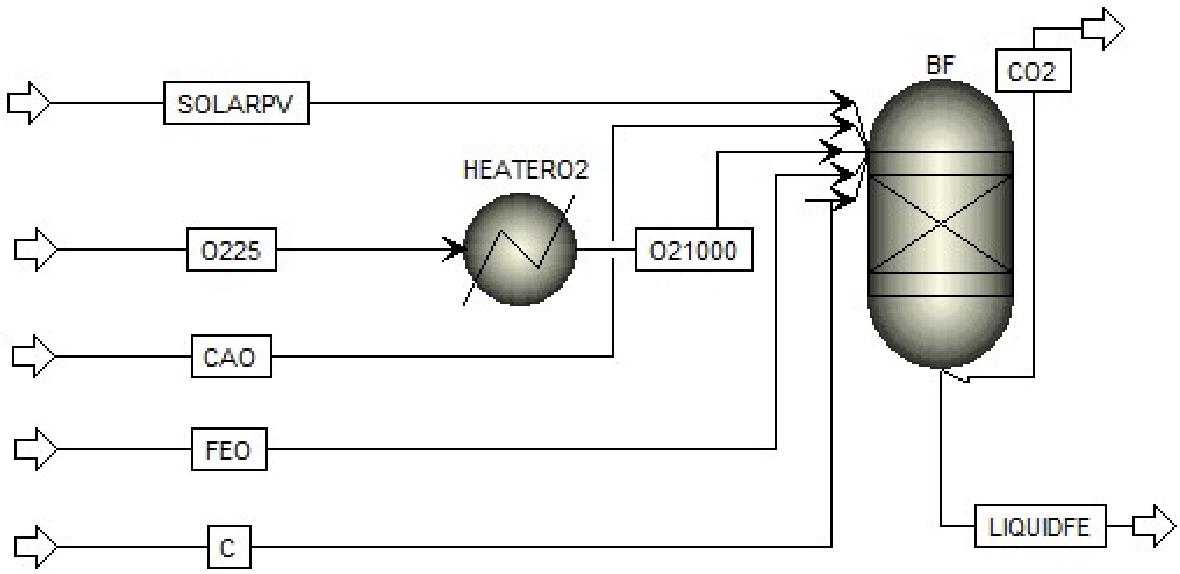


Figure 6-8: Aspen BF process with solar photovoltaic installation

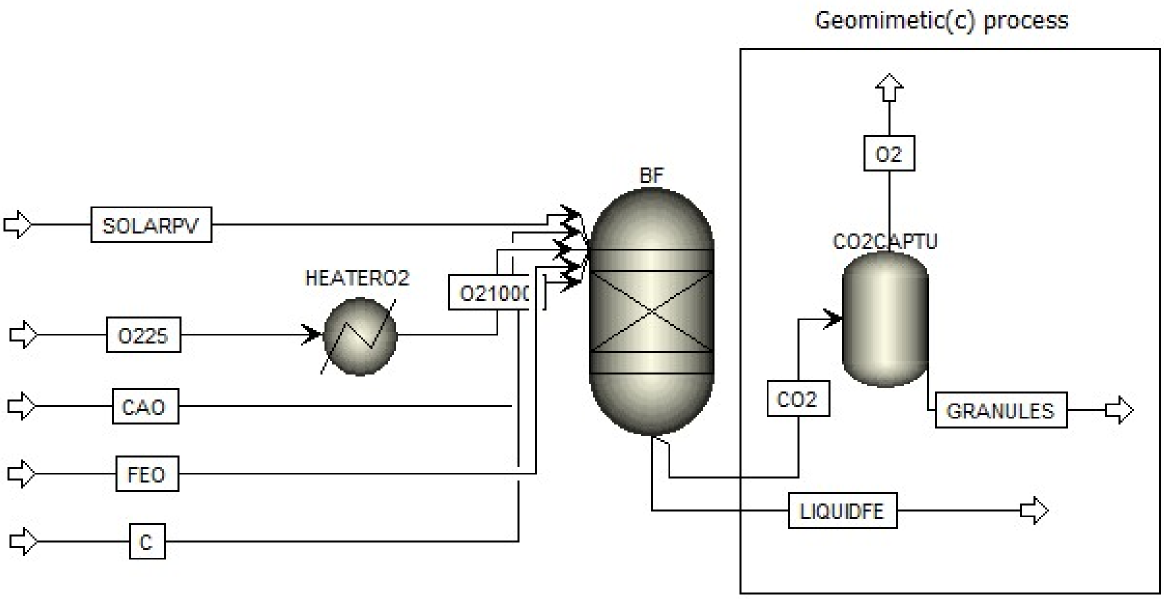


Figure 6-9: Aspen BF process with solar photovoltaic and Geomimetic© installation

Encouraged by the verification of the preliminary research results from the literature review, mathematical investigations and MS Excel analysis by the initial process simulations in Aspen, the BF/BOF configuration was compiled, as displayed in Figure 6-10:

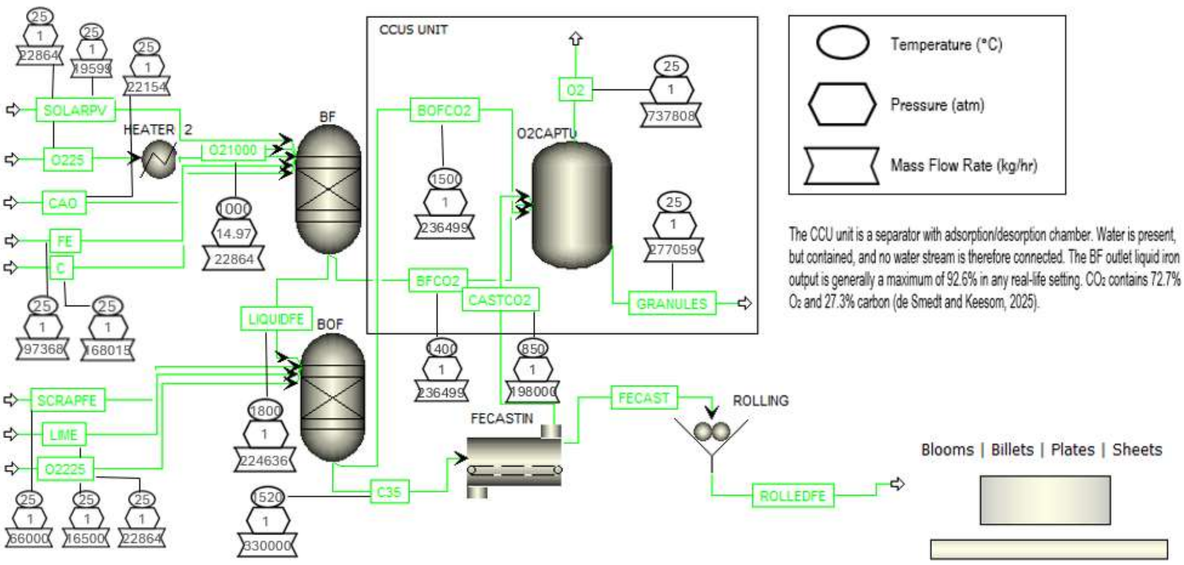


Figure 6-10: Aspen BF/BOF configuration with input data variation; including CCUS/BiSC

Again: the findings were confirmed, as Table 6-1 will demonstrate, using the quantity input data shown in table 7-3.

Table 6-1: Aspen stream flow report BF

	Units	C	CAO	FE	O21000	CO2	LIQUFE	GRANULES
Maximum Relative Error				1.1264e-16				
Cost Flow	$/hr							
− MIXED Substream								
Phase		Liquid Phase	Liquid Phase		Vapor Phase	Vapor Phase	Liquid Phase	Liquid Phase
Temperature	C	25	25	25	1000	1700	1700	150
Pressure	bar	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Molar Vapor Fraction		0	0	0.927242	1	1	0	0
Molar Liquid Fraction		1	1	0.0727585	0	0	1	1
Molar Solid Fraction		0	0	0	0	0	0	0
Mass Vapor Fraction		0	0	0.909444	1	1	0	0
Mass Liquid Fraction		1	1	0.090556	0	0	1	1
Mass Solid Fraction		0	0	0	0	0	0	0
Molar Enthalpy	cal/mol	18030.2	-67175.3	-88612	7732.46	-72499.2	-1274.32	-18210.1
Mass Enthalpy	cal/gm	1123.89	-1197.9	-1974.81	241.648	-1647.34	-22.8181	-326.071
Molar Entropy	cal/mol-K	-37.3413	-13.5786	-0.0095936	11.2238	23.3392	13.6602	-3.76466
Mass Entropy	cal/gm-K	-2.32761	-0.24214	-0.000213804	0.350756	0.530317	0.2446	-0.0674103
Molar Density	mol/cc	0.280497	0.00115284	4.41842e-05	9.53974e-06	6.1555e-06	0.12173	0.129314
Mass Density	gm/cc	4.49994	0.0646482	0.00198259	0.00030526	0.000270903	6.79823	7.2218
Enthalpy Flow	cal/sec	5.24528e+07	-7.37164e+06	-5.34121e+07	1.53474e+06	-1.0822e+08	-468418	-260.959
Average MW		16.0428	56.0774	44.8711	31.9988	44.0099	55.847	55.847
+ Mole Flows	**kmol/hr**	**10473**	**395.054**	**2169.95**	**714.527**	**5373.76**	**1323.3**	**0.0515896**
+ Mole Fractions								
+ Mass Flows	**kg/hr**	**168015**	**22153.6**	**97368**	**22864**	**236499**	**73902.1**	**2.88112**

6.4 Process simulations in Simul8

Process simulations in Simul8 and Aspen+ were used to explain the individual production process implications.

The BF/BOF route is the most widespread method of steelmaking, representing ca. 70% of current global crude steel production (Li *et al.*, 2022). The layout is displayed in Figure 6-12:

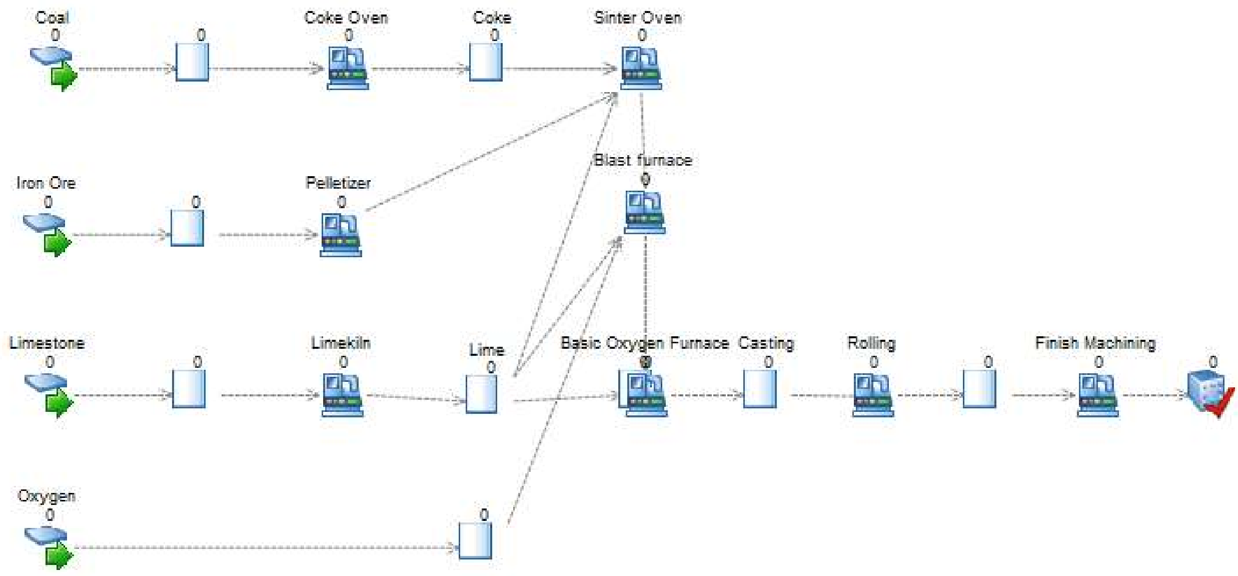


Figure 6-11: Simul8 Process simulation of the **BF/BOF** steelmaking route

It needs to be emphasised, though, that the following CO_2 emissions in metric tonnes are representing the CO_2 emissions at their respective stage, per t of product, and *not* per tonne of steel, yet. The emissions burden on each of the input streams in the simulation software systems Simul8, and Aspen+ are already set within the system parameters and therefore calculated during the process simulations, and are providing a more detailed set of data, per metric tonne of respective product produced. Additionally, in order to represent the overall mean CO_2 emissions burden in t per t of steel, the mean value of 4.95t/t cs was allocated for entering in the input stream in S8 as BF 2950kg/2.9t of CO_2 per metric tonne of liquid iron produced and BOF 2000kg/2t of CO_2 per metric tonne of steel produced.

The resulting Carbon Report has been created subsequently after operating this configuration, and presented the following statement, in Figure 6-12:

Carbon Emissions	21,000.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Basic Oxygen Furnace	2,000.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	0.00 CO2e
Total Environmental Impact	**21,000.00 CO2e**

Figure 6-12: S8 Carbon Report **BF/BOF** route operation

This was followed by the creation of a BF-EAF-process-route simulation, representing the second most-common method of steelmaking, with a share of ca. 20% of global production. Emphasis is again laid on the point that the CO_2 emissions declared are to be seen as per t of product at the respective stage. Figure 6-13 displays the configuration of the BF/EAF configuration of steelmaking, and the CO_2 report in Figure 6-14:

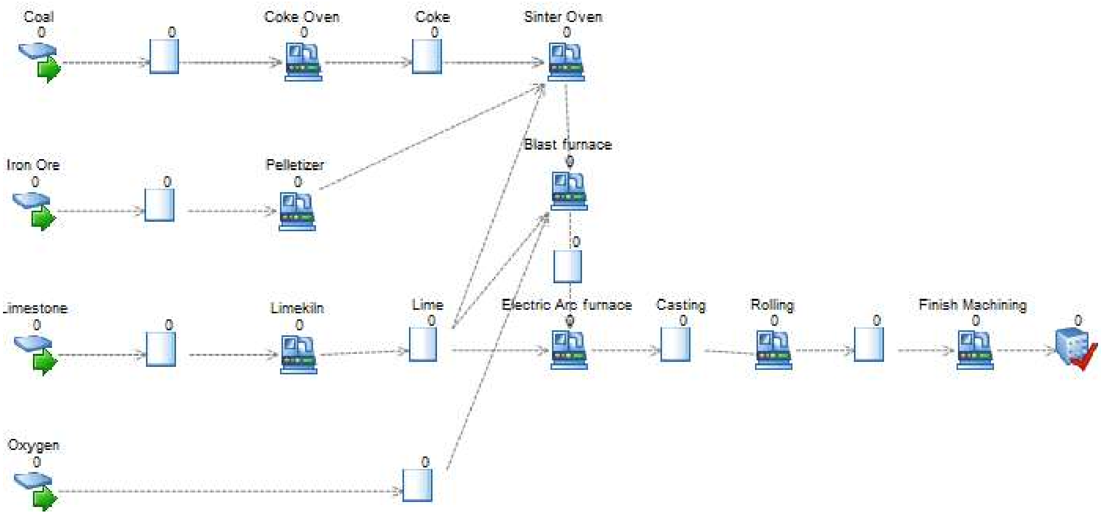


Figure 6-13: Simul8 **BF/EAF** configuration of steelmaking

Carbon Emissions	19,300.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Electric Arc Furnace	300.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	0.00 CO2e
Total Environmental Impact	**19,300.00 CO2e**

Figure 6-14: **BF/EAF** route carbon emissions report S8

Initially, and as biomass has the potential to reduce CO_2 emissions by ~30%, the usage of biomass was implemented. The carbon reports displayed in Figures 6-15 - 6-18 provide the details, in direct comparison with the MS Excel iterations, and mathematical calculations:

Carbon Emissions	21,000.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Basic Oxygen Furnace	2,000.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	7,000.00 CO2e
Total Environmental Impact	**14,000.00 CO2e**

Figure 6-15: S8 Carbon Report **BF/BOF** with usage of biomass

Carbon Emissions	19,300.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Electric Arc Furnace	300.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	6,400.00 CO2e
Total Environmental Impact	**12,900.00 CO2e**

Figure 6-16: S8 Carbon Report **BF/EAF** with usage of biomass

The Simul8 process simulations and subsequent carbon reports 6-17/18 demonstrate the effect of implementing biomass in the steelmaking process, as one of the Bio Steel Cycle components. These simulations were followed by configurations including the implementation of the Geomimetic© process, as the implementation of this process, which includes off-gas flue stack filters, makes it possible to produce steel at almost '0' CO_2 emissions – for both, the BF/BOF and BF/EAF-process-route.

Carbon Emissions	21,000.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Basic Oxygen Furnace	2,000.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	21,000.00 CO2e
Geomimetic(c)	21,000.00 CO2e
Total Environmental Impact	**0.00 CO2e**

Figure 6-17: S8 Carbon Report **BF/BOF** with the Geomimetic© process

Carbon Emissions	19,300.00 CO2e
Coal	5,430.00 CO2e
Iron Ore	2,190.00 CO2e
Limestone	35.00 CO2e
Oxygen	260.00 CO2e
Sinter Oven	930.00 CO2e
Pelletizer	35.00 CO2e
Limekiln	2,210.00 CO2e
Blast furnace	2,950.00 CO2e
Electric Arc Furnace	300.00 CO2e
Casting	1,220.00 CO2e
Rolling	1,000.00 CO2e
Finish Machining	150.00 CO2e
Coke Oven	2,590.00 CO2e
Carbon Offset	19,300.00 CO2e
Geomimetic(c)	19,300.00 CO2e
Total Environmental Impact	**0.00 CO2e**

Figure 6-18: S8 Carbon Report **BF/EAF** with the Geomimetic© process

6.5 Process simulations in INOSIM

For the process simulations in INOSIM, the same parameters as for MS Excel, Aspen and INOSIM have been applied. The results reports in Inosim were matching those produced by standard mathematical procedure, MS Excel, Aspen and Simul8. Figure 6-19 will depict an image of the INOSIM BF/BOF process simulation with CCUS and Table 6-2 the reports and results overview:

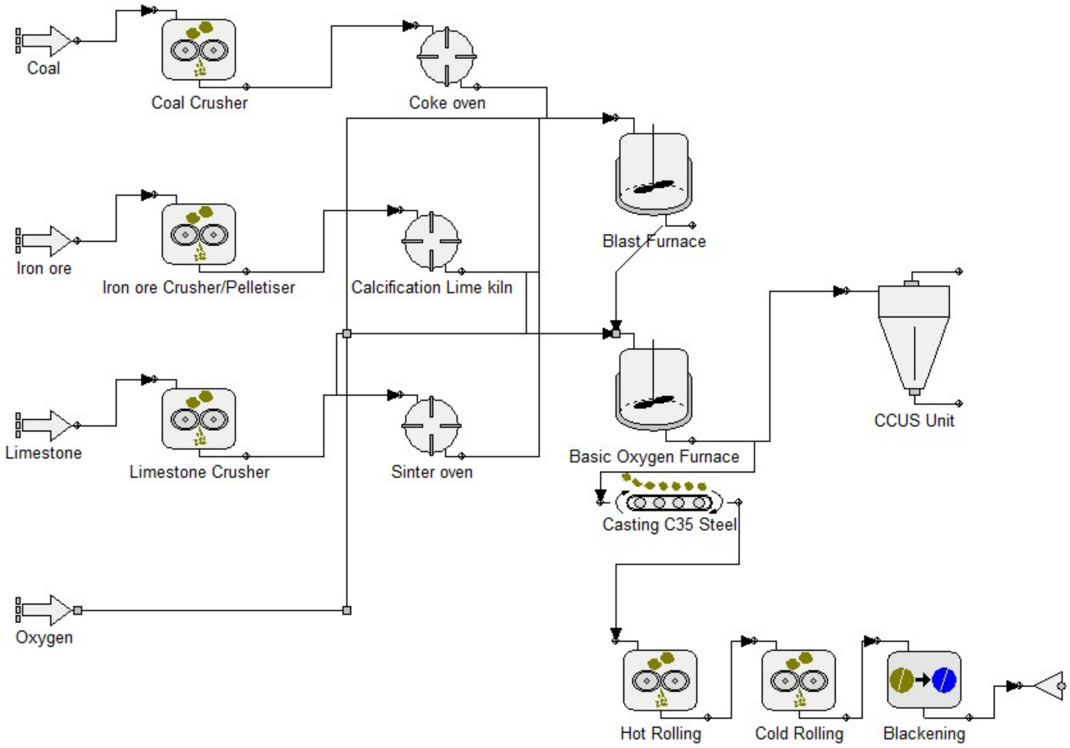


Figure 6-19: INOSIM BF/BOF standard process simulation with CCUS unit

INOSIM provides a vast range of reactors and bioengineering components, which allowed for easy integration of the innovative Bio Steel Cycle model. Components such as fermenters are provided, which have yet to be found to be included in any other process simulation software.

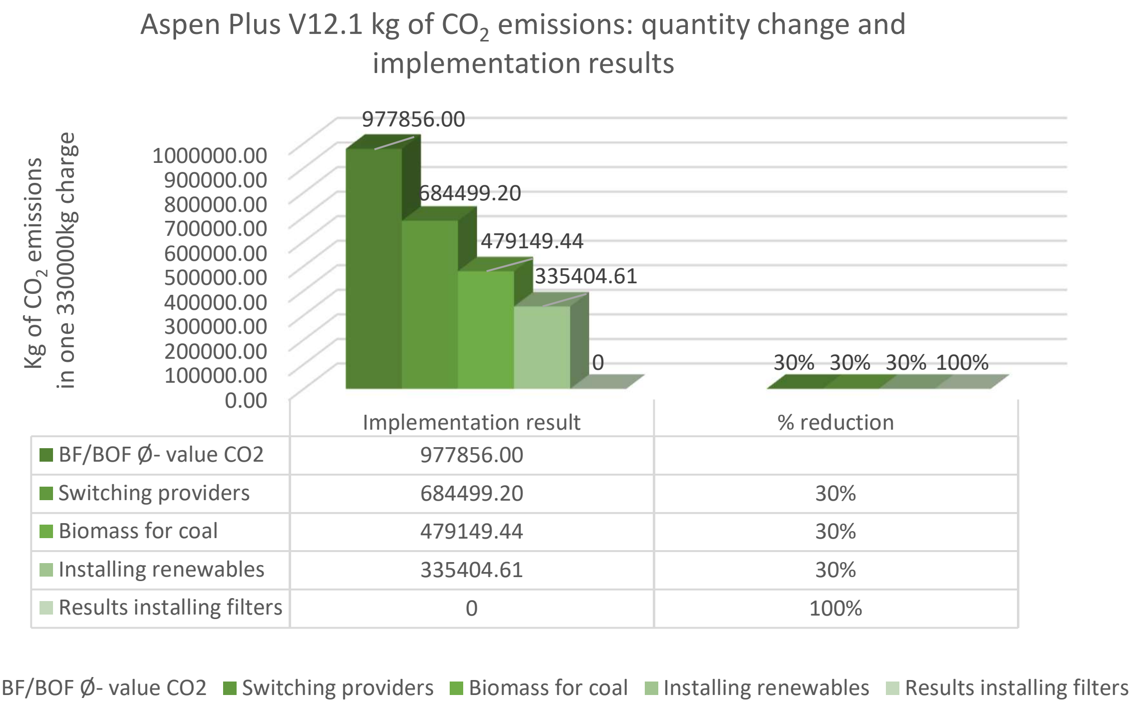
6.6 Results

As demonstrated in the following overview Table 6-2, the results from the various process simulations are shown to be similar to those in standard mathematical calculations and MS Excel verification and extrapolations. As the results from the process simulations were almost identical, the different steps achieving CO_2 emissions reduction were listed according to their savings potential.

Table 6-2: BF/BOF Process simulation reports overview

Reduction % change	Energy Independence Increase % change	Simul8 kg of CO_2 emissions reduction results	Aspen™ kg of CO_2 emissions successive change	Aspen™ kg of CO_2 emissions reduction result	INOSIM kg of CO_2 emissions reduction result
-	-	977856.00	-	977856.00	977856.00
30	30.00	684499.20	293356.80	684499.20	684499.20
30	60.00	479149.44	205349.76	479149.44	479149.44
30	88.00	335404.61	143744.83	335404.61	335404.61
		0	143744.83	0	0

Table 6-2 and Figure 6-21 provide a summary of the results reported by the process simulations in the three software applications:



	Implementation result	% reduction
BF/BOF Ø- value CO2	977856.00	
Switching providers	684499.20	30%
Biomass for coal	479149.44	30%
Installing renewables	335404.61	30%
Results installing filters	0	100%

Figure 6-20: Process and flowchart simulations results summary

For verification and validation purposes, the model process simulations and available experimental data in Simul8, Inosim and Aspen Plus were compared with peer reviewed publications of these and other process simulations in other industries (Madeddu, Baratti and Errico, 2016; Arachchige, Rasenthiran and Liyanage, 2019; Madeddu, Errico and Baratti, 2019; Madeddu *et al.*, 2020; Özge and Zeng, 2020; Ahmed, 2021; Fermeglia, 2021; Kovbasiuk *et al.*, 2021; Luderer *et al.*, 2021; Abdul Azeez *et al.*, 2023), where carbon avoidance or reduction process technologies were applied, similarly to what has been achieved during this research. The available experimental data as a result of the process simulations in Simul8, Inosim and Aspen Plus V12.1 displayed in this work align with the afore mentioned author's works (Madeddu, Baratti and Errico, 2016; Arachchige, Rasenthiran and Liyanage, 2019; Madeddu, Errico and Baratti, 2019; Madeddu *et al.*, 2020; Özge and Zeng, 2020; Ahmed, 2021; Fermeglia, 2021; Luderer *et al.*, 2021; Abdul Azeez *et al.*, 2023) and others, which will be explained in the following in more detail.

6.7 Validation and verification of the preliminary research results under application of process simulation software models

6.7.1 Introduction

First of all, it needs to be determined what process simulation model verification and validation actually means:

- Verification: the process of determining that a model implementation in a simulation software solution accurately represents the author's conceptual description of the model and the solution to the model (Sargent, 1998; Thacker *et al.*, 2004) (Aggarwal and Jalote, 2006; Zhang, Zhao and Huang, 2019; de Paula Ferreira, Armellini and De Santa-Eulalia, 2020; Zou and Zhao, 2020)
- Validation: the process of determining if a model is the accurate representation of a real-world application with regards to the intended uses of the model (Sargent, 1998; Thacker *et al.*, 2004) (Aggarwal and Jalote, 2006; Zhang, Zhao and Huang, 2019; de Paula Ferreira, Armellini and De Santa-Eulalia, 2020; Zou and Zhao, 2020).

There are three basic approaches for the determination of whether a verified simulation model is valid or invalid.

I) First of all, the model development author will conduct verification and validation during the model development process. It needs to be emphasised that this is a subjective decision based on the results of the various reports as a result of running this research project's process simulation models, statistical tests and mathematical evaluations conducted as a phase of the model development process.

II) Secondly, during IV&V (independent verification and validation) an independent third party decides whether the model can be considered valid. This procedure is usually used for large cost projects, where the credibility is of paramount importance in relation to return on investment (ROI).

III) The third approach for determining validity of a model is to use a range of scoring systems. Scores or weights are determined subjectively when carrying out the different aspects of the validation process and then combined to establish first a category score and then an overall score for the simulation model. Validity of a simulation model is considered established if the overall and category scores are greater than a random passing score. It needs to be emphasised that this approach is infrequently used in practice, as the determination of the weights and scores is highly subjective.

This work as part of the PhD research project was entirely self-funded, and the first and second method were chosen for the verification and validation of the developed model and process simulations using the three different software packages (Madeddu, Baratti and Errico, 2016; Madeddu, Errico and Baratti, 2019; Madeddu *et al.*, 2020; Özge and Zeng, 2020; Fermeglia, 2021; Luderer *et al.*, 2021).

6.7.2 Verification of process simulations

Model verification via static and dynamic analysis are the two main methods used in process simulation model testing (Aggarwal and Jalote, 2006; Zhang, Zhao and Huang, 2019; de Paula Ferreira, Armellini and De Santa-Eulalia, 2020; Zou and Zhao, 2020). During verification via static testing the computer program used to create the computerised model is analysed for correctness, which in this case the settings were read against existing industry standards, such as ISO (International Organization for Standardization) and investigated whether the model structure and output represents the author's process simulation model layout. Also, using methods such as correctness proofs (in this case: runtime reports output observed to be without error or fault messages), structure-walk-through (in this case: checking against gathered data and literature against the input parameters), and examining the structure properties of the program (in this case: checking the existing program settings and finding that i.e. Aspen+V12.1 in 2023 still works with the 2009 US CO_2 emission data at the time of thesis submission, whereas Inosim and Simul8 are operating with current data) (Sargent, 1998; Thacker *et al.*, 2004) (Aggarwal and Jalote, 2006; Zhang, Zhao and Huang, 2019; de Paula Ferreira, Armellini and De Santa-Eulalia, 2020; Zou and Zhao, 2020). Dynamic testing of the process simulation software model involves execution of the model under different stresses (i.e. extreme condition test, Table 7-3). The subsequent output is then used to determine if the computer program, the process simulation program and its implementations in line with the model structure are correct (Aggarwal and Jalote, 2006; Zhang, Zhao and Huang, 2019; de Paula Ferreira, Armellini and De Santa-Eulalia, 2020; Zou and Zhao, 2020).

This involves both the values observed during the program execution and the final report output. In dynamic testing, three different strategies are commonly used:

- bottom-up testing (initially testing the subcomponents (sub-models) and then the complete model;
- top-down testing (testing programming stubs (sets of data) for each of the subcomponents and then testing the sub models;
- mixed testing (a combination of bottom-up and top-down testing (Caspari *et al.*, 2020)

The methods commonly used in dynamic testing are traces, investigations of input-output relations using different validation techniques, internal consistency checks, and reprogramming critical components to determine if the same results are obtained; in this case, the integrated RGIBBS reactors were set at different temperatures, material quantities and CO_2 per t of throughput. If there are a large number of variables, one might aggregate some of the variables to reduce the number of tests needed or use certain types of design of experiments (Kleijnen, 1997), e.g. use factor screening experiments to identify the key variables in order to reduce the number of experimental conditions that need to be tested. It is necessary to be aware while checking the correctness of the computer program and its implementation.

6.7.3 Validation of simulation models

Moreover, the validation of all three software-based process simulation models and extrapolations in MS Excel follow a range of validation techniques and tests (Sargent, 1998, 2020; Thacker *et al.*, 2004). These were used objectively by using statistical test methods, such as the t-test (section 7.4), or standard mathematical procedures (section 7.2), the hypothesis tests (section 7.4), and facilitating confidence intervals. As a combination of these techniques was being used, it was paramount to choose the most suitable for this project. The models in the different software solutions and the experimental data have been verified and validated using statistical tests, mathematical calculations and existing verified and validated models, as well as having been compared against each other. For the purpose of providing proof of replicability, verifiability, and therefore validity of the reported results (Sargent, 1998, 2020;

Lavery *et al.*, 2020), the same input data set was used for the purpose of compiling the process simulation in three different sets of simulation software packages. Calculations and process simulations were based on a sample plant with 330 metric tonnes capacity, similar to British Steel's Scunthorpe plant.

Several publications have been identified as scientific benchmark publications for the steel industry, using the three process simulation software applications, as follows in Table 6-3:

Table 6-3: Benchmark publications

SOFTWARE	TITLE BENCHMARK PUBLICATION	REFERENCE
ASPEN	Eco-Techno-Economic Analysis of steel manufacturing off-gas valorisation	Deng, 2023
	Benchmarking of developed steelmaking chain models	Matino *et al.*, 2023
	Carbon Dioxide Capture in the iron and steel industry: Thermo-dynamic analysis..	Mio *et al.*, 2023
SIMUL8	DISCRETE EVENT SIMULATION – PRODUCTION MODEL IN SIMUL8	Fousek, Kuncova and Fábry, 2017
	Simulation of a Real Life Problem in Flexible Manufacturing System without Breakdown and Having Alternate Machines Using SIMUL8	Debta, Mishra and Mishra, 2017
INOSIM	EmKus: Process Simulation for steel and iron industries	Inosim, 2025
	The Bio Steel Cycle: 7 Steps to Net-Zero Emissions Steel Production	Kiessling, Darabkhani and Soliman, 2022

Although the same data has been used for each application, interestingly, every simulation software resulted in different, but similar, reported results, with the same parameters and material flow quantities applied. The same quantities and values were applied, specifically the CO_2 emissions as this was tested for, were quite close. The fluctuations can largely be attributed to the different functionalities of the process simulation software packages and what different process parameters these are operating with. Table 7-3 displays the individual values entered into the three simulation software solutions, and table 6-4 (below) displays the technique, description of process and the respective software used. It needs to be emphasised, though, that mostly the process simulation layout and some simulation parameters could be validated against, as most publications do not state their input for establishing material balance and mass flow. Table 6-5 describes the verification and validation protocol, and validation of the various process simulations, resulting experimental data, and the BiSC principle of carbon emissions reduction using various standard mathematical methods, software and machine algorithms .

For detailed validation, the software input data form the current work was additionally validated against work stating the actual parameters, mass balance date, information on operational pressure and temperature and data on CO_2 emissions.

Table 6-4: Verification and validation protocol

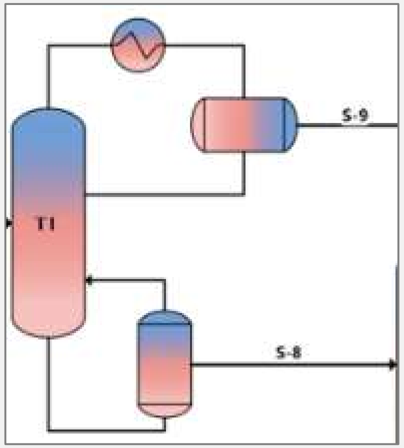
Verification and Validation Techniques	Description	Applied, verified and deemed valid
		Simul8, Inosim. Aspen+V12.1
Animation	The model's operational behaviour during a test run through the steelmaking process is depicted graphically. The results are declaring as the simulation moves through time during the production process (sections 6.3, 6.4 and 6.5). The results in the different animated software solutions were compared and found to corroborate the research findings.	✓
Comparison to other models	The output (reports) of the models as they move through time are being compared to other valid models (sections 6). The simple models of this research were compared to known results of analytic modes within the three used software packages and were compared with similar, previously verified and validated simulation models (He *et al.*, 2024; Hu, Wang and Fang, 2023; Xin *et al.*, 2020; Özge and Zeng, 2020; Abdul Azeez *et al.*, 2023; Madeddu *et al.*, 2020; Ahmed, 2021; Zhao *et al.*, 2021; Liu *et al.*, 2024; Michailos and Gibbins, 2022; Mio *et al.*, 2023; Matino *et al*., 2023; Deng, 2023). The results in the different software solutions were compared to other models and were found to corroborate the research findings.	✓
Degenerate test	Degeneracy of the model behaviour was tested against a selection of values (input/output parameters: Tables 7-1 and 7-4 and section 6.7; data as basis for figures 2-6 and 3-3). I.e.: Does the average emission quantity increase over time with increased throughput (material)? The degenerate test established a congruent behaviour upon increase and decrease of material flow.	✓
Event validity	The stages of the BiSC steelmaking process (figures 2-6 and 3-3) within the models were compared to existing steelmaking models in Aspen (various versions) and others to compare if they were similar (He *et al.*, 2024; Hu, Wang and Fang, 2023; Xin *et al.*, 2020; Özge and Zeng,	✓

	2020; Abdul Azeez *et al.*, 2023; Madeddu *et al.*, 2020; Ahmed, 2021; Zhao *et al.*, 2021; Liu *et al.*, 2024; Michailos and Gibbins, 2022; Mio *et al.*, 2023; Matino *et al*., 2023; Deng, 2023). The similarity between the compared models was deemed sufficient to arrive at event validity.	
Extreme condition test	The model output (report; chapters 6 and 7) should plausibly show significant differences under exposure to extreme conditions, such as input (i.e. iron ore, lime, coal, oxygen, electricity) inventory set at '0' should display carbon emissions at '0' (data from figures 2-6 and 3-3; sections 6.3, 6.4, and 6.5; tables 7-1 and 7-4). Extreme condition testing was carried out in all three software solutions, in application of all possible scenarios, reducing the material flow by 30% step changes, in cascade, to '0'. Biomass, renewables, biogas, carbon capture with flue stack filters. The differences in material flow showed significant congruent differences.	✓
Face validity	Discussion with and receiving expert confirmation and advice who are proficient in the application of the software packages, whether they think the model and its behaviour is reasonable and within known parameters, and to determine whether the logic in the conceptual model with respect to input-output relationships are reasonable. The process simulation experts at Simul8, Aspen and Inosim confirmed the face validity of the simulations.	✓
Fixed values	Varying set values (constants) are utilised in a variety of model input and internal parameters (Tables 7-1 and 7-4). These were mathematically checked against calculations provided by the individual system (Section 6.3, 6.4 and 6.5). And for validity, replicability and verification purposes, the same material flow values were applied throughout all applications.	✓
Historical methods	It is accepted that the three historical methods are described as <u>1) rationalism</u> <u>2) empiricism and</u> <u>3) positive economics.</u> Chapters 1-9; specifically chapters 3,4 and 7; sections 6.3-7; Tables 7-1 and 7-4; provide images, tables and workings to the three methods applied. With applied <u>rationalism</u> it is	✓

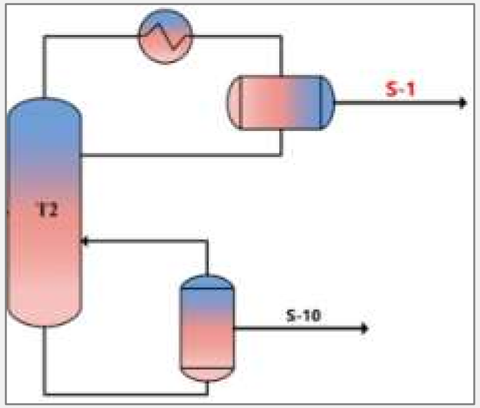
	accepted that everyone knows that the underlying assumptions of a model are true. The author displayed all entries made with description of the values and components entered into all software packages, so all audiences would be in a position to know the underlying model assumptions. With the application of empiricism, it is assumed that every parameter has been empirically validated. Every value and figure used has been referenced and researched for evidence as to their correctness, applicability and validity. Positive economics tests were carried out against the models' ability to predict future outcomes, testing causal relationships and applied mechanisms. The results confirmed the models' validity.	
Internal validity	A range of repetitions (simulation model runs) of stochastic (technical) process simulation models were carried out to establish the variability of the models under investigation (Chapters 1-9; tables 7-1 and 7-4; underlying data for figures 2-6 and 3-3). The consistency in the levels of carbon emissions, reported from all three systems (chapters 6 and 7), proved the models' validity.	✓
Multistage validation	Model validation method which combines historical methods (rationalism, empiricism and positive economics) with three steps: 1) Developing the model parameters based on theory, general knowledge, observations, and operational (stochastic/technical) function. 2) Testing the model's assumptions against empirical data. 3) Comparing the model's input-output results with existing, real-world systems. This has been successfully carried out and comparison with systems such as British Steel in Scunthorpe (Page 3 of the full accounts as of 2023, for 2021 (British Steel, 2021) have provided a positive validation result for all three simulation systems.	✓
Operational graphics	Observation of performance measures as the model moves through time (chapters 3 and 4; sections 6.3-5), i.e. the amount of material in the queue-point and different components (such as coal coking, blast furnace, basic oxygen furnace)(Table 7-3) at the different production stages (figures 2-6 and 3-3). Evidence of the models' validity was provided by the observation of dynamic (time-related) system behaviours of performance indicators shown as the simulation models moved through time, in the three software solutions (chapters 6 and 7).	✓

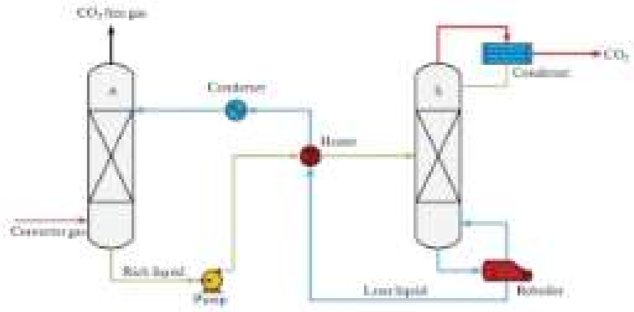
Parameter variability-sensitivity analysis	Similar to the extreme condition test, the model parameters were observed as to the changes of the input-output parameters and their effect upon the models' behaviour (chapters 6 and 7).	✓
Predictive validation	The created initial flowchart models (figures 2-6 and 3-3) as basis for the simulations in the three software applications were utilised to forecast the systems' behaviour, and the models' forecasts compared for similarity. Flowcharts were created in MS Word, then filled with data in MS Excel and the extrapolated calculations in MS Excel were used for input-output parameter setting in the process software simulation models.	✓
Traces	The behaviour of different parameters (set quantities of iron ore, limestone, oxygen, coal, liquid iron, steel) were traced during their journey through the process simulation models in the three applications and it was found that the models' logic was correct. The required accuracy was ascertained.	✓
Turing tests	In adaptation of the Turing test method (Oppy and Dowe, 2021), people sufficiently knowledgeable about the three simulation software solutions were asked if they are able to discriminate between their system and the newly created model behaviours and outputs and responded in the affirmative. They commented on the fact that there is a positive response of the emissions levels, and the models were deemed correctly displayed in relation to input-output (tables 7-1 and 7-4). Correct display of the carbon emissions reports was confirmed, therefore validating the models accordingly.	✓

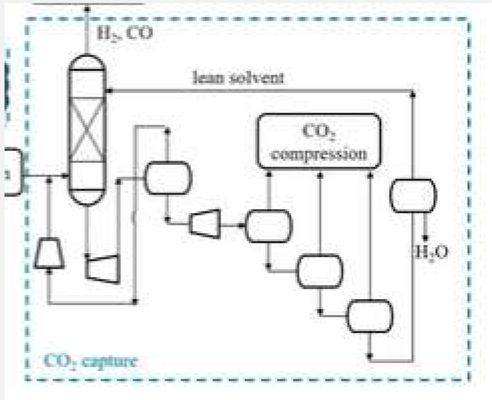
Table 6-5: Validation of the various process simulations, resulting experimental data, and the BiSC principle of carbon emissions reduction using various standard mathematical methods, software and machine algorithms

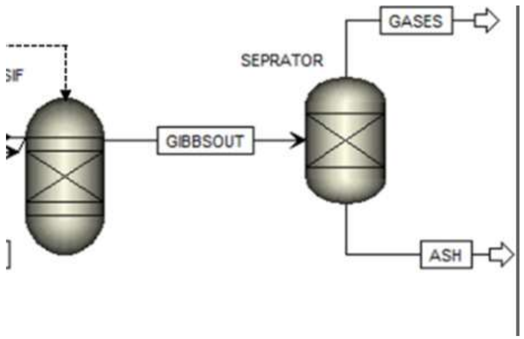
No.	***Author***	***Title***	***Description***	***Validation and similarity***	***Text, figures and tables***
1	(He *et al.*, 2024)	Vinyl Chloride Distillation Process Simulation Optimisation Evaluation	This research used Aspen Plus to optimize the vinyl chloride distillation process, aiming to reduce energy consumption and thus CO_2 emissions. The study employed the non-dominated sorting genetic algorithm III (NSGA-III) to optimise key parameters and improve process safety.	A precedent providing validation of the author's work via comparison of the CO_2 capture process simulations using Aspen Plus. All three studies and the author's research aim to reduce CO_2 emissions in their respective fields, emphasising the importance of sustainable practices. Each study highlights the need for improving energy efficiency to achieve their goals, whether through process optimisation, renewable energy integration, or innovative (production process) technologies. The overarching theme of sustainability is present in all three studies, promoting practices that reduce environmental impact and enhance resource efficiency. Advanced technologies and methodologies are employed in all studies to achieve their objectives, from carbon capture and hydrogen utilisation to optimisation algorithms and risk analysis. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's	"…Based on the actual operation of the vinyl chloride distillation process in enterprises, this research employs the Non-dominated Sorting Genetic Algorithm III (NSGA-III) to optimize key parameters of the distillation operation, aiming to achieve multiple objectives such as improving product quality, reducing energy consumption, decreasing CO_2 emissions, and enhancing process safety. . ..." "..achieve multiple objectives such as improving product quality, reducing energy consumption, decreasing CO_2 emissions, and enhancing process safety.." ".. The results highlight that the optimized schemes significantly decreased CO_2 emissions compared to the original design.." 

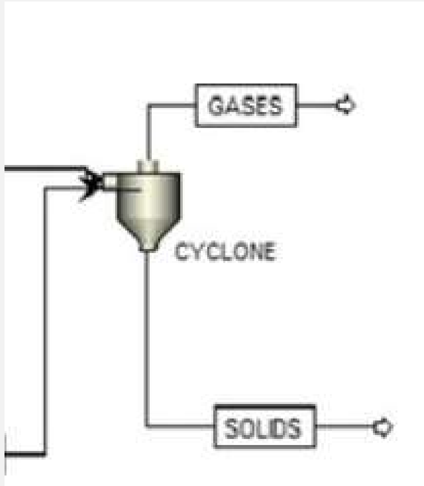
conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.



2	(Hu, Wang and Fang, 2023)	Simulation and Analysis of CO_2 Capturing from Converter Gas Using Monoethanolamine	This study used Aspen Plus to simulate a post-combustion capture process for CO_2 from converter gas in the steel industry. The results showed that increasing the depletion flow rate, temperature, and MEA concentration can improve the CO_2 capture rate.	A precedent providing validation of the author's work via comparison of the CO_2 capture process simulation using Aspen Plus and the ELECNRTL thermodynamic model, similar to the author's various process simulations. This study carried out analysis of absorption and desorption performance of MEA on converter gas, which is in line with the author's BiSC component CEPS. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	"… Increasing the depletion flow rate, temperature, and MEA concentration can help to improve the CO_2 capture rate; the feed position and desorption pressure affect the CO_2 desorption effect, and the best desorption effect is achieved when the feed position is the second tray, and the desorption tower pressure is 1.9 bar. The results of the study can provide a new idea for CO_2 capture at the end of converter steelmaking, …" 
3	(Xin *et al.*, 2020)	Process Simulation and Economic Analysis of Pre-combustion CO_2 Capture With Deep Eutectic Solvents	This paper developed an Aspen Plus rate-based absorber model to simulate CO_2 capture from a coal gasification combined cycle power plant. The study compared different mass transfer correlations and evaluated the economic feasibility of using deep	A precedent providing validation of the author's work via comparison of the CO_2 capture process simulation using Aspen Plus. All studies either directly use or imply the use of advanced simulation tools like Aspen Plus for modeling complex processes. Both the Bio Steel Cycle and the Deep Eutectic Solvents study focus on carbon capture technologies, and a variety	"…To incorporate CO_2 capture, the IGCC plant design entails two additional subsystems. … The first additional system is a two-stage WGS reaction unit (including a high-temperature reactor and a low temperature reactor) located downstream of the gasifier quench chamber. The second sub-system is the CO_2 capture unit, which is a commercial physical absorption process, similar to the Selexol process used for sulphur (H_2S) removal in plants without CCS…"

	eutectic solvents for CO_2 separation.	of simulation models are used for designing and optimising these systems with the aim to maximise CO_2 capture efficiency. Each study takes a slightly different approach but emphasises that improving energy efficiency and process simulations were used to identify opportunities for energy savings and to optimise operating conditions. Simulation tools were also used not only to optimise processes, but also to assess their economic and environmental impacts. This helps in making informed decisions that balance cost and sustainability. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	

4	(Özge and Zeng, 2020)	Challenges and opportunities of modeling biomass gasification in Aspen Plus: A review	This review focuses on recent developments and studies on modeling biomass gasification in Aspen Plus including key aspects such as tar formation and model validation. Accordingly, challenges in modeling due to specific assumptions and limitations will be highlighted to provide a useful basis for researchers and end-users for further process modeling of biomass gasification in Aspen Plus.	A precedent providing validation of the author's work via comparison of the CO_2 capture process simulation using Aspen Plus. This review focuses on recent developments and studies modeling biomass gasification in Aspen Plus, including key aspects such as tar formation and model validation. While the review does not provide specific carbon emissions percentage reductions, it highlights the potential of biomass gasification to significantly reduce CO_2 emissions by converting biomass into cleaner energy sources, which is also a component of the Bio Steel Cycle. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	

5	(Abdul Azeez *et al.*, 2023)	Aspen Plus Simulation of Biomass Gasification: a Comprehensive Model Incorporating Reaction Kinetics, Hydrodynamics and Tar Production	Process simulation and analysis of fluidized bed gasification using Aspen Plus software are considered in this study. Among the three Aspen Plus models developed in the present study, model 1 and model 2 are developed based on equilibrium and kinetic approach. Reaction kinetics, gasifier geometry and bed hydrodynamics are considered in model 3.	A precedent providing validation of the author's work via comparison of the CO_2 capture process simulation using Aspen Plus. This study focuses on biomass gasification as a method to reduce CO_2 emissions and emphasises the role of biomass as a sustainable energy source to reduce greenhouse gas emissions, which is a key component of the BiSC model and strategy. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	
6	(Madeddu *et al.*, 2020)	The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)	This work presents the results from a comprehensive bottom-up analysis of the energy use in 11 industrial sectors (accounting for 92% of Europe's industry CO_2 emissions) and estimate the technological potential for industry electrification in three stages.	A precedent providing validation of the author's work via using a variety of calculations of the CO_2 capture process. The study estimates that direct electrification of heat supply could cut CO_2 emissions by 78%, almost entirely abating energy-related CO_2 emissions. The work also covers eleven industrial sectors, accounting for 92% of Europe's industry CO_2 emissions. It was	"…CO_2 reductions for diverse industrial processes are unknown."…". 78% of the energy demand is electrifiable with technologies that are already established, while 99% electrification can be achieved with the addition of technologies currently under development. Such a deep electrification reduces CO_2 emissions already based on the carbon intensity of today's electricity (~300 g CO_2/kWhel). With an increasing decarbonisation of the power sector (IEA: 12 gCO_2/kWhel in 2050), electrification could cut CO_2 emissions by 78%, and almost entirely abate the energy-related CO_2 emissions…"

found that at least 78% of the energy demand is electrifiable with technologies that are already established, and a 99% electrification can be achieved with the addition of technologies currently under development and at TRL 6-7. With an increasing decarbonization of the power sector (projected to be 12 g CO_2/kWh_{el} in 2050), electrification could significantly reduce CO_2 emissions: deep electrification would reduce the industry bottleneck to only residual process emissions. The study underscores the significant potential of direct electrification (power-to-heat) in reducing CO_2 emissions across European industries, and by leveraging established and developing technologies, industries can achieve substantial emissions reductions, which could be contributing to achieving the EU's climate neutrality goals. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon

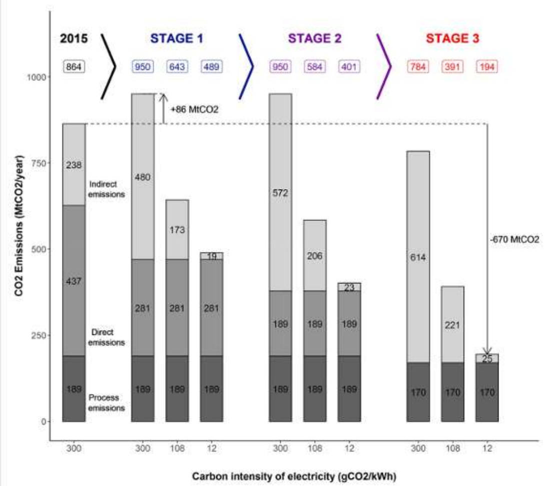
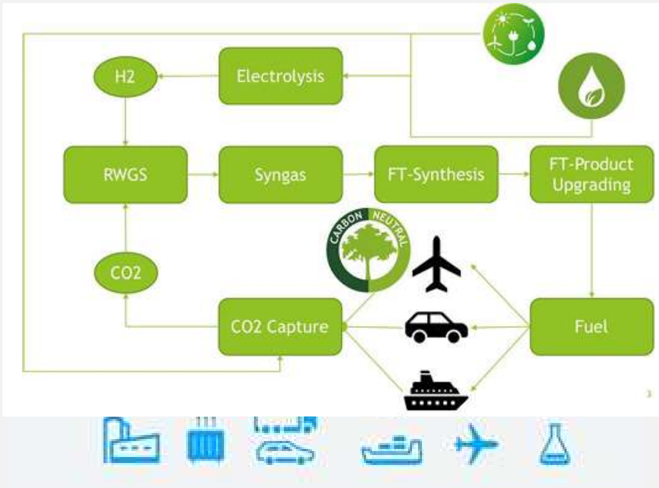


Figure 3. CO_2 reduction potential of industry electrification in 2015 under St1, St2, St3, calculated at the following carbon intensities of electricity: 300, 108 and 12 $gCO_2\ kWh_{el}^{-1}$. See also supplementary figure A.8 for a variant of figure 3 without process emissions.

				emissions and promoting sustainable practices.	
7	(Ahmed, 2021)	Power-to-X: Modeling of Fischer-Tropsch synthesis in Aspen Plus	In this work, first, a summary of some PtX technologies is given, where their contribution in defossilising the energy sector is investigated. Then, a techno-economic analysis of carbon-neutral FT synthesis is conducted, where Aspen Plus is used to model the process with having hydrogen and carbon dioxide as feedstock.	A precedent providing validation of the author's work via comparison of experimental data results and simulation of the CO_2 capture process using Aspen Plus. All three studies focus on significant CO_2 emissions reductions through advanced technological and process improvements. The author's work, and both "The Bio Steel Cycle" and "Power-to-X" studies emphasise the use of carbon capture technologies to achieve emissions reductions. The importance of renewable energy sources is highlighted in "The Bio Steel Cycle" and "Greater Energy Independence with Sustainable Steel Production," while "Power-to-X" utilises renewable electricity for hydrogen production. Each study employs advanced process optimisation techniques, whether it's through process simulations, integrating renewable technologies, or optimising chemical synthesis pathways. Both "The Bio Steel Cycle" and "Greater Energy Independence with Sustainable Steel Production" have long-term objectives of achieving near or net-zero CO_2 emissions, while "Power-to-X" aims for significant	"..The second approach is direct hydrogenation of carbon dioxide to produce C5+ liquid fuels, where RWGS reaction and FT synthesis are activated by the same catalyst in the same reactor simultaneously [57], [58]. The direct hydrogenation of CO_2 ap proach is less mature than the two-step approach. Many research attempts are being currently done to develop catalysts that can improve the selectivity of C5+liquid fuels in the case of direct hydrogenation of carbon dioxide…" 

				reductions through innovative fuel synthesis. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	
8	(Zhao *et al.*, 2021)	Cutting Parameter Optimization for Reducing Carbon Emissions Using Digital Twin	This paper presents a method of cutting parameter optimization based on the construction of a digital twin of a CNC machine tool. The method dynamically optimizes machining process parameters to reduce carbon emissions.	A precedent providing validation of the author's work via creating a digital twin with the focus on CO_2 emissions reduction. Both studies emphasize the importance of reducing CO_2 emissions, though they apply to different industrial processes (steel production vs. machining). Both studies highlight the use of advanced technologies (carbon capture and renewable energy in steel production, digital twin optimization in machining) to achieve emissions reductions. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data	Similar to the BiSC model, this paper is demonstrating a method of process optimisation. This is conducted by cutting parameter optimisation on basis of constructing a digital twin of a CNC machine tool. A dynamic optimisation method on cutting parameters is presented according to the simulation and optimization of the virtual twin with the dynamic perception of the machining conditions of the physical machine. This work at last, presents a case study which validates this method for effectively optimizing the cutting parameters and decreasing carbon emissions.

				similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	
9	(Liu *et al.*, 2024)	Modeling and Assessment of Carbon Emissions in Additive-Subtractive Integrated Hybrid Manufacturing	This research assesses the carbon emission characteristics of additive-subtractive integrated hybrid manufacturing (ASIHM) and compares it with conventional subtractive manufacturing. The results show that ASIHM has a significantly lower carbon footprint.	A precedent providing validation of the author's work via calculations and flowcharts demonstrating the CO_2 capture process. Objective: Assess carbon emissions in additive-subtractive integrated hybrid manufacturing (ASIHM) and compare it with conventional subtractive manufacturing (CSM). Results: The study found that ASIHM has the highest proportion of carbon emissions during the additive forming stage, reaching over 54%. However, compared to conventional milling, ASIHM has an 80% lower carbon footprint. The work of all authors focuses on CO_2 emissions reduction, and all studies emphasize the importance of reducing CO_2 emissions, though they apply to different industrial processes (steel production vs. hybrid manufacturing). All studies highlight the use of advanced technologies to achieve emissions reductions. All documents suggest process improvements and technological advancements to reduce carbon emissions. Optimisation of parameters to improve CO_2 capture efficiency is	".. the carbon emissions of the ASIHM process were analysed, and comparative research on the carbon emissions in material and energy consumption was also carried out with the conventional subtractive manufacturing (CSM) process. The results have revealed that ASIHM has the highest proportion of carbon emissions during the additive forming stage, reaching over 54%. Compared to conventional milling, ASIHM has an 80% lower carbon footprint…"

				present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.	
10	(Michailos and Gibbins, 2022)	A Modeling Study of Post-Combustion Capture Plant Process Conditions to Facilitate 95–99% CO_2 Capture Levels From Gas Turbine Flue Gases	The principal purpose of this study is to examine the changes in process conditions that might be needed to achieve up to 99% capture levels in amine post-combustion capture (PCC) plants for combined cycle gas turbine (CCGT) flue gases.	A precedent providing validation of the author's work via calculations and flowcharts focusing on the CO_2 capture process. All author's work emphasise the importance of reducing CO_2 emissions, though they apply to different industrial processes (steel production vs. gas turbine flue gases). All studies highlight the use of advanced technologies to achieve emissions reductions and suggest process improvements and technological advancements to reduce carbon emissions, using mathematical extrapolations as well as Aspen Plus process simulations to demonstrate post-combustion carbon capture. Optimisation of parameters to improve CO_2 capture efficiency is present, similar to the author's conducted experiments and validation protocol (Table 6-3). The validation is also based on similarity of principles, process	"…For a given amount of CO_2 captured and constant rich loading, lower lean loadings also increase specific energy consumption, … for a capture level of 95% using the modified Sherman case (i.e., a fixed CO_2 capture rate of 39.985 kg/s), reports calculated specific energy consumption for three rich loadings, 0.422, 0.446, and 0.463 $molCO_2/molMEA$. .."

simulations and experimental data similarity which indicate a common commitment to reducing carbon emissions and promoting sustainable practices.

Deng (2023), Mio et al. (2023), and Matino et al. (2023) compiled process simulation models with which the current work is very closely aligned to. Here an example from Matino et al. (2023), who created a simulation model very similar to the current work, but continued with the flowsheet development by adding blast furnace gas dedusting and cleaning operation simulations, as displayed below:

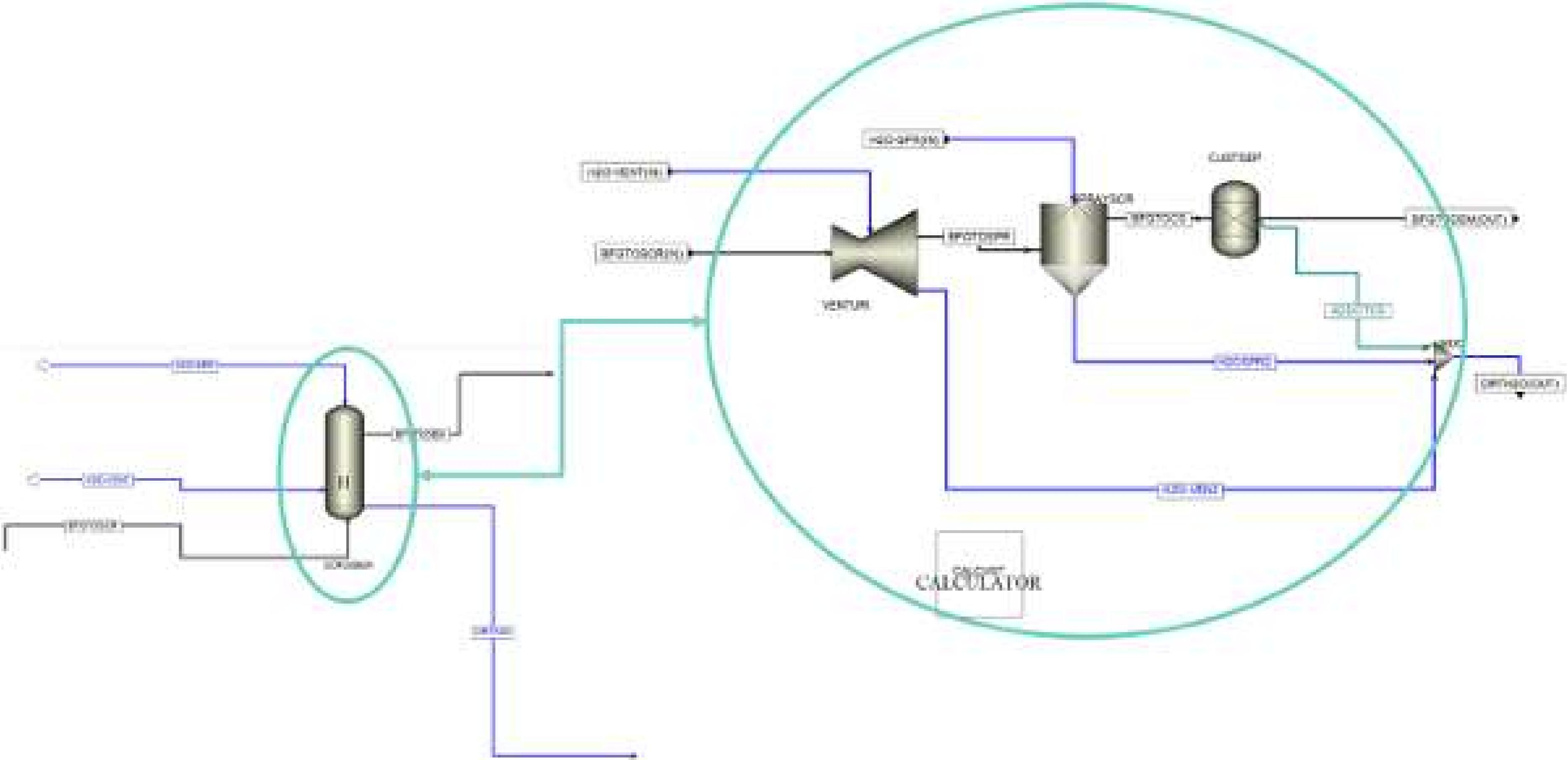


Figure 6-21:Internal flowsheet BFG dedusting/cleaning system model (Matino *et al.*, 2023)

6.7.3.1 Graphical display of simulation models validation results

In the following, tables and graphical displays will demonstrate the validation of experimental data and results for the models and process simulations of the different stages during the steelmaking process:

Coking

Below, the input data for the coal coking process is displayed in Table 6-6 and the data presented in graphs in figures 6-22 - 6-24:

Table 6-6: Coking process experimental input and results data

Stage	Process	Resource	Quantity	Result Weight kg	Quantity confirmed by	Quantity kg cited	Temperature °C	Temperature °C confirmed or range stated	Pressure	Pressure Confirmed by	CO_2 emissions energy/combustion per t product/kiln	CO_2 emissions confirmed by	CO_2 emissions stated in t per t of product
Preparation	Coking	Coal, bituminous	Kiln capacity	36000kg/36t	Neuwirth and Redemann, 2014	45,000			1/14.69/1.01	EPA, 2024		Chen *et al.* 2018	2.59
					Neuwirth, 2014	55,000		1,275		Pandey, 2025		Firsbach, Senk and Babich, 2022	0.27-3.93
					Kertcher and Linsky, 1974	15,000	1100-1400				0.27-3.93t/t coke		
					Hao *et al.*, 2024	28,000-36,000		1050-1300					
					Ergul and Selimli, 2024	20,000		1200-1300					

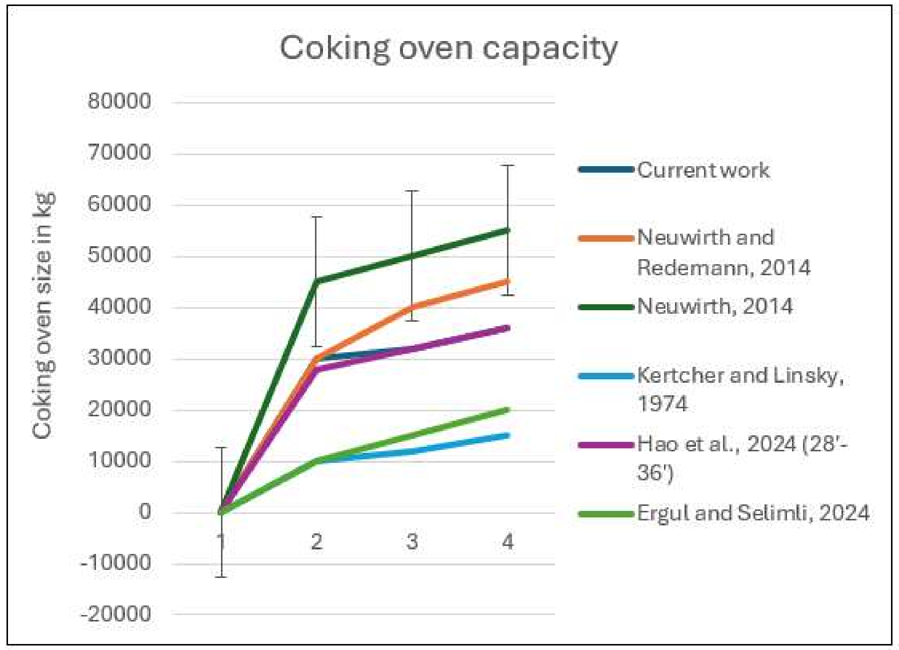


Figure 6-22: Coal coking oven size

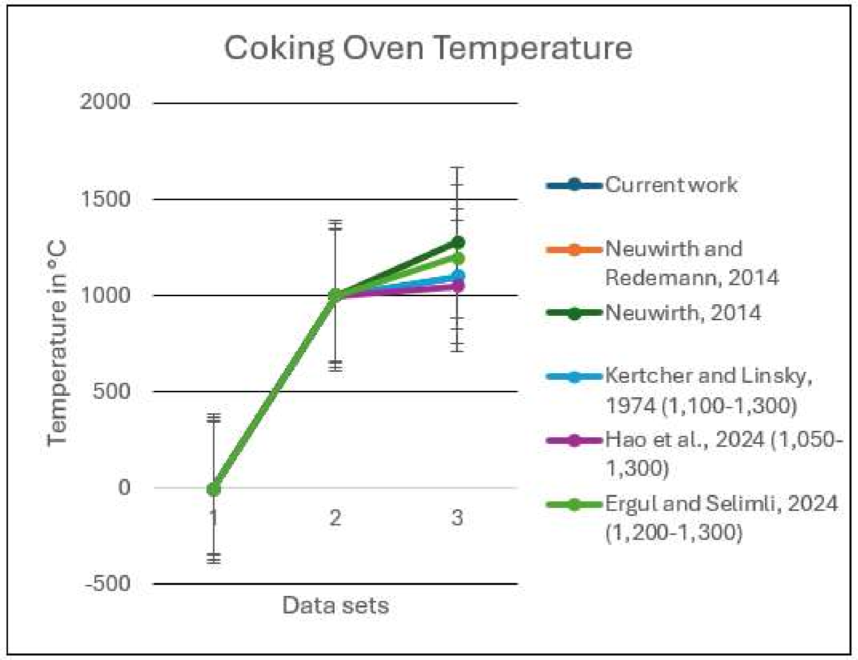


Figure 6-23: Operational temperature in the coking oven

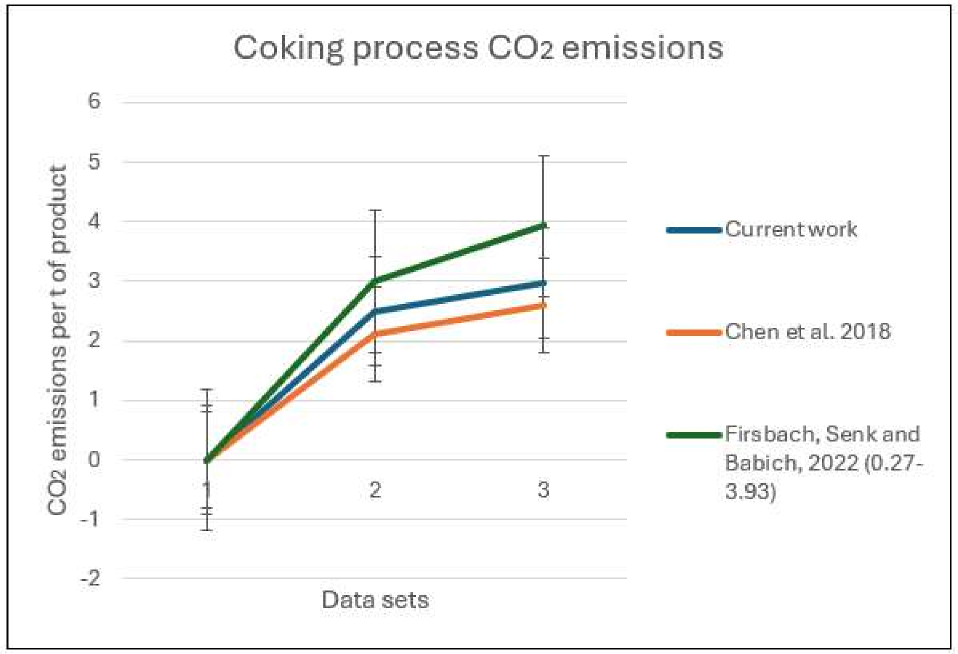


Figure 6-24: Variations of CO_2 emissions from coking coal

The current works' input and experimental data for coking coal, represented by a dark blue line, is partly obscured by the lines representing the authors confirming the current work's data, as they represent the same values.

Calcification

Below, the input data for the calcification process is displayed in Table 6-7 and the data presented in graphs in figures 6-25 – 6-27:

Table 6-7: Calcification process experimental input and results data

Stage	Process	Resource	Quantity	Result Weight kg	Quantity confirmed by	Quantity kg cited	Temperature °C	Temperature °C confirmed or range stated	Pressure	Pressure Confirmed by	CO_2 emissions energy/combustion per t product/kiln	CO_2 emissions confirmed by	CO_2 emissions stated in t per t of product
Preparation	Calcification	Limestone Water	Kiln capacity	50000kg/50t	Krause *et al*, 2015	50'-400000	900	900	1/14.69/1.01	Liu, 2020	1.26-2.21t/t lime	Chen *et al.* 2018	2.21
					Ryan, Bussman, and DeMartini, 2022	50'-400000		900-2000				Wu, Wang, Ke and Zang, 2023	1.10-1.26
					Henan Zhengzhou, 2025	50'-400000		1050-1150					

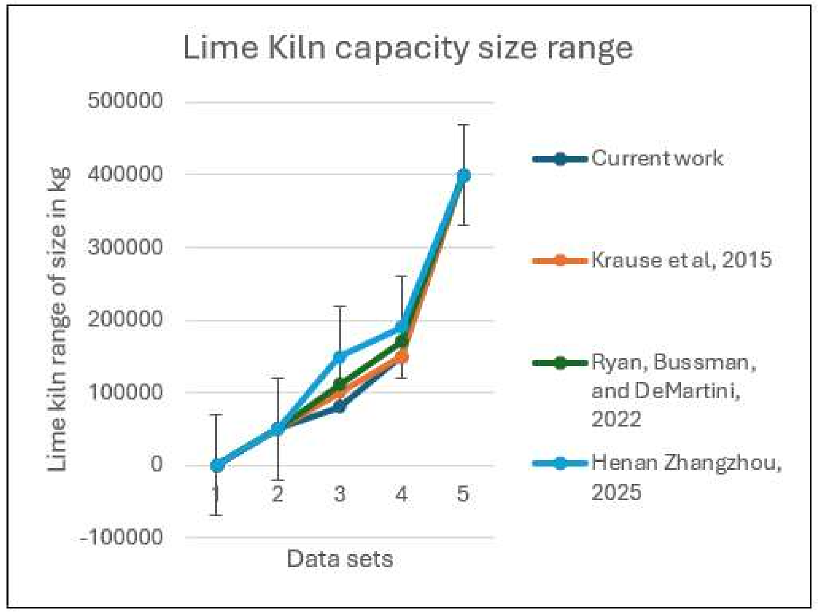


Figure 6-25: Lime kiln size variations

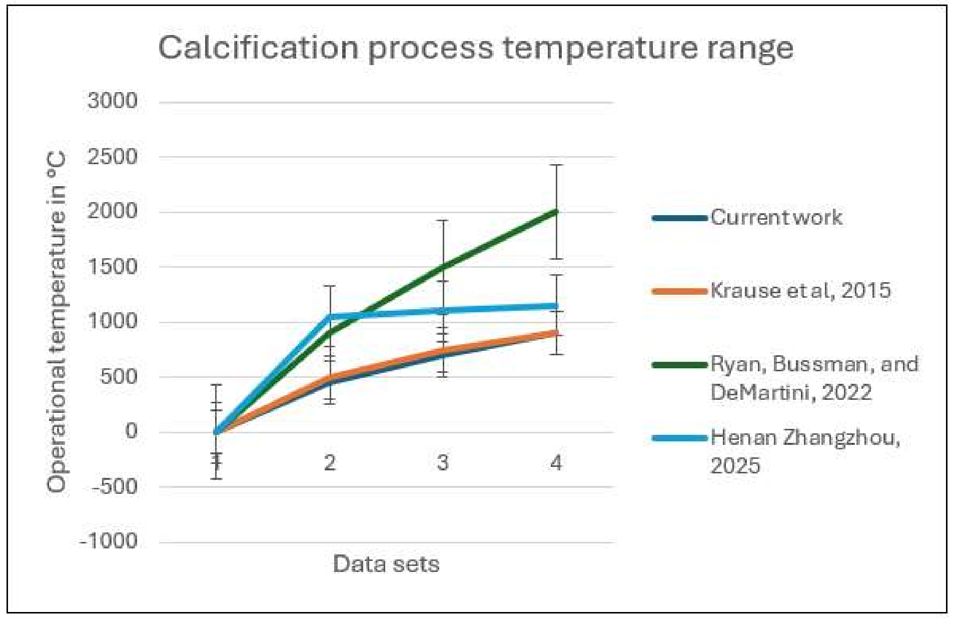


Figure 6-26: Lime kiln temperature variations

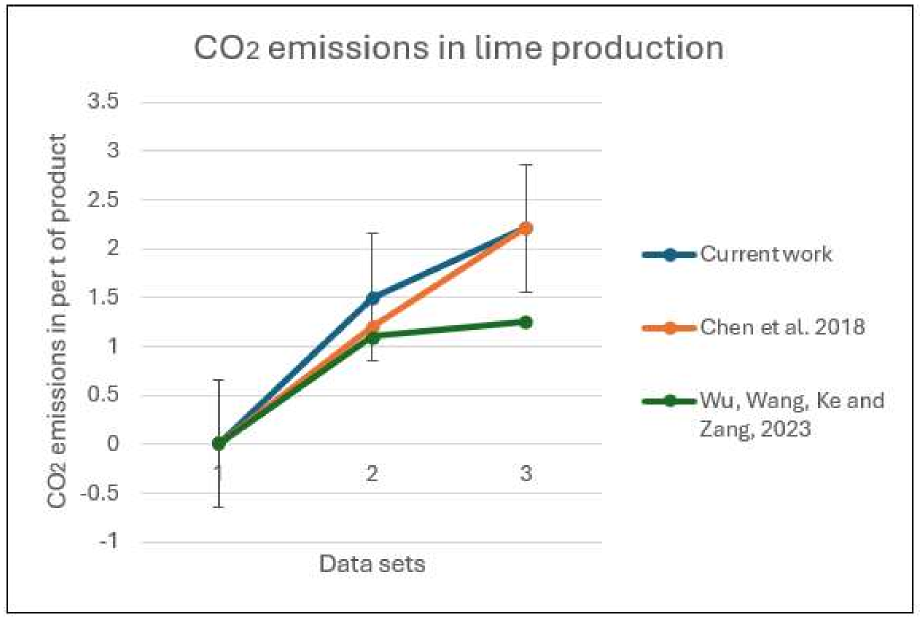


Figure 6- 27: CO_2 emission of the calcification process

The current works' input and experimental data for calcification, represented by a dark blue line, is partly obscured by the lines representing the authors confirming the current work's data, as they represent the same values.

Sintering

Below, the input data for the sintering process is displayed in Table 6-8 and the data presented in graphs in figures 6-28 – 6-30:

Table 6-8: Sintering process experimental input and results data

Stage	Process	Resource	Quantity	Result Weight kg	Temperature 1480 °C confirmed by	Temperature °C confirmed or range stated	Pressure 1/14.69/1.01 confirmed by	CO_2 emissions energy/combustion per t product/kiln	CO_2 emissions confirmed by	CO_2 emissions stated in t per t of product
Preparation	Sintering	Oxygen	Ambient		Liang *et al.*, 2023	1020-1080	Singh et al., 2022		Riesbeck *et al.* 2013	0.02
		Iron ore	62.85%	207405	Cores *et al.*, 2013	1250-1350	Liang et al., 2023		Ecofys 2009	0.28
		Lime	24.15%	79695	Zhou *et al.*, 2020	1000-1500		0.02-0.97t/t sinter	Mohammad, Patra	
		Coke	5.00%	16500	Wang *et al.*, 2024	1000-1250			and Harichandan, 2023	0.37
		Limestone	8.00%	26400	Fernández-González *et al.*, 2017	1300-1480			Wang *et al.*, 2023	0.97
					Worrell et al., 2010	1300-1480				

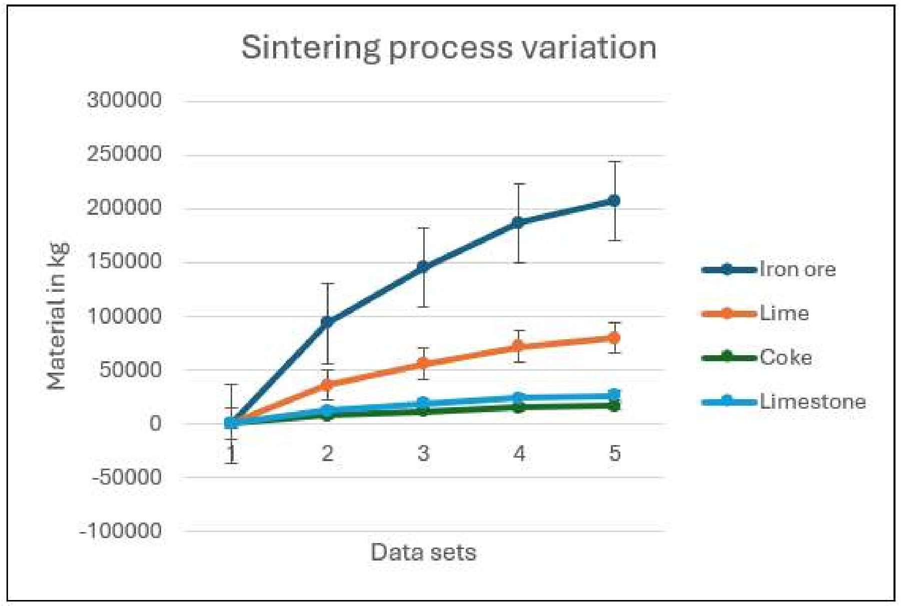


Figure 6-28: Sintering material quantity variation

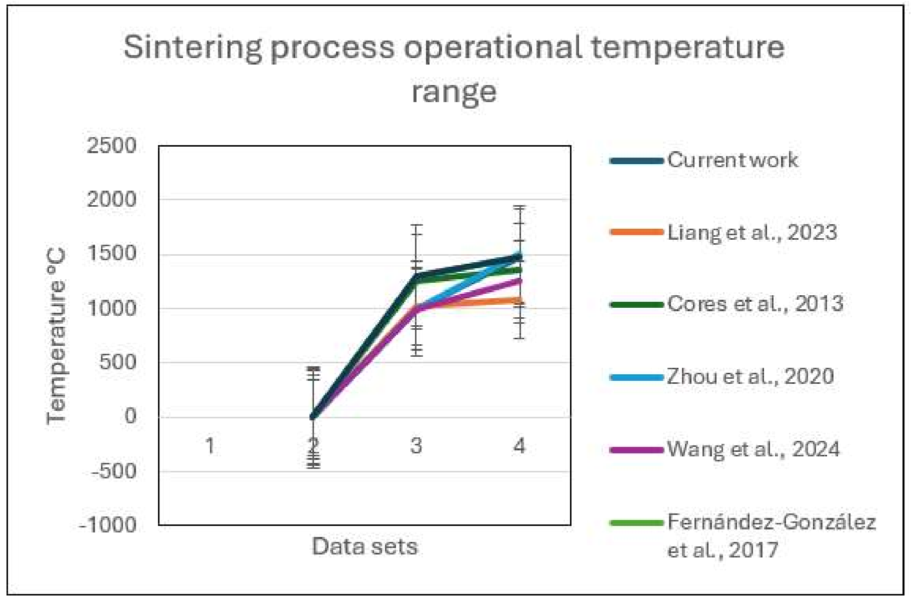


Figure 6-29: Sintering operational temperature variation

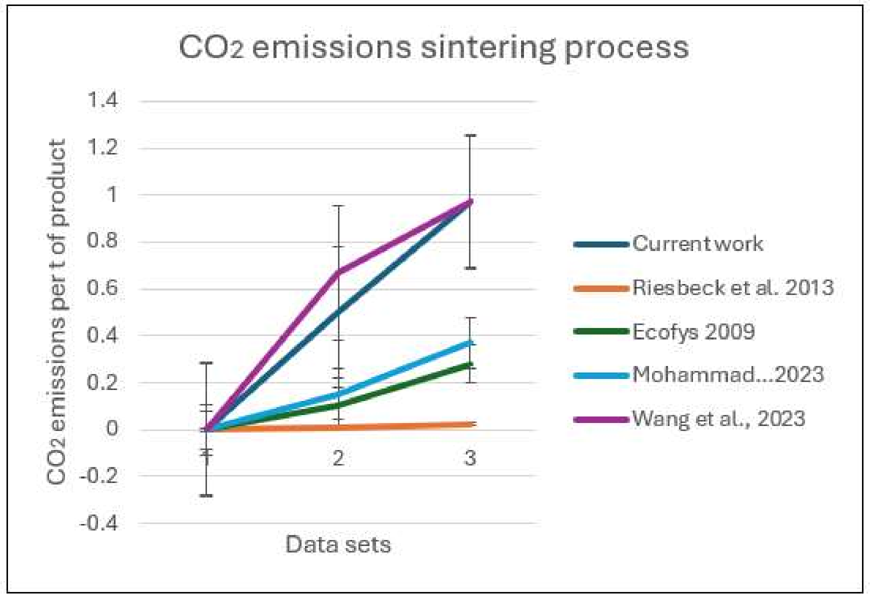


Figure 6-30: CO_2 emission of the sintering process

The current works' input and experimental data for the sintering process, where represented by a dark blue line, is partly obscured by the lines representing the authors confirming the current work's data, as they represent the same values.

Blast furnace operation

Below, the input data for the blast furnace operation is displayed in Table 6-9 and the data presented in graphs in figures 6-31 – 6-33:

Table 6-9: Blast furnace process experimental input and results data

Stage	Process	Resource	Quantity	Result Weight kg	Confirmed current quantities/% range	System Temperature 1650-2300°C confirmed by	Temperature °C confirmed or range stated	Pressure 1-2.5atm	Pressure Confirmed by	CO_2 emissions energy/combustion per t product/kiln	CO_2 emissions confirmed by	CO_2 emissions stated in t per t of product
Blast Furnace	Smelting	Coke	28-50.9% capacity	168015.25	Li *et al.*, 2022	Kawashiri *et al.*, 2022	2000-2400	~1-2.5bar	Kawashiri *et al.*, 2022		Toktarova 2020	1.60-2.20
	Reduction	Limestone		16500	Yang *et al.*, 2024	Satyendra, 2015	1650		Babich and Senk, 2015		Griffin Hammond 2019	0.90-3.20
		Oxygen	800m³/min=kg	22864	Chen *et al.*, 2018	Bailera *et al.*, 2021	1550-2300	220psi		*7.52t CO_2/t cs*	Mandova 2019	17.98
		Lime	4.5-19.5%	5653.62	Wang *et al.*, 2019						OECD 2015	5.85
		Iron ore	20-22.5%	28268.11	Kawashiri *et al.*, 2022						EERE 2021	1.16
		Iron oxide	50-55.0%	69099.8	Satyendra, 2015						Chen 2018	2.50
		Silicon dioxide	2.5-10.5%	3140.9	Babich and Senk, 2015						Hasanbeigi Springer 2019	1.49-2.80
		Magnesium oxide	3.5-4.5%	5653.62							Wang *et al.*, 2023	1.90
		Aluminium oxide	1-3%	3769.08							Suer 2022	2.10-3.00
		Zinc		1256.36						2.1-3.2t/t steel		
		Titanium	2-5%	1256.36								
		Potassium		1256.36								
		Chromium		1256.36								
		Manganese		1256.36								
		Water	0-0.6%	753.82								

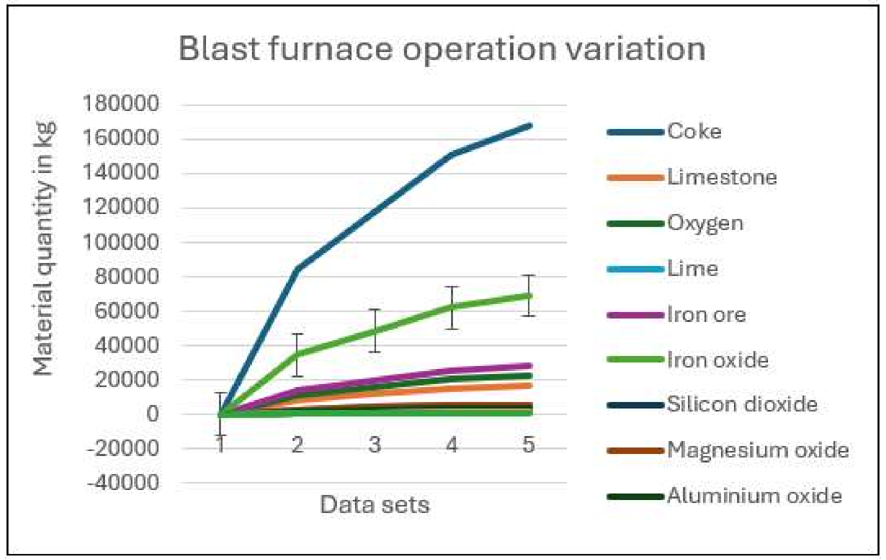


Figure 6-31: BF material quantity variation

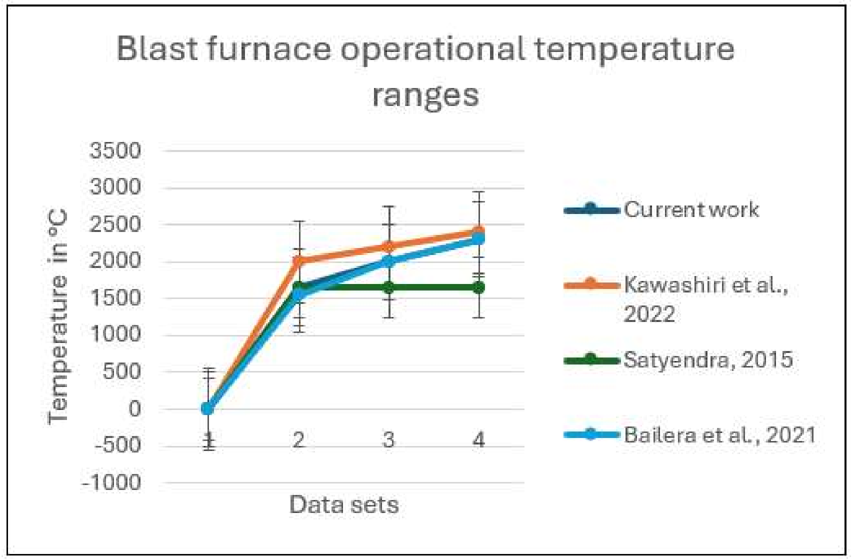


Figure 6-32: BF temperatures

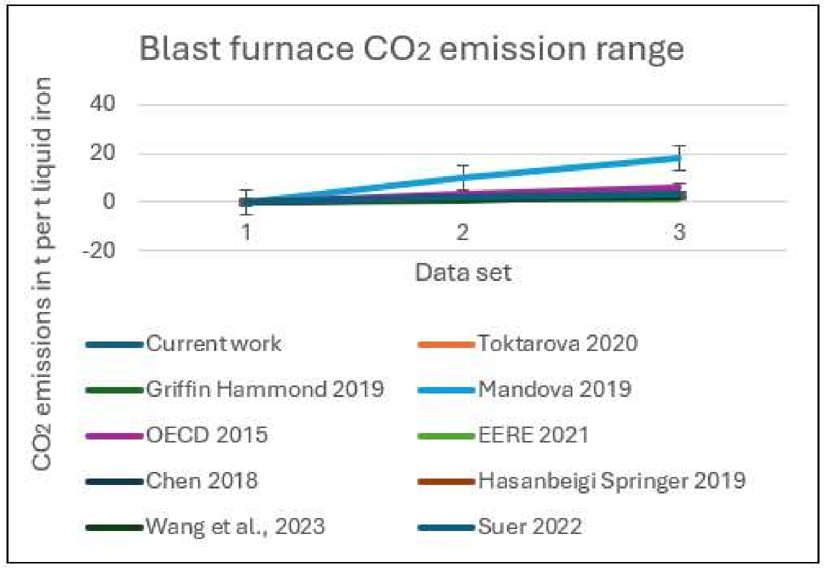


Figure 6-33: BF CO_2 emissions

The current works' input and experimental data for the blast furnace operation is partly obscured by the lines representing the authors confirming the current work's data, as they represent the same values.

Basic oxygen furnace operations

Below, the input data for the basic oxygen furnace operation is displayed in Table 6-10 and the data presented in graphs in figures 6-34 – 6-36:

Table df: Basic oxygen furnace process experimental input and results data

Stage	Process	Resource	Quantity	Result Weight kg	Confirmed current quantities/% range	System Temperature 1650-2300°C confirmed by	Temperature °C confirmed or range stated	Pressure 1-2.5atm	Pressure Confirmed by	CO_2 emissions energy/combustion per t product/kiln	CO_2 emissions confirmed by	CO_2 emissions stated in t per t of product
Basic Oxygen	Oxygen	Liquid Fe		224636	Hasanbeigi Springer 2019		1600-1650	1atm/14.69psi			Toktarova *et al.* 2020	2.20
Furnace	Converter	Lime	50kg/t liquid steel	16500	Griffin Hammond 2019		1600		Griffin Hammond 2019		Mandova 2019	7.71
	Process	Oxygen 99%		22864	Garvey Norman and Barrett 2022	25	~1600	150	Garvey Norman and Barrett 2022		Khalid *et al.* 2021	2.10
		Scrap metal		66000	Hasanbeigi Springer 2019	1700	1600-1650			*66tx4.95tCO_2*	Griffin Hammond 2019	2.76
				330000						1.6-3.13t/t steel	Martelaro 2016	1.60
											Garvey Norman and Barrett 2022	1.85-2.20
											Hasanbeigi Springer 2019	1.49-2.80
											Napp *et al.*, 2014	2.27

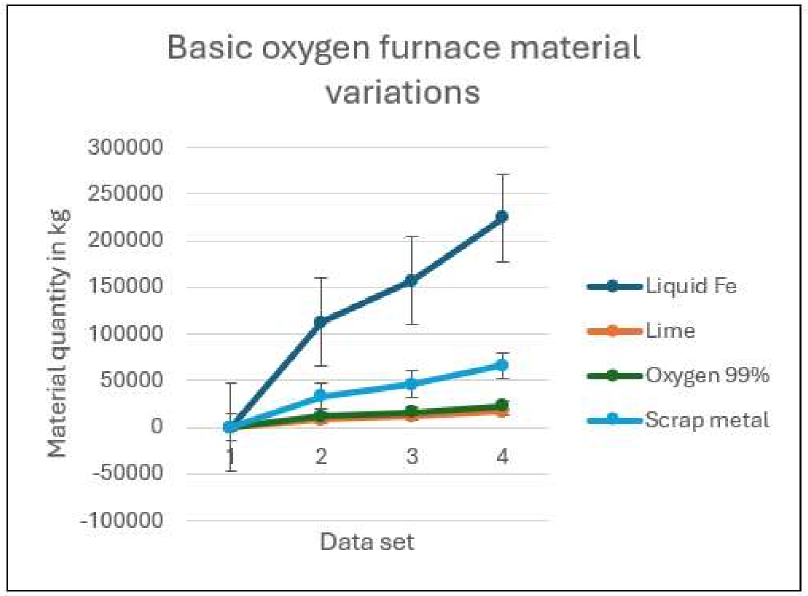


Figure 6-34: BOF material quantity variation

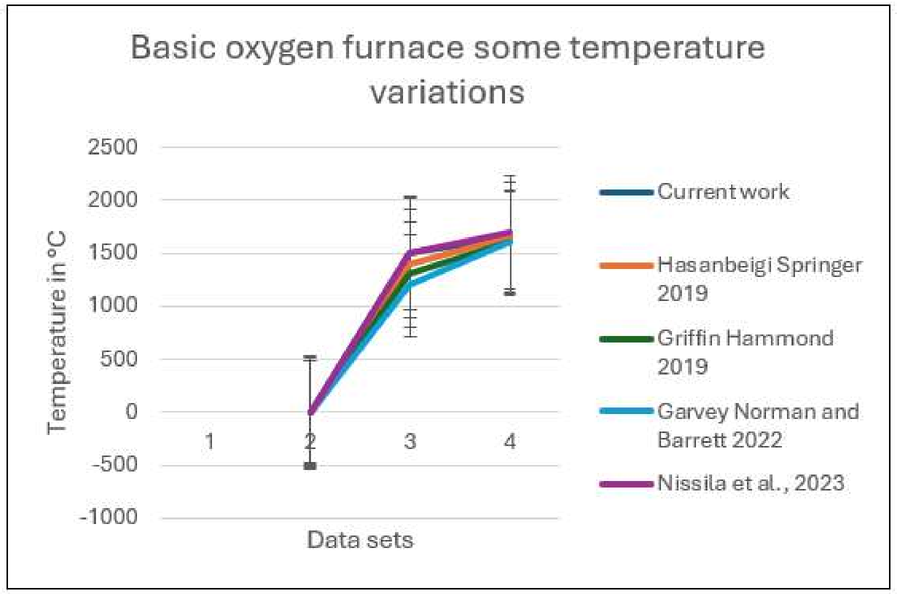


Figure 6-35: BOF temperature ranges

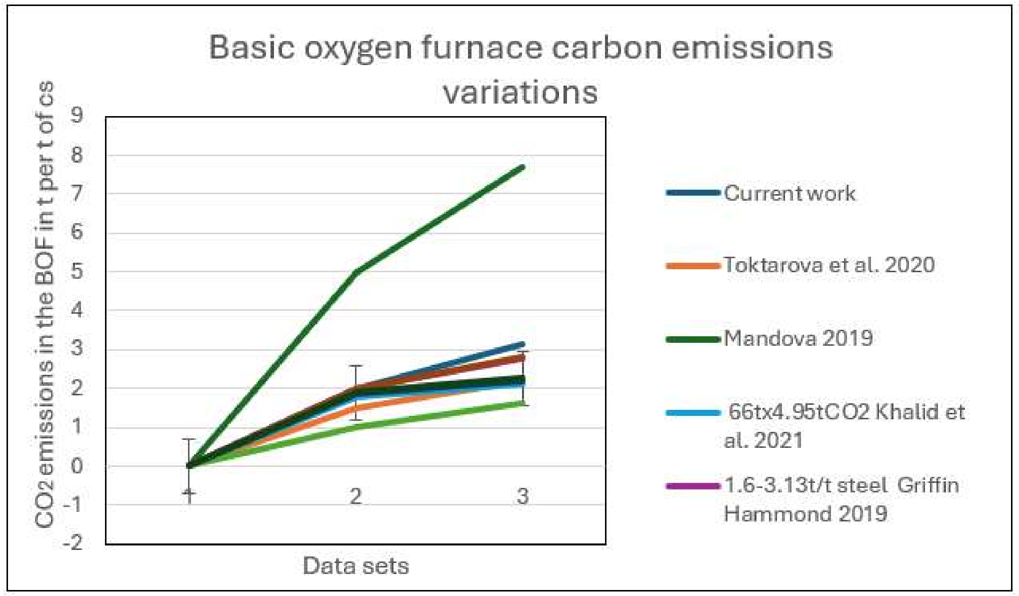


Figure 6-36: BOF CO_2 emissions

The current works' input and experimental data for the basic oxygen furnace operation is partly obscured by the lines representing the authors confirming the current work's data, as they represent the same values.

The current Aspen Plus, Simul8 and INOSIM simulations largely align with the simulation models in Table 6-3 and Table 6-5, as far as process design, flowcharts, component selection and layout are concerned. However, as the identified benchmark simulations did not provide detailed input data for comparison of mass balance, temperature, or furnace pressure, the validation against scientific literature including references from Table 6-5, confirming the parameters and input data used, was carried out.

The differences between the CO_2 emissions stated in the current work and the literature confirming the levels of emissions and material quantities used can be explained by a) a difference in approach to gathering emissions data, b) a difference in the furnaces or oven size in coking, calcification, sintering and BF/BOF vessels, and c) inclusion of the emissions as a result of the specific energy requirements at the different stages.

It is my understanding from undertaking this research, that the findings are pointing to a research gap: the energy (derived from fossil fuels, primarily) required to heat the oxygen for the blast furnace operation. To date, there seems to be a lack of scientific publications which combine the elements of providing data on CO_2 emissions at all stages of the steelmaking process from mining to finish machining, and process simulations using either Aspen Plus, Simul8 or INOSIM, and also providing input data for mass balancing and validation purposes. Further research seems to be necessary in this regard, and to identify mechanisms to further reducing carbon emissions in steel production, possibly in connection with TGRBF, EAF and oxy-fuel combustion systems.

6.8 Discussion and conclusions

The input values according to table 7-3 are the result of extensive research into all stages involved in the steelmaking process, from mining materials to finish machining steel. For decades, the value of two metric tonnes of CO_2 emission per metric tonne of steel produced has been widely accepted as industry standard. Within the last 30 years, publications have emerged which challenge this status quo and have been mentioned throughout.

Therefore, it was imperative to a) conduct this study to establish the factual CO_2 emissions along all processes required for making steel and b) using this data within the process simulations to demonstrate the validity of these findings. As a result of the integration of all phases and the resulting CO_2 emissions from mining to finish machining into the steelmaking process, the summarised CO_2 emissions are higher than the previously widely accepted status quo of 2 t CO_2 emissions per metric tonne of crude steel, as these only focused generally on the BF/BOF-stages of steelmaking.

Moreover, establishing the similarities between and validation of the author's process simulations, flowcharts, and resulting experimental data, with benchmark publications and suitable literature were carried out and corroborated the author's findings and therefore validated the author's work.

Conclusively, it can be said that the pentagonal approach to investigation, verification and validation of the research findings has proven to provide a range of viable results. The choice not to rely on just one process simulation software, but to use three simultaneously, has removed the pressure from one single method to provide proof of concept. In addition, to use mathematical standard procedure (algebra), statistical methods, MS Excel calculations and extrapolations has delivered proof of viability for the hypothesis one: stating that it is possible to reduce CO_2 emissions in steel production by at least 20% and achieve a higher degree of energy independence at the same time.

Chapter 7 Results

7.1 Introduction

Compiling a report with the data and results of a 3-year-project has proven to be an interesting challenge, as the framework changed as a result of gaps in knowledge found during the literature review. As a pragmatist approach had been taken, driven by a contemporary issue, quantitative as well as qualitative data had to be organised in a meaningful way.

During reviewing literature, gaps in the knowledge about the level of emissions in the iron and steel industry have been discovered. Influenced by events such as the Paris agreement being ratified (UN United Nations, 2016), the UN Climate Change Conferences (COP25: Madrid, Spain, from 2 to 13 December 2019 under the presidency of the Chilean government; COP26, 2-9 December 2019, Glasgow/UK) taking place, and subsequent IPCC (2021, 2022, 2023a, 2023b, 2022a, 2022) reports, aims and objectives were set as a result of formalising the arising research questions:

- Which level of CO_2 emissions are being produced at which stage of the steel production process?
- How can CO_2 emissions be effectively reduced in steel production?
- Can the newly developed Bio Steel Cycle model and strategy support energy independence?

7.1.1 Methodology

The methodology followed a pentagonal approach, and the research-derived results will be presented accordingly, as mentioned in Chapter 2: Methodology. Step 4: Analysis, will use standard mathematical procedures and principles; further analysis and modeling via MS Excel. Step 5: Validation, will be using standard mathematical procedures, principles and statistics (t-test), MS Excel functionality and process simulation results and reports.

The results of each section of the pentagonal pyramid are presented in graphs/figures, tables and calculations. In every section of 6.1-6.3, the aim is to present all findings and results in a way which answers the 3 research questions adequately. Therefore, the questions are being set as the framework in which order the findings are being presented.

7.2 Mathematical analysis

As already described in chapter 2: Methodology, a set of formulae has been compiled for the purpose of calculating the total of CO_2 emissions per metric tonne of crude steel produced and the emissions savings in application of the various decarbonisation methods. For this purpose, the input datasheet for the process simulation software applications had to be compiled first, to use the correct quantities of CO_2 emissions along the steelmaking process route, all levelled with CO_2 emissions per metric tonne of crude steel produced. Algebraic function calculation was deemed best suited to determine the overall CO_2 emissions of the steelmaking process, from mining to marketing. Because, if the *function* is the solution of some polynomial (an expression of more than two algebraic terms, particularly the sum, expressed as ∑, of several terms), it is said to be algebraic. The decision to choose the algebraic function was made because they are functions which satisfy a polynomial equation whose coefficients are polynomials. Meaning, the function $f(x)$, is an algebraic function if $y=f(x)$, and a solution of the polynomial $p_n(x)y^n+\ldots+p_1(x)y+p_0(x)=0$ (Kench, 2023).

The basis equation $ECO_2 = E_{fos} + E_{flu} - E_{seq}$ expressed as Equation 7-1

$$CO_2E_{total} = \sum \text{x } \Omega \qquad \text{Equation 7-2}$$

$CO_2E_{total} = \sum$ x Ω (∑ Sigma as sum of Ω Omega products/terms) have been developed (formulae 1-4) (adapted from Zhao *et al.*, 2020; Kench, 2023; Kuramochi *et al.*, 2011, 2018; Khakimov *et al.*, 2019; Julia, 1918; Arnold, 1980) to simplify calculating the greenhouse gas emissions and the possible effect in real term carbon savings and in percentages of the identified technologies in steel production. For the BF/BOF the value of 3.6-6.3t (mean: 4.95t) of CO_2 emissions and for the BF/EAF route 0.3-3.6t (mean: 1.95t) of CO_2 emissions per t of steel produced has been applied.

Theoretically, this approach will work - but there are the technical issues of different percentage level CO_2 emissions of various reduction technologies, with different approaches to emission avoidance, mitigation and capture, at every stage along the linear steel producing process (mining, preparation, coking, calcination etc.). However, the research focus was to determine the levels of CO_2 emissions at all stages leading to and constituting steelmaking and following through up to the output point, with a wide range of different values of CO_2 emissions for BF or BOF operations stated.

The ensuing calculations taking into consideration all CO_2 emissions from mining coal to finish machining and the BF/BOF-route, have therefore been used (Zhao *et al.*, 2020; Kuramochi *et al.*, 2011, 2018; Khakimov *et al.*, 2019; Arnold, 1980). It needs to be emphasised, that at this point, the actual quantities determined by the literature review have been entered. The defined resource quantities (coal, lime, iron ore, oxygen etc.) and resulting CO_2 emission will be detailed during the steelmaking process software simulations. Once this has been carried out, the values from the literature review may be replaced by the values determined as input data for the process simulations.

$$\boldsymbol{CO_2E_{total} = \sum \text{(emissions per ton of steel) x } \Omega \text{ (output tonnes produced)}} \qquad \text{Equation 7-3}$$

1 charge Equation 7-3

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2RE_{limes} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \text{ x } (CapBF \text{ x } t)$$

1 day Equation 7-4

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2RE_{limes} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \text{ x } 330{,}000$$

30 days/1 month Equation 7-5

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2RE_{limes} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \text{ x } (330{,}000 \text{ x } 30)$$

1 year (p.a.) Equation 7-6

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2RE_{limes} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM)) \text{ x } (330{,}000 \text{ x } 365)$$

And to determine the effects of the carbon saving or reduction methods, the following has been developed:

The base calculation for establishing the carbon reduction effects:

$$\boldsymbol{CO_2E_{total} = \sum\text{(emissions per ton of steel)} \times \Omega \text{ (output tonnes produced) x } Red\%} \qquad \text{Equation. 7-8}$$

In order to determine the effect of the chosen emissions reduction factor and component has been calculated, as follows:

1 charge Equation 7-7

$$\boldsymbol{CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2RE_{limes} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times (CapBF \times t) \times Red\%}$$

To support identification of the equation components from within the text, a key to formulae and components has been compiled:

Key to formulae components and factors:

CO_2E_{total} = CO_2 emissions Total
CO_2RE_{coal} = CO_2 emissions resource extraction coal
CO_2RE_{ore} = CO_2 emissions resource extraction iron ore
CO_2RE_{oxy} = CO_2 emissions resource extraction oxygen
CO_2RE_{limes} = CO_2 emissions resource extraction limestone
CO_2PT_{coal} = CO_2 emissions primary resource transformation coal > coke
CO_2PT_{lime} = CO_2 emissions primary resource transformation limestone > lime
CO_2ST_{sint} = CO_2 emissions secondary resource transformation coke and iron > sinter
CO_2BF = CO_2 emissions blast furnace
CO_2BOF = CO_2 emissions basic oxygen furnace
CO_2EAF = CO_2 emissions electric arc furnace
CO_2C = CO_2 emissions casting
CO_2M = CO_2 emissions milling
CO_2FM = CO_2 emissions finish machining
CapBF = Capacity blast furnace / basic oxygen furnace
t = time (charges per day) 400 tonnes per charge every 40 minutes, Ø of 10,000 tonnes/day
Red% = Reduction of CO_2 emissions in percent (%)

The formulae is then adjusted, to represent certain sections within the steelmaking process, such as the BF/BOF-route:

1 charge Equation 7-8

$$CO_2E_{total,1c} = \sum(CO_2BF + CO_2BOF) \times (CapBF \times t)$$

In order to answer research question 1: What are the current levels of CO_2 emissions of steelmaking?, the base formula has to be applied. The calculations are based on a 330t capacity furnace, for one charge/cycle.

For the BF/BOF route and the BF/BOF route the mean values have been applied. The resulting operations for the BF/BOF route and the BF/EAF route, as follows:

BF/BOF route 1 charge Equation 7-11

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t)$
$CO_2E_{total,1c} = (4.95) \times (330 \times 1) =$
$CO_2E_{total,1c} = 4.95 \times 330 =$
$CO_2E_{total,1c} = 1{,}633.50\text{t}$

BF/EAF route *1 charge* Equation 7-12

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2EAF) \times (CapBF \times t)$
$CO_2E_{total,1c} = (1.95) \times (330 \times 1) =$
$CO_2E_{total,1c} = 1.95 \times 330 =$
$CO_2E_{total,1c} = 643.50\text{t}$

This means that, for the BF/BOF route, 1,633.50t of CO_2 emissions and for the BF/EAF route 643.50t of CO_2 emissions per charge of 330t of crude steel produced are being released.

BF/BOF route *1 charge* Equation 7-13

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t)$
$CO_2E_{total,1c} = (4.95) \times (330 \times 1) =$
$CO_2E_{total,1c} = 4.95 \times 330 \times 0.7 =$
$CO_2E_{total,1c} = 1{,}143.45\text{t}$

In order to answer research question 2: How can a reduction of the CO_2 emissions be achieved?, the formulae have to be adapted accordingly and will result in processing, as follows. As basis the charge capacity of 330t has been assumed, for one charge. Initially, the usage of biomass has been applied, resulting in a 30% reduction of CO_2 emissions.

BF/EAF route *1 charge* Equation 7-14

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2EAF) \times (CapBF \times t) \times \text{Red\%}$
$CO_2E_{total,1c} = (1.95) \times (330 \times 1) \times 0.7 =$
$CO_2E_{total,1c} = 1.95 \times 330 \times 0.7 =$
$CO_2E_{total,1c} = 450.45\text{t}$

This means that for the BF/BOF route 1,455.30t of CO_2 emissions and for the BF/EAF route, 808.50t of CO_2 emissions per charge of 330t of crude steel produced are being released, when biomass has been used instead of coal.

In order to calculate the CO_2 emissions for the BF/BOF and BF/EAF route process emissions reductions when a) *biomass* has been used instead of coal, additionally, b) *renewable energy* is being installed, and subsequently to this c) *biogas* is being circulated into the steelmaking process, the calculation process will be, as follows:

BF/BOF route a) Equation 7-15

$$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$$
$$CO_2E_{total,1c} = \sum (4.95) \times (330 \times 1) \times 0.7 =$$
$$CO_2E_{total,1c} = 4.95 \times 330 \times 0.7 =$$
$$CO_2E_{total,1c} = 1{,}143.45t$$

BF/BOF route b) Equation 7-16

$$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$$
$$CO_2E_{total,1c} = ((4.95) \times (330 \times 1) \times 0.7) \times 0.7 =$$
$$CO_2E_{total,1c} = (4.95 \times 330 \times 0.7) \times 0.7 =$$
$$CO_2E_{total,1c} = 800.42t$$

BF/BOF route c) Equation 7-17

$$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$$
$$CO_2E_{total,1c} = ((3.2 + 3.1) \times (330 \times 1) \times 0.7) \times 0.7) \times 0.7 =$$
$$CO_2E_{total,1c} = ((4.95 \times 330 \times 0.7) \times 0.7) \times 0.7 =$$
$$CO_2E_{total,1c} = 560.29t$$

This means, that for the BF/BOF route, the following t of CO_2 emissions per charge of 330 tonnes of crude steel produced, have to be considered for scenarios:

a) $CO_2E_{total,1c} = 1{,}143.45t$

b) $CO_2E_{total,1c} = 800.42t$

c) $CO_2E_{total,1c} = 560.29t$.

Implementation of most Bio Steel Cycle components and capturing CO_2 emissions via flue stack filters, such as with the Geomimetic© process, simply reduces the CO_2 emissions to almost '0'. For the BF/EAF route, the same applies:

BF/EAF route a) Equation 7-18

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$

$CO_2E_{total,1c} = [(1.95) \times (330 \times 1) \times 0.7] =$

$CO_2E_{total,1c} = 1.95 \times 330 \times 0.7 =$

$CO_2E_{total,1c} = 450.45t$

BF/EAF route b) Equation 7-19

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$

$CO_2E_{total,1c} = [(1.95) \times (330 \times 1) \times 0.7] \times 0.7 =$

$CO_2E_{total,1c} = [(1.95 \times 330 \times 0.7] \times 0.7=$

$CO_2E_{total,1c} = 315.32t$

BF/EAF route c) Equation 7-20

$CO_2E_{total,1c} = \sum (CO_2BF + CO_2BOF) \times (CapBF \times t) \times Red\%$

$CO_2E_{total,1c} = [(1.95) \times (330 \times 1) \times 0.7] \times 0.7) \times 0.7 =$

$CO_2E_{total,1c} = [(1.95 \times 330 \times 0.7) \times 0.7] \times 0.7 =$

$CO_2E_{total,1c} = 220.72t$

This means, that for the BF/BOF route, the following t of CO_2 emissions per charge of 330 tonnes of crude steel produced, have to be considered for scenarios:

a) Biomass (BG) $CO_2E_{total,1c} = 450.45t$

b) BG + Renewable energy (RE) $CO_2E_{total,1c} = 315.32t$

c) BG, RE + Biogas $CO_2E_{total,1c} = 220.72t$.

As with the BF/BOF route, implementation of most Bio Steel Cycle components within the BF/EAF route and capturing CO_2 emissions via flue stack filters, such as with the Geomimetic© process, simply reduces the CO_2 emissions to almost '0'.

The previous step answers the third research question at the same time: How can a higher degree of greater energy independence be made a reality?, as the usage of biomass reduces the amount of coal and coke produced under usage of energy derived from fossil fuels. The energy not required for coking does not have to be imported. Additionally, the installed renewable energy technologies (solar, or wind, geothermal, hydro power/hydrogen) and the back-feeding of biogas from anaerobic digestion all provide the industrial processes with renewable energy, from their own infrastructure. Thus, the energy produced on site will make most industries inevitably more energy independent.

7.3 Data modeling

As mentioned in Chapter 2: Methodology; the data gathered and insights gained during the literature review have been compiled in a comprehensive MS Excel database, which poses the foundation of the development of the Bio Steel Cycle model and strategy and the basis which all presented data has been extracted from.

- Figure 8-3, provides answers to question 1: What are the current levels of CO_2 emissions of steelmaking?
- Currently, the preliminary research findings are pointing towards a total of between 3.6-6.3t (median: 4.95t) of CO_2 emissions per metric tonne of crude (low carbon) steel produced via the **BF-BOF-route only**, which have been applied throughout the calculations and simulations.

There are some additional quantities to be considered, which will be discussed in section 6.2.1. It so seems that, within blast furnace operations, the emissions for heating the oxygen from ambient temperatures to 1000°C, have not yet been included in any of the publications researched for answers during the literature review.

One of the few exceptions was a report administered by the Australian Department for resources, which confirmed, that, indeed, not only process CO_2 emissions need to be considered, but also the energy required for heating the oxygen (produced using fossil fuels), via the BF-BOF route (Pandit, Qader and Lim, 2021).

Therefore, deductions with standard mathematical procedure has been applied to calculate the level of CO_2 emissions produced as a result of the heating process, with electricity used to increase the temperature of the injected oxygen, derived from fossil fuel sources. Additionally, the level of CO_2 emissions as a result of injecting the heated oxygen at 220psi into the blast furnace have also, so far, not been included in any of the sources of information. Therefore, at this point, mathematical principles have also been applied to determine the level of CO_2 emissions as a result of this exact procedure. Additionally, a question of logical deduction needs to be answered: the up to 30% scrap steel content in the basic oxygen would have to be considered as already having caused 66t of CO_2 emissions (in a 330t capacity furnace, similar to the British Steel blast furnace in Scunthorpe). One could argue that these would have to be added to the CO_2 emissions balance, too.

Furthermore, in answering the research question 2: How can a reduction of the CO_2 emissions be achieved?, the literature review has provided a multitude of possible procedural and technical solutions (see chapter 3, section 3.6 and chapter 4), which have the potential to reduce the CO_2 emissions from iron and steelmaking significantly. Particularly, in chapter 4: The Bio Steel Cycle engineering aspects – THE SOLUTION, a 7-step-strategy to net-zero CO_2 emissions steel production has been explored in more detail.

Figure 7-1 shows details of the CO_2 emissions reduction development in application of emission reduction measures, whilst simultaneously increasing the levels of energy independence.

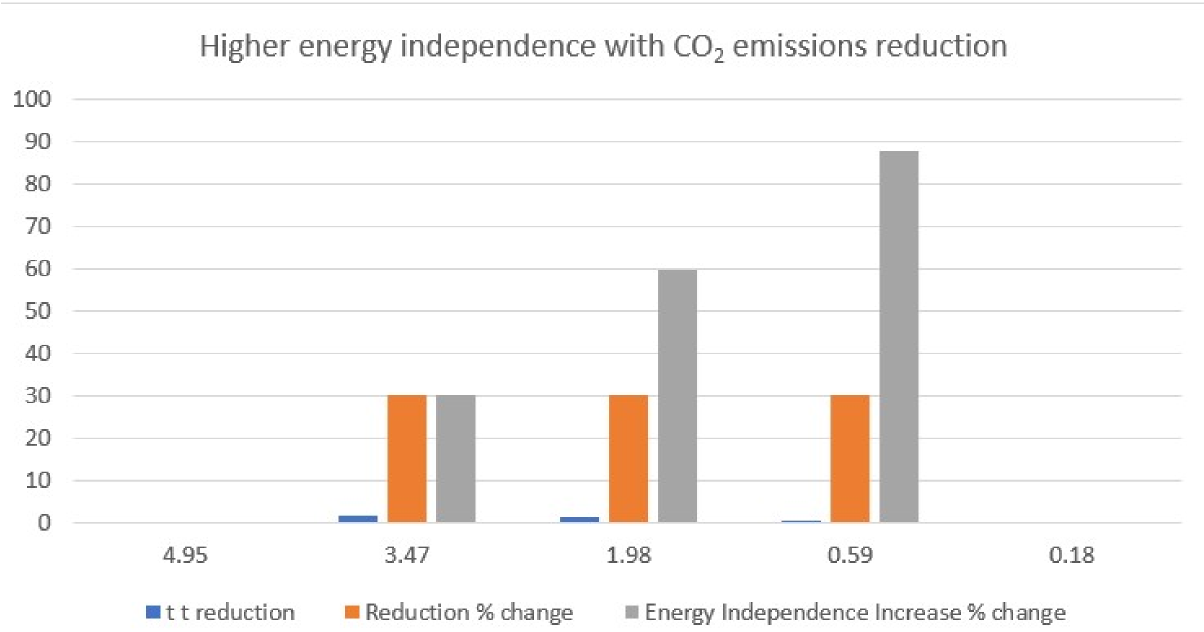


Figure 7-1: Steelmaking CO_2 emissions reduction
with simultaneous increased energy independence

Figure 7-2 will display a screen copy of the MS Excel database with the parameters, data and findings for most processes associated with the steelmaking process and Figure 7-3 comments timeline with literary sources confirming the preliminary findings:

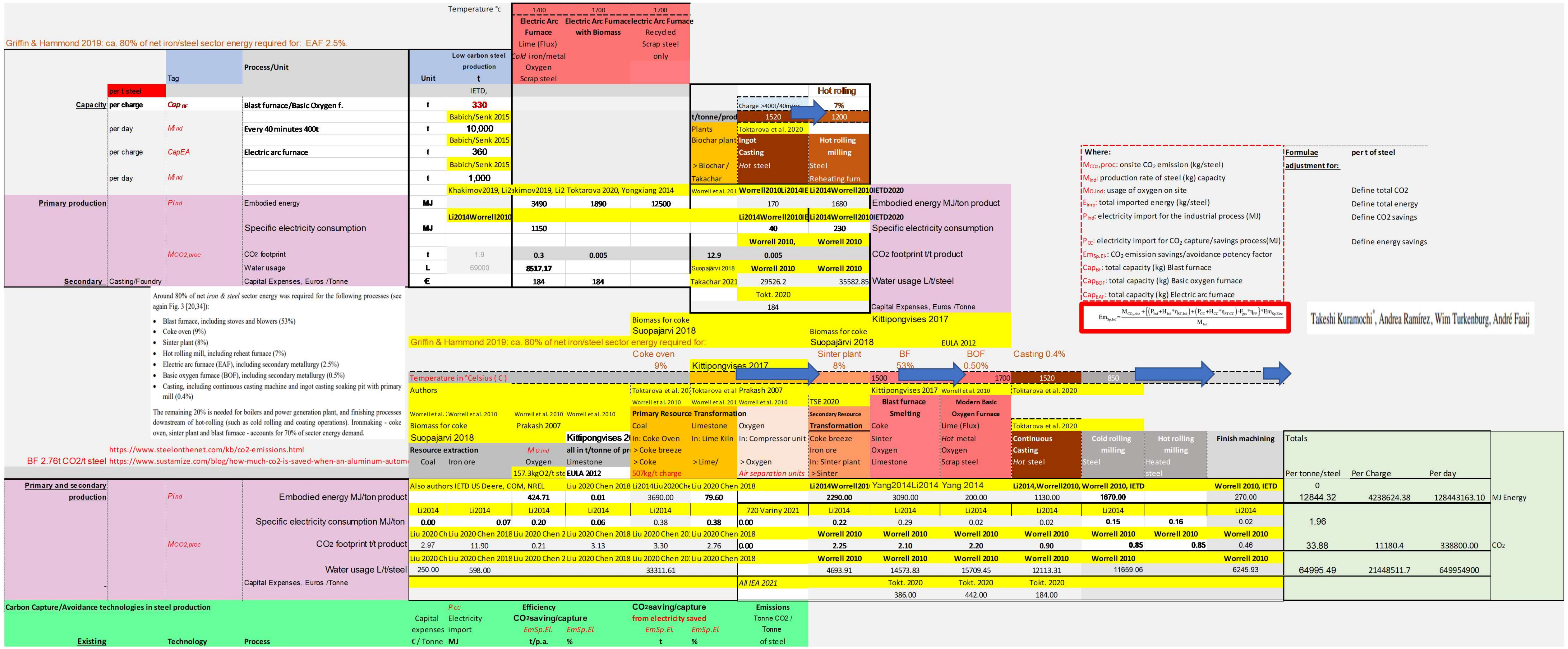


Figure 7-2 : MS Excel compilation of gathered data

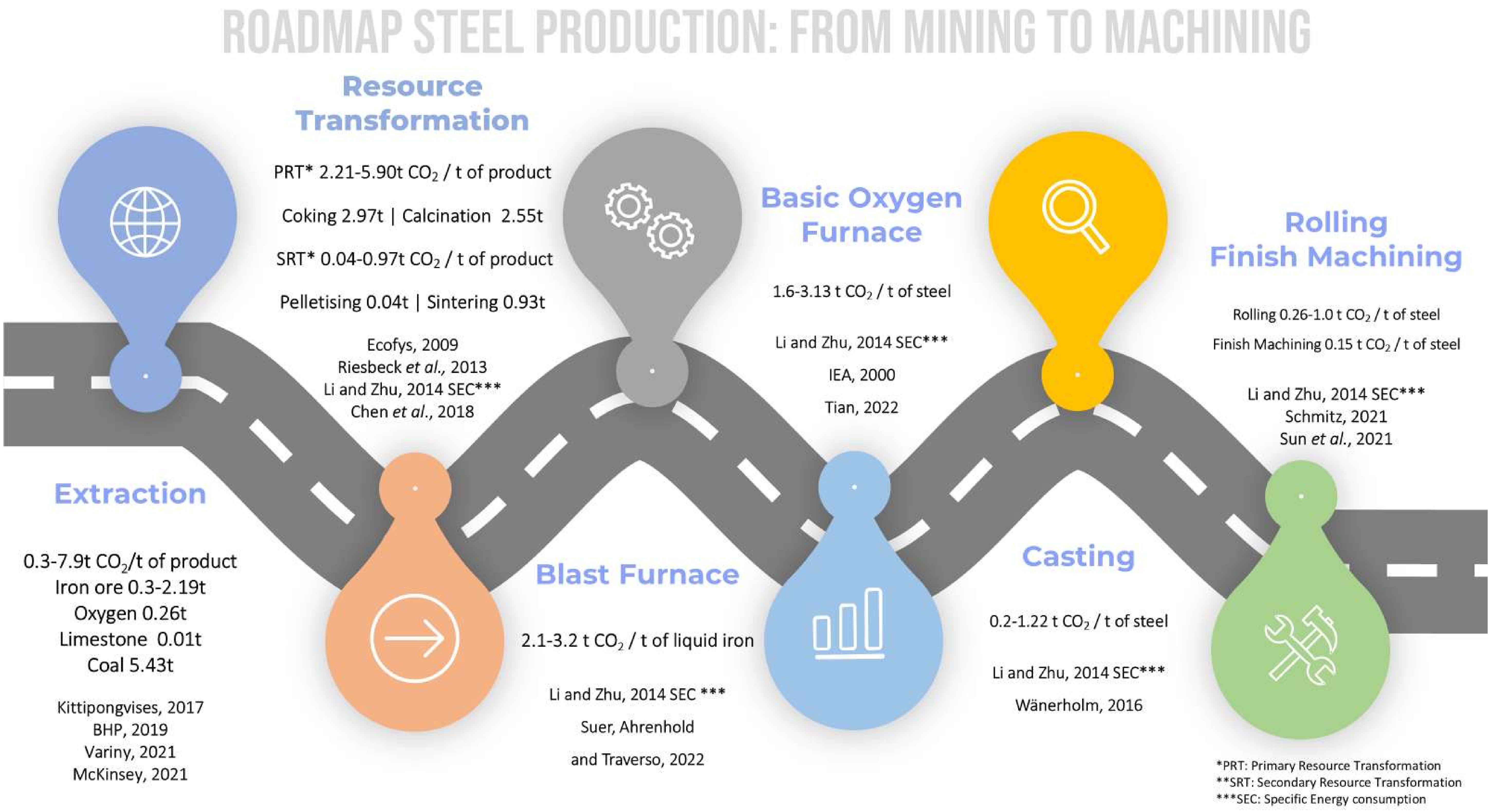


Figure 7-3: Process roadmap from mining iron ore, limestone, coal and extracting oxygen to finish machining steel (Variny, 2021; Kittipongvises, 2017; BHP, 2019; Chen et al., 2018; Li Zhu, 2014; Ecofys, 2009; Riesbeck et al., 2013; Suer, Ahrenhold and Traverso, 2022; IEA, 2000; Tian, 2022; Wänerholm, 2016; Schmitz, 2021; Sun *et al.*, 2021).

Figure 7-2 displays a section of the master datasheet, with Figure 7-3 pointing towards specific sections in literary sources of information for emissions along the steelmaking process. During the literature review, further insights were gained in application of standard mathematical procedure. But the purpose of this study was not to question and evaluate existing information, but rather a mere compilation of established facts in a comprehensive manner to give an overview of the CO_2 emissions along the steelmaking process.

Some answers in relation to research question 2: How can a reduction of the CO_2 emissions be achieved? and 3: How can a higher degree of greater energy independence be made a reality?

CO_2 emissions from every stage along the steelmaking process have been considered. From mining over to calcination of limestone, coking of coal, making sinter from lime and iron ore pellets and the blast furnace, basic oxygen furnace, casting and finishing operations have all been investigated throughout – to the point of product issue.

However, the issue with the data in the datasheet is, that – at present – the levels of CO_2 emissions represent the levels at every production stage, per metric tonne of the individual product, *not* metric tonne of steel.

This led to the conclusion, that for the overall CO_2 emissions per resource, such as coal, oxygen, limestone, iron ore and their respective products along the transformation process, such as lime, iron ore pellets, concentrated oxygen and sinter, the requirement per metric tonne of steel, and extrapolated to furnace capacity, produced will have to be determined, and the overall CO_2 emissions cannot be summarised from the datasheet.

This required input sheet needs compilation to function as the basis for the process simulations in S8, Aspen+ and Inosim, which will be shown in Chapter 6: Results. The input datasheet is required to enter the individual resources and materials into the software as material streams and parameters, which enables the systems to determine the CO_2 emissions along the processes. These insights will be used in sections 6.3.4-6.3.6.

The conventional BF/BOF route CO_2 emissions net total seems to be varying at between 3.6-6.3t (mean: 4.95t) of CO_2 emissions per t of steel produced. At this point it is worth emphasising, that there is a great range and difference of recorded levels of CO_2 emissions in steelmaking in existing literature, due to a) different approaches to collecting data, b) populations of any survey, c) different frameworks of valid data points and d) lack of guidance for collecting CO_2 emissions and how to measure the various levels.

In Chapter 4: The Bio Steel Cycle, the mechanisms leading to a CO_2 emissions reduction to almost '0' CO_2 emissions are explored in greater detail. Some deductions on this basis, as follows: Switching the energy provision to a commercial entity producing their energy entirely using renewable energy technologies leads to a reduction in fossil fuel derived energy consumption of 30%, with CO_2 savings at the same percentage rate – reducing the CO_2 emissions from 4.95t by 1.49t to 3.47t. With the replacement of coal with biomass a further 30% reduction from 3.47t of CO_2 emissions leads to an emissions reduction of 1.39t to 1.98t to of CO_2 emissions per metric tonne of crude steel, whilst simultaneously increasing the level of energy independence by 60%. At this point, it cannot be stressed enough that the replacement of coal with biomass will not only directly reduce the CO_2 emissions during the BF-BOF-route, but also eliminate the GHG emissions entirely for mining the coal, preparing and coking, with the elimination of processing emissions from energy usage at the same time. Biomass does have some carbon footprint, but pales in comparison with coal-based steelmaking. Besides, biomass is a more sustainable carbon source, and the increased usage and production would have the positive side-effects of potentially increased re-wilding, habitat rehabilitation and providing an increased volume of CO_2 sinks. Therefore, it could be argued, the carbon capture capabilities of biomass should be taken into consideration when calculating the overall impact on CO_2 emissions, as DAC of biomass can be between 9 and 17t per hectare, per year, depending on the species. If renewable energy resources can be installed, using the existing infrastructure, a further 30% of CO_2 emissions can be reduced, leading to a reduction to 0.18t of CO_2 emissions per tonne of steel produced, and '0' with the introduction of CO_2 flue stack CO_2 filters. At the same time, a higher degree of energy independence can be achieved, at 88%.

The data processing in MS Excel provided a meaningful insight into the development of the different scenarios of sustainable and renewable energy technology and process component applications, in ceteris paribus (Latin for: All else being equal), investigated in specific process stage emission component values.

The MS Excel extrapolations demonstrated the impact of the different component implementations. The currently accepted value of between 3.6-6.3t (mean: 4.95t) of CO_2 emission per t of steel produced (in answer to research question 1) were demonstrably reduced (in answer to research question 2), by only switching to an energy provider who derive their energy entirely from renewable energy sources, replacing coal with biomass and installing renewable energy technologies for energy production on site. This will not only help to reduce CO_2 emissions, but (in answer to research question 3) will supply the production site with renewable energy, where 30% of energy does not have to be imported from third parties and paid for, bringing the reduction in CO_2 emissions reduced to -60%.

At the point in production, where biomass has already replaced the use of coke, and renewable energy technologies (solar, solar PV, wind, hydro) have been installed, the remaining energy requirement can be provided by using biogas, produced in the link-connected anaerobic digester, which produces biogas from the connected biomass producing agri-businesses. This might even provide an additional source of income, as surplus energy fed into the national grid is financially rewarded.

7.4 Statistics: T-Test

Statistical relevance requires to be added and therefore, a t-test (Table 7-3) was performed in MS Excel. The data relevant for this test is the data-extract from Table 7-1:

Table 7-1: Data-extract BF/BOF and BF/EAF

BOF	4.95	1633.50
BOF+B	4.95	1143.45
BOF+B/RE	4.95	800.42
BOF+B/RE/BG	4.95	560.29
EAF	1.95	643.50
EAF+B	1.95	450.45
EAF+B/RE	1.95	315.30
EAF+B/RE/BG	1.95	220.72

<u>Hypothesis</u>

The directional hypothesis states that it is possible to reduce the CO_2 emissions per tonne of steel produced by at least 20%, possibly to '0', and achieve greater energy independence at the same time, for the same percentage value.

The null-hypothesis states that it is not possible to reduce the CO_2 emissions per tonne of steel produced by at least 20%, possibly to '0' and achieve greater energy independence at the same time, for the same percentage value.

<u>*Expressed as equations*</u>:

1 Hypothesis: $H_1{:}>20\%$

0 Hypothesis: $H_0{:}\leq 20\%$

Interpreting the Two-Sample t-Test Results in Table 7-2:

Table 7-2: *t-Test*

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.45	720.95375
Variance	2.571428571	219618.8
Observations	8	8
Pearson Correlation	0.71506427	
Hypothesized Mean Difference	0	
df	7	
t Stat	-4.341073061	
P(T<=t) one-tail	0.001695811	
t Critical one-tail	1.894578605	
P(T<=t) two-tail	0.003391622	
t Critical two-tail	2.364624252	

The output indicates that mean CO_2 emissions quantity per tonne of crude steel for BF/BOF and BF/EAF is 3.45t and for the applied technologies and processes in BF/BOF and BF/EAF operation it is 720.95t per charge or production cycle.

The *significance level* is 0.05. As the *p-value* is 0.000168 and therefore less than the significance level, the difference between means is statistically significant.

Therefore, the '0' Hypothesis needs to be rejected and the '1' Hypothesis needs to be accepted: It is possible to reduce the CO_2 emissions per tonne of steel produced by at least 20% and achieve greater energy independence at the same time, for the same percentage value.

7.5 Total CO_2 emissions from BF/BOF operating oxygen

As previously mentioned in section 3.4, the energy required to inject the compressed 99% oxygen into the blast furnace at 220psi and 1000°C and at 150psi at ambient temperature does not seem to have been taken into consideration in any of the investigated sources of information. Therefore, the enthalpy, the energy required, and the resulting CO_2 emissions have been calculated with application of basic mathematical principles. In order to determine those values, additional questions required answers, such as 'How much oxygen m^3 is being used in BOF per minute in a 20-minute-blow?'. It was determined that $800m^3$ of oxygen are being used per minute, weighing in at 1143.20kg (AVC LLC, 2023). Furthermore, 'How much CO_2 for use of energy is being emitted via the blast furnace when heating 800m^3 oxygen per minute for 20 minutes from 25°C to 1000 °C?'.

For this purpose, the required formula and equation is that of enthalpy (Treptow, 1999; Canagaratna, 2000; McClary *et al.*, 2016) using the heat capacity of oxygen at 918J/kg°C (Giauque and Johnston, 2002). Given are: Any 330t charge capacity will result in 92,6% yield (Encyclopedia Britannica, 2023) of steel from liquid iron ladled into the BOF from the BF, resulting in 370.4t of liquid steel.
1000J = 0,0002777778kWh; 0,46kg (Protons for Breakfast, 2019) of CO_2 per kWh produced (AVCalc LLC, 2023). 1 minute of 800m3 oxygen = 1143,20kg.
Therefore: 20 minutes of 800m3 oxygen per minute = 22864.0kg in weight of oxygen per oxygen blow.
ENTHALPY = a thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume (Meador and Smart, 2005; A-Level Chemistry, 2023).

Heat energy calculation Equation 7-9

$$\mathbf{Q = mcs\Delta T}$$
$$= \text{mcs}(T_{\text{final}} - T_{\text{initial}})$$
$$= (918\text{J/kg°C}) \times (2.2864 \times 10^4\text{kg}) \times (1{,}000\text{-}25)\text{°C}$$
$$= (918\text{J/kg°C}) \times (2.2864 \times 10^4\text{kg}) \times (925)\text{°C}$$
$$= 918 \times 2.2864 \times 10^4 \times 925$$
$$= 1.94145 \times 10^{10}\text{J (per 20-minute blow)}$$

Conversion to kWh Equation 7-10

$$1.94145 \times 10^{10} \times 2.7778\ 10^{-4} = 5.393 \times 10^6\ \text{kWh}$$

CO_2 emissions calculation Equation 7- 11

$$(5.393 \times 10^6\ \text{kWh}) \times (0.46\text{kgCO}_2/\text{kWh}) = 2.481 \times 10^6\ \text{kg of CO}_2$$

CO_2 emissions per metric tonne of steel Equation 7- 12

$$\frac{2.481 \times 10^6\ \text{kg CO}_2}{3.3 \times 10^5\ \text{kg steel}} = 7.52\ \text{t CO}_2\ /\ \text{metric tonne of steel}$$

Now, to determine how much CO_2 emissions are being produced for the injection of the oxygen into the blast furnace at 220psi, and at 150psi into the basic oxygen furnace, it is required to calculate pressure in relation to oxygen value in weight and heat value (J):
pressure x volume = energy

Blast furnace (BF) energy calculation Equation 7-13

$(220psi) \times (2.2864 \times 10^4 kg)\ kg = 5.03008 \times 10^6\ J$

$(5.03008 \times 10^6\ J) \times (2.777778 \times 10^{-4}) = 1.397 \times 10^0 kWh$

Basic oxygen furnace (BOF) energy calculation Equation 7-14

$(150psi) \times (2.2864 \times 10^4\ kg) = 3.4296 \times 10^6\ J$

$(3.4296 \times 10^6\ J) \times (2.7778 \times 10^{-4}) = 9.527 \times 10^{-1}\ kWh$

CO_2 emissions calculation Equation 7-15

$0.46kgCO_2/kWh$ (METI, 2022; PFB, 2023)

BF $(1.397 \times 10^0\ kWh) \times (4.6 \times 10^{-1}\ kg\ CO_2/kWh) = 6.42 \times 10^{-1}\ kg\ CO_2$/BF blast at 220psi

BOF $(9.527 \times 10^{-1}\ kWh) \times (4.6 \times 10^{-1}\ kg/CO_2/kWh) = 4.38 \times 10^{-1}\ kg\ CO_2$/BOF blast at 150psi

Therefore, $7.52t/CO_2$/metric tonnes of steel and an additional 0.64kg CO_2 for the 220psi exerted pressure of 220psi for the injection of oxygen at 1000°C into the blast furnace will have to be added to the CO_2 balance, per metric tonne of crude steel produced. As the oxygen injection is operated at 150psi in the basic oxygen furnace, unheated, an additional 0.44kg of CO_2 needs to be considered. As the oxygen does not need to be heated for injection into the basic oxygen furnace, no energy requirement or enthalpy needs to be determined. The established values have been added to the calculations for determination of the mean values for BF/BOF and BF/EAF route operations in Table 7-3:

Table 7-3: Input data for entry in process simulation software based on data and sources of information in chapters 1-8

Stage or Process	Resource	Chem. Formula	State	Result	Quantity	Result Weight kg	°C	Pressure	State	Electricity kWh/t	CO_2 Emissions per t product
Coking	Coal, bituminous	$C_{137}H_{97}O_9NS$	Solid	Coke	Kiln capacity	36000kg/36t		1atm/14.69psi	Solid	937.82	
							1100-2000				2.97t/t coke
Calcification	Limestone	$CaCO_3$	Solid	Lime	Kiln capacity	50000kg/50t	900	1atm/14.69psi	Solid	1180.57	
	Water	H_2O	Liquid					1atm/14.69psi			
											2.21t/t lime
Sintering	Oxygen	O_2	Gaseous		Ambient			1atm/14.69psi	Gaseous	2100	
	Iron ore	FeO	Solid		62.85%	207405		1atm/14.69psi	Solid		
	Lime	CaO	Solid	Sinter	24.15%	79695		1atm/14.69psi	Solid		
	Coke	$C_{135}H_{96}O_9NS$	Solid		5.00%	16500		1atm/14.69psi	Solid		
	Limestone	$CaCO_3$	Solid		8.00%	26400	1480	1atm/14.69psi	Solid		0.93t/t sinter
Blast	Coke	$C_{135}H_{96}O_9NS$	Solid		≤50.9% capacity	90000-168015.25		1-2.5atm	Solid		
Furnace;	Limestone	$CaCO_3$	Solid	Quicklime		16500		14.69-36.74psi	Solid		
Smelting	Oxygen	O_2	Gaseous		$800m^3$/min=kg	22864	1000-2200	220psi*[1]	Gaseous		
Reduction	Lime	CaO	Solid		4.5-19.5% of*	5653.62		1-2.5atm	Solid		
	Iron ore	Fe	Solid		<22.5% of*	28268.11		14.69-36.74psi	Solid		
	Iron oxide	Fe_2O_2	Solid		>55.0% of*	69099.8		1-2.5atm	Solid		
	Silicon dioxide	SiO_2	Solid		2.5-10.5% of*	3140.9		14.69-36.74psi	Solid		
	Magnesium oxide	MgO	Solid		<4.5% of*	5653.62		1-2.5atm	Solid		
	Aluminium oxide	Al_2O_3	Solid		<3% of*	3769.08		14.69-36.74psi	Solid		
	Zinc	Zn	Solid			1256.36		1-2.5atm	Solid		
	Titanium	Ti	Solid		<5% of*	1256.36		14.69-36.74psi	Solid		
	Potassium	K_2O	Solid			1256.36		1-2.5atm	Solid		
	Chromium	Cr	Solid			1256.36		14.69-36.74psi	Solid		
	Manganese	Mn	Solid			1256.36		1-2.5atm	Solid		
	Water	H_2O	Liquid		0-0.6%	753.82		14.69-36.74psi	Liquid		
				Liquid iron		*161984.75*	1800			600	3.2t/t liquid iron
Basic Oxygen	Liquid Fe	FEO	Liquid			224636		1atm/14.69psi	Liquid		
Furnace;	Lime		Solid		50kg/t liquid steel	16500		1atm/14.69psi	Solid		
Oxygen	Oxygen 99%		Gaseous			22864	25	150	Gaseous		
Converter	Scrap metal		Solid			66000	1700		Solid		
Process				Steel		*330000*				50	3.1t/t steel

In Figure 7-4, the most prominent sources stating the CO_2 emissions at every stage of the steelmaking process are shown, down to detailed passages and images shown in the text. Great efforts have been made to ensure that the input data reflects current common practice in the iron and steel industry. In order to provide comparable evidence, the basic input materials were used, which were available across the software packages. All process simulation software have one issue in common: they only operate on the material, work or heat flow principle. Components such as solar panels work on the conversion of UV rays into electric energy, which are not yet available as building blocks. There are ways to work around this lack of provision, as will be demonstrated later in the images of the various configurations. The latest environmental data set available on Aspen+V12.1 used for CO_2 reporting stems from the 2009 USEPA (United Nations Environmental Protection Agency) report. The 2023 report is available (USEPA, 2023), so the data and results presented by Aspen+ need to be viewed cautiously, bearing this in mind.

7.5.1 Simul8

Staffordshire University provides students with a range of process simulation software packages, one of which is Simul8 (Simulate). It is a quite intuitively laid-out simulation tool, where even beginners can become proficient fairly quickly. As one of the first simulations, the Bio Steel Cycle layout has been created using Simul8. The different components for simulation had to be identified, for then to determine the parameters of the input data. To understand the process of working with Simul8, initially a BF-BOF-process-route simulation has been created. The BF/BOF route is the most widespread method of steelmaking, representing ca. 70% of current global crude steel production (Li *et al.*, 2021). It needs to be emphasised, though, that the following CO_2 emissions in metric tonnes at this stage of the project are representing the CO_2 emissions at their respective stage, per t of product, and *not* per tonne of steel. The emissions burden on each of the input streams in the simulation software systems Simul8, Aspen+ and Inosim are already set within the system parameters and therefore calculated during the process simulations, and are providing a more detailed set of data, per metric tonne of steel produced. Additionally, in order to represent the overall mean CO_2 emissions burden in t per t of steel, the mean value of 4.95t/t cs was allocated for entering in the input stream in S8 as BF 2950kg and BOF 2000kg. the input stream in S8 as BF 2950kg and BOF 2000kg. Figure 7-4 will display the sections of Figure 6-14 relevant to the CO_2 S8 Carbon Report, at every stage in the steelmaking process, in t per t of product:

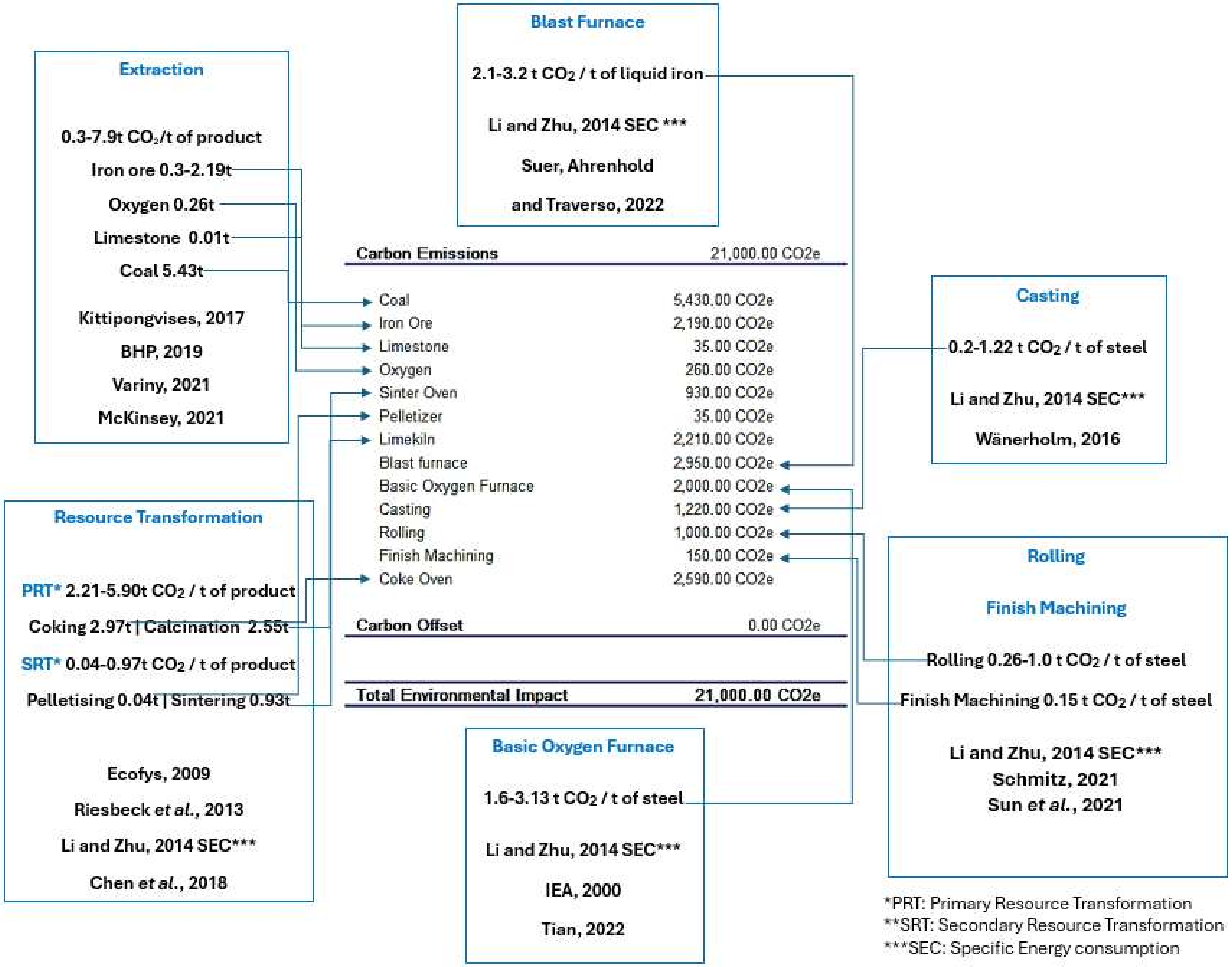


Figure 7-4: CO_2 emission evidence, per tonne of *product*, linked with the S8 Carbon Report (Variny, 2021; Kittipongvises, 2017; BHP, 2019; Chen *et al.*, 2018; Li Zhu, 2014; Ecofys, 2009; Riesbeck *et al.*, 2013; Suer, Ahrenhold and Traverso, 2022; IEA, 2000; Tian, 2022; Wänerholm, 2016; Schmitz, 2021; Sun *et al.*, 2021).

The Carbon Report for the BF/BOF route has been created subsequently after operating the configuration in Figure 6-10, and presented the statement, displayed in Figure 6-11. This was followed by the creation of a BF-EAF-process-route simulation (Figure 6-12), representing the second most-common method of steelmaking, with a share of ca. 20% of global production. The emissions are per t of product at the respective stage. Figure 6-12 displays the configuration of the BF/EAF process route of steelmaking and Figure 6-13 the Carbon Report as produced by the S8 software. Initially, and as biomass has the potential to reduce CO_2 emissions by ~30%, the usage of biomass was implemented. The carbon reports displayed in Figures 6-14 and 6-15 provide the details, in direct comparison with the mathematical calculations from section 6.2 and the data from the MS Excel main spreadsheets and input data. The switching to energy suppliers which derive 100% of their energy from renewable energy sources is external to these configurations. The overall effect of switching to a green energy supplier, implementing renewable energy technology and using biogas from own production in on-site turbines, on CO_2 emissions and the achieved degree of energy independence are displayed in Chapter 5. The Simul8 process simulations and subsequent carbon reports demonstrate the effect of implementing biomass in the steelmaking process, as one of the Bio Steel Cycle components. These simulations were followed by configurations including the implementation of the CCUS process, and also the implementation of the Geomimetic© process, including off-gas flue stack filters, makes it possible to produce steel at almost '0' CO_2 emissions – for both, the BF/BOF and BF/EAF-process-route. The carbon reports to this effect are displayed in Figures 6-16 and 6-17. The simulations and resulting reports provided proof of concept of the Bio Steel Cycle, insofar as with implementation of only these two steps, out of seven (biomass and the carbon capture with filters and the Geomimetic process), the steel production CO_2 emissions could be reduced by 30% and to almost '0'. Therefore, proving the hypothesis that it is possible to produce steel without CO_2 emissions if the novel concept and strategy was being implemented.

7.5.2 Aspen+V12.1

The work with the Aspen+ software suites has been a steep learning curve, as this particular software has originally been designed for the chemical industry. Similar to other process simulation software packages, Aspen+ works on the principle of material, heat and work flows, whereas components such as solar panels (due to their UV rays to electricity conversion principle) and anaerobic digesters - are not available just yet. There are, however, ways to construct a working configuration, nonetheless.

To demonstrate a comparable configuration in either system, the basic components of steelmaking were used every time. For proof of concept, the basic input stream components were chosen to be used to simulate the one-hour BF process in a single blow of 20 minutes, based on a 330t capacity blast furnace. The Aspen+ greenhouse gas emissions calculations are also based on combustion events, which in the case of iron making is not the reality: the CO_2 emissions are the result of the O_2 being injected into the BF charge at 220psi and 1000°C, also causing the exothermic reaction and creating a 1700°C environment. The blast furnace operation is simulated in Aspen+ with an RGibbs reactor. Some general assumptions had to be made to simulate the BF/BOF process and focusing on the BF operation. As Aspen+ works with continuous flows and the calculations are in steady state, the amount of gas emitted per ton of hot metal produced in the blast furnace has been converted to a flow. 1.01325bar BF vessel pressure was set. In the simulation it has been considered that the production of one ton of hot metal lasts one hour, as the time to inject the 1000°C oxygen via tuyeres into the charge, called a blow, usually lasts ~20 minutes. The overall process producing liquid iron usually lasts ~40 minutes. Therefore, the gas emitted per ton of hot metal produced has been introduced in Aspen+ as a flow per hour. This assumption is making scaling of the simulation to the size of a real steel mill, such as the 330t capacity British Steel furnace in Scunthorpe, significantly easier. It will not have any impact on the final results, but it will be helpful in understanding the analysis of the final results, in that the energy produced in one hour - or the moles emitted per hour - equal to the energy or mass per ton of hot metal. The use of process simulation software to simulate situations in the iron and steel industry has been a useful tool for recreating otherwise costly pilot plants. Scientists, academics and professionals have used this technology to their advantage. As a relevant example, attempts have been made to incorporate biomass in steelmaking, in Wang *et al.* (2019). Encouragingly, also the integration of technical advances in the iron and steel industry have been re-created in a range of process simulation software packages. As documented in Wang *et al*. (2019), the usage of biomass and the processes involved have already been given some attention. The aim was to reduce the amount of coal and coke used, by introducing hydrogen and syngas. As demonstrated in Figure 7-5:

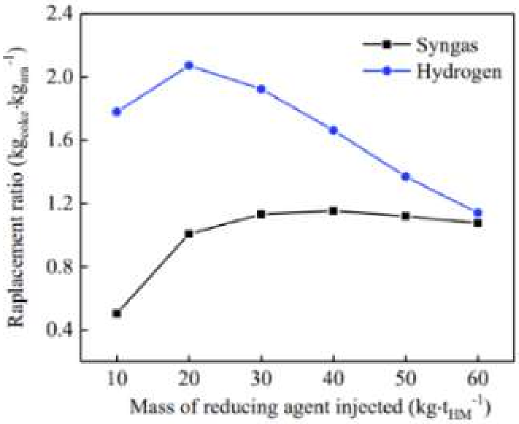


Figure 7-5: Influence of different reducing agents on coke rate (Wang, 2019)

Figure 7-5 illustrates the effect different reducing agents have on the coke rate, by using the replacement ratio. It seems apparent that a higher amount of coke (in weight) could be saved if the injection rate of syngas was increased from 10 kg·tHM-1 to 40 kg·tHM-1. The replacement ratio seems to vary after 40 kg·tHM1. Potentially, this could be associated with the higher percentage of hydrogen, alongside the increased injection of syngas. As is the nature of these elements, in the case of injecting 100% hydrogen into the BF, a smaller amount of coke can be replaced per injected amount of hydrogen. Considering an injection rate of >20 kg·tHM-1. In conclusion, it was found that lower hydrogen injection rates are a better mechanism to save on coke usage. Publications like these were the inspiration for the creation of a working model and 7-step to net-zero steel strategy, and attempts have been made to use the different already tried and tested system and combining these into one circular iron and steel production process: the Bio Steel Cycle.

In order to demonstrate proof of concept, process simulation configurations were built in Aspen+V12.1. To establish whether Aspen+ was suitable to trial selected stages of CO_2 emissions reduction measures implementation, the calcination and sintering process were taken as initial trial. RGibbs reactors in steady state were chosen, with an inside vessel pressure of 1.01325bar. 50000kg capacity was assumed. The section, as displayed in Figure 7-6:

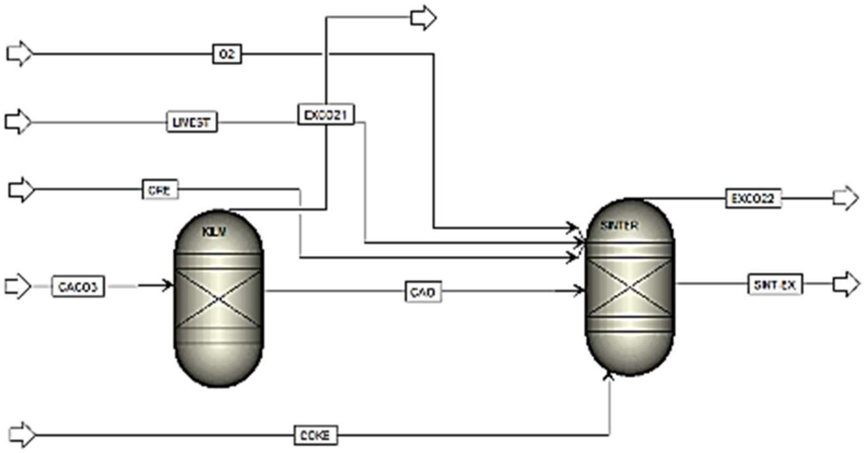


Figure 7-6: The limekiln and sinter oven section of the steelmaking process

Preliminary research findings pointed towards a CO_2 emissions burden of 2.760t and 2.25t of CO_2/ t of product, which was reported by the Aspen+ calculations, as displayed in Figure 7-7:

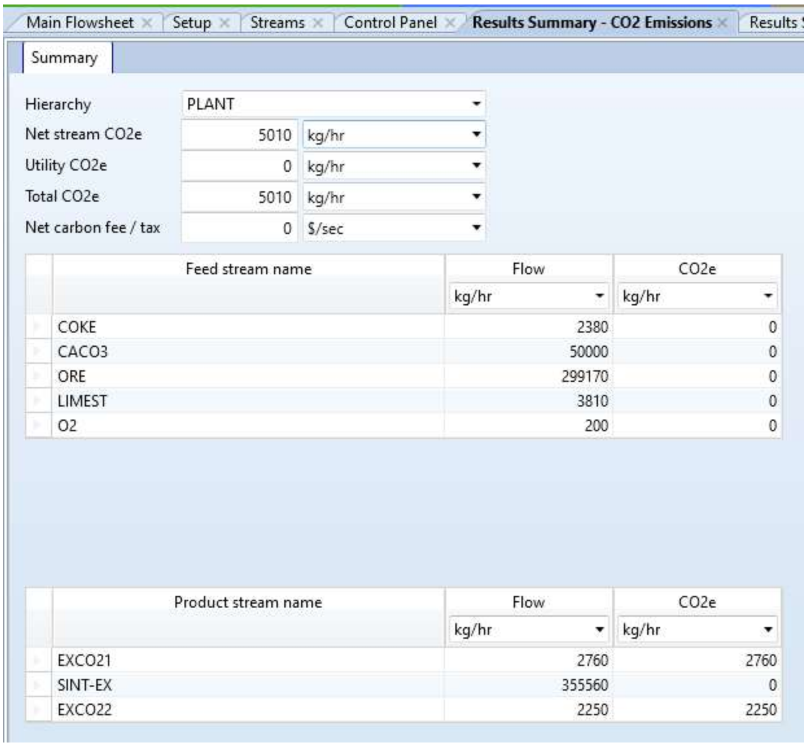


Figure 7-7: Aspen+ overview material flow and CO_2 emissions

Encouraged by these results, the basic layout of the BF operation was constructed as the starting configuration for the simulations, as displayed in Figure 7-8:

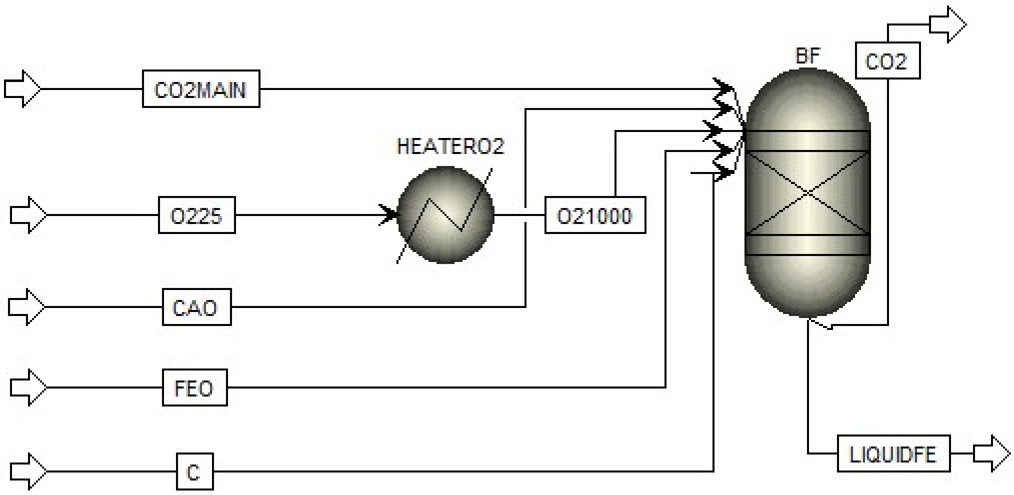


Figure 7-8: Blast furnace basic configuration for the production of liquid iron

Similar to the established between 2.1 - 3.2t as a result of preliminary research findings, the Aspen BF process simulation effectuated 977856t of CO_2 per charge, meaning 2.96t of CO_2 emissions per t of liquid iron (later steel), tapped from the bottom of the blast furnace. Thus confirming the findings of the literature review and mathematical corroborations of between 2.1 – 3.2t of CO_2e /t cs. The calculations were set to work for a 330000kg/330t blast furnace, similar to the British Steel site in Scunthorpe, and for the operational year of 1 hr, to reflect the 40-minute average charge processing and discharge time. The setup parameters, as follows, in Figures 7-9 - 7-11:

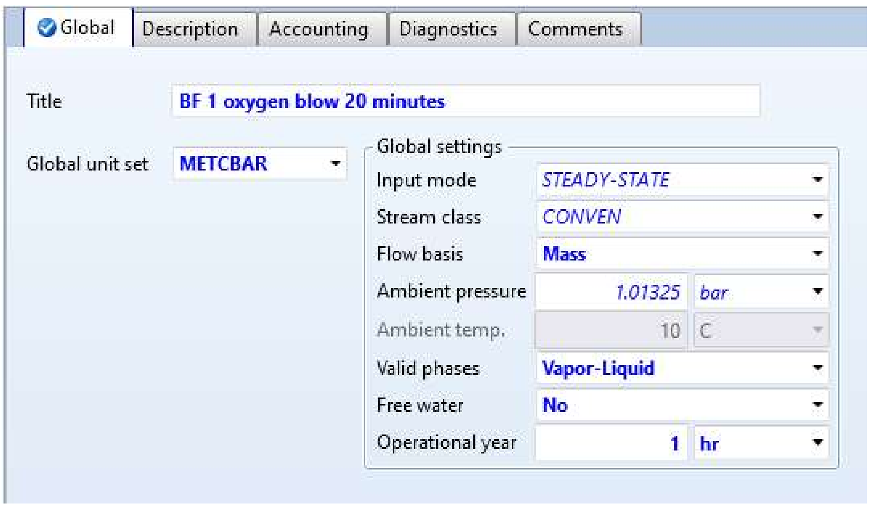


Figure 7-9: Setup parameters in Aspen

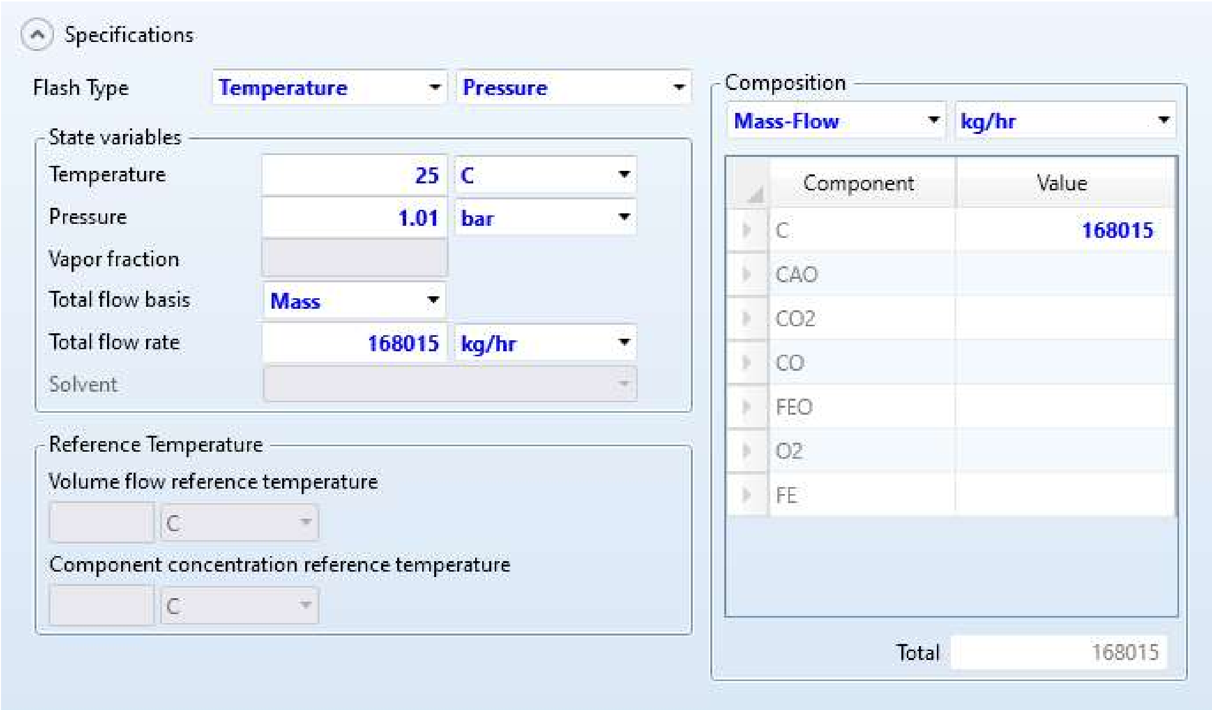


Figure 7-10: Material flow setup parameters in Aspen, with the example for coal/coke (C)

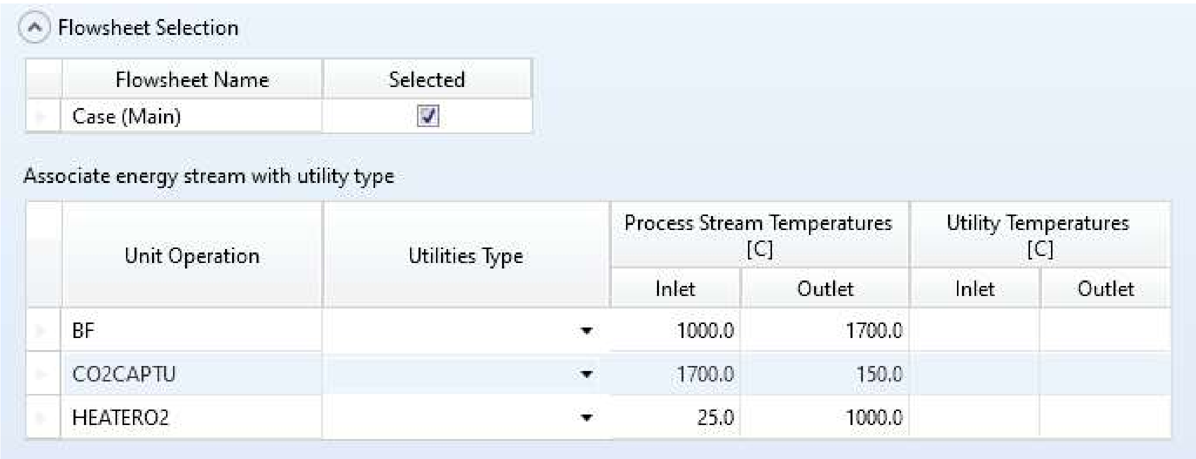


Figure 7-11: Input and outlet temperatures of the blast furnace configuration

The next step was to establish the reduction in CO_2 emissions when solar photovoltaic systems have been introduced, resulting in this configuration, as displayed in Figure 7-12:

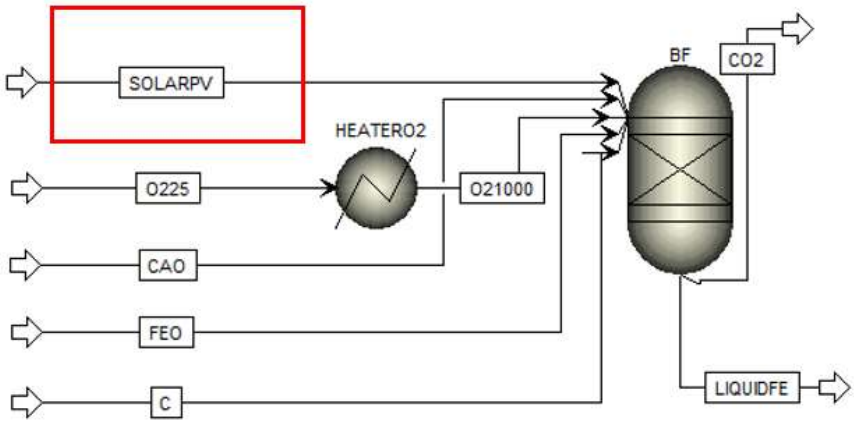


Figure 7-12:
Blast furnace basic configuration with solar PV panels for energy production on site installed

Based on research findings from the literature review, evaluation and extrapolations in MS Excel and mathematical validation, a 30% reduction in CO_2 emissions was the expected result to be seen reported. With 684499t of CO_2e reported, the 30% potential CO_2 emissions reduction was confirmed.

The Geomimetic© process has the single-highest impact, as it can reduce the CO_2 emissions (in theory, not only) in steel production to almost '0'. A Flash2 separator was used and an inside vessel pressure of 1.01325bar was assumed. This configuration was extended to the following, displayed in Figure 7-13:

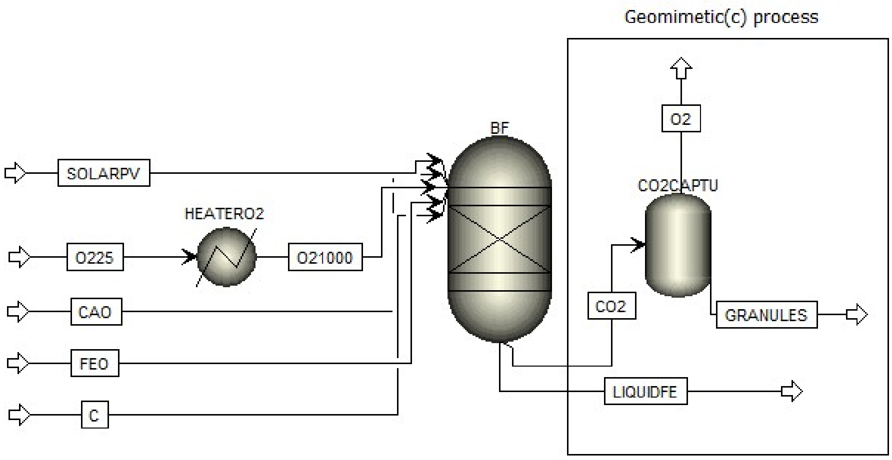


Figure 7-13: BF configuration with solar PV and the Geomimetic© process installed

As initially mentioned, all simulation software work in a similar, yet different way. Confirmed 100% CO_2 capture with the installed Geomimetic© system, insofar as the captured off-gas was split into 72.71% O_2 and 27.29% CO_2 granules for further usage in a different environment. Interestingly, though, the CO_2e result has increased again by implementation of the Geomimetic© process from 684499kg to 758019kg of CO_2 emissions, which upon investigation, was identified as the energy required to separate the O_2 and CO_2, as displayed in Figure 7-14:

Product stream name	Flow	CO2e
	kg/hr	kg/hr
LIQUIDFE	236872	0
O2	758019	758019

Figure 7-14: Increased CO_2 emissions after splitting the BF CO_2 gas into O_2 gas and CO_2 granules

Encouraged by these results, the configuration for the basic oxygen furnace was constructed, also containing the section of the Geomimetic© process, and additionally, twice the 30% reduction in CO_2 emissions considered due to switching to a "green" energy provider *and* installing solar PV panels for energy generation. Additionally, the Geomimetic© process was also implemented here, splitting of the off-gas CO_2 into O_2 gas and CO_2 granules, resulting in a CO_2 greenhouse gas emission of effectively '0', as the CO_2 from the BOF was captured at 100% in the Geomimetic© unit, as displayed in Figure 7-22.

The resulting CO_2 emissions report calculated 469243kg of CO_2 emissions per 20-minute oxygen blow at 25°C of 22864kg of oxygen at 150 psi in the BOF, as shown in Figure 7-15:

Product stream name	Flow	CO2e
	kg/hr	kg/hr
C35STEEL	146633	0
O2	469243	469243
GRANULES	5.71657	0

Figure 7-15: BOF configuration with "green energy" provider, solar PV panels installed and the Geomimetic9c) process in place

The integration of Bio Steel Cycle components in Aspen followed subsequently, as displayed in Figure 7-16:

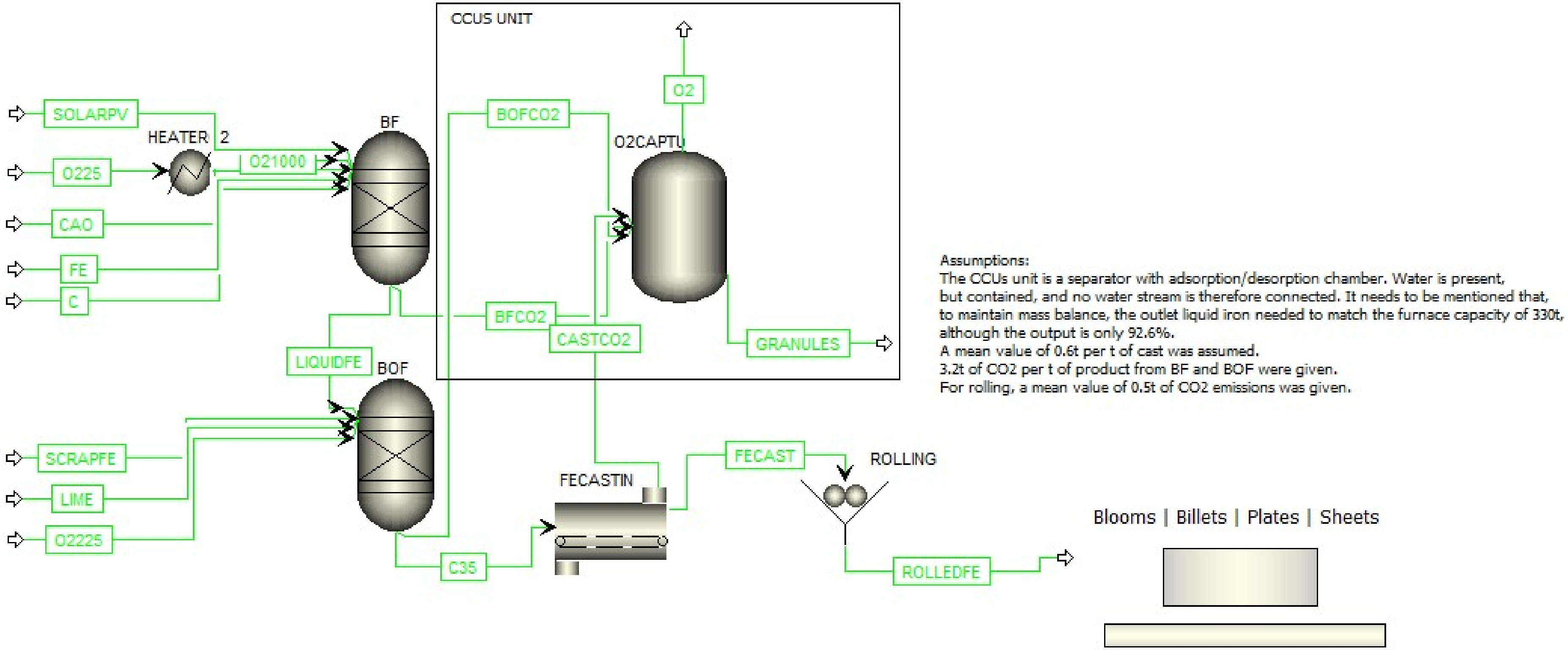


Figure 7-16: Aspen Bio Steel Cycle component integration layout

7.5.3 INOSIM

As mentioned in section 7.6.2, all simulation software work in a similar, yet different way. Most operate with an MS Excel-like structure underneath all the surface applications and input screens, and hence the results are similar. INOSIM is no exemption yet has some features which are not available in other applications, such as Simul8 or Aspen: there are pre-installed functions for bioprocess engineering features, such as autoclave, fermenter, heat steriliser and UV steriliser. Most elements of the BiSC could be demonstrated using INOSIM (Figure 7-17):

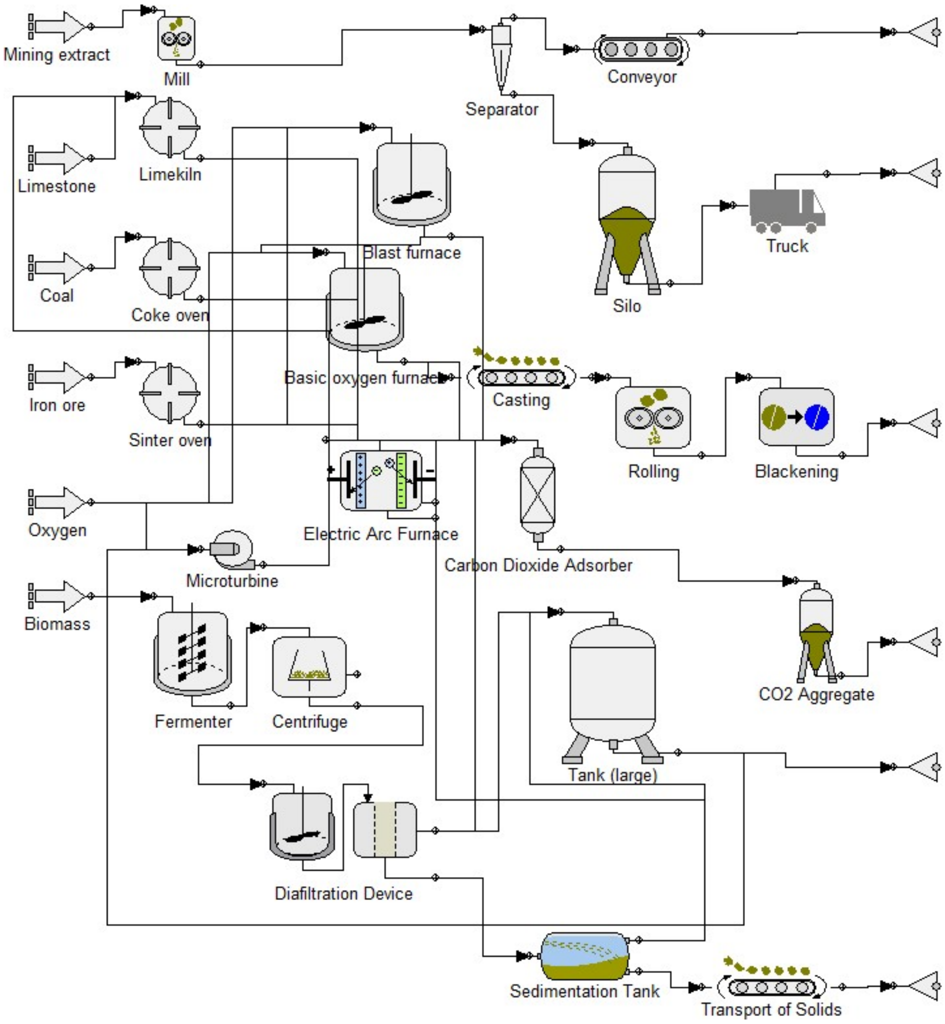


Figure 7-17: INOSIM BF/BOF process simulation with CCUS and biogas utilisation

Confirmed 100% CO_2 capture with the installed CCUS system, insofar as the captured off-gas was split into 72.71% O_2 and 27.29% CO_2 granules for further usage in a different environment. Interestingly, though, the CO_2e result has increased again by implementation of the CCUS process from 684499kg to 758019kg of CO_2 emissions, which upon investigation, was identified as the energy required to separate the O_2 and CO_2. INOSIM provides a vast range of reactors and bioengineering components, which allowed for easy integration of the innovative Bio Steel Cycle model. Components such as fermenters are provided, which have yet to be found to be available from any other process simulation software.

7.6 Conclusions

The following table 7-4 will display the values and sources in literature, as a result of mathematical extrapolations, iterations in MS Excel, leading to establishing the values later applied in the process simulations:

Table 7-4 : Overview CO_2 emissions values applied and literature sources/URLs

*Specific energy consumption (SEC) was added where appropriate (Li Zhu 2014)
**References from table 3-3

Steel production stage	LR MS EXCEL CO_2 / t product*	Values applied in simulations	Literature Reference**
Oxygen	*0.26t*	*0.26t*	*Variny, 2021*
Limestone	*0.04t-2.31t*	*0.035t*	*Kittipongvises, 2017*
Iron ore	*2.19-6.40t*	*2.19t*	*BHP, 2019*
Coal	*5.43-12.31t*	*5.43t*	*BHP, 2019*
Coking	*2.97-3.14t*	*2.59t*	*Chen et al., 2018 (SEC) Li Zhu, 2014*
Calcination	*2.21-2.32t*	*2.21t*	*Chen et al., 2018 (SEC) Li Zhu, 2014*
Iron ore pelletising	*0.04-0.45t*	*0.035t*	*Ecofys, 2009*
Sintering	*0.04 – 0.97t*	*0.93t*	*Ecofys, 2009 Riesbeck et al., 2013*
Blast Furnace	*2.1-3.20t*	*2.95t*	*Suer, Ahrenhold and Traverso, 2022*
Basic Oxygen Furnace	*1.6-3.13t*	*2.0t*	*IEA, 2000 Tian, 2022*
Casting	*0.2 -1.22t*	*1.22t*	*Wänerholm, 2016*
Rolling	*0.26-1.00t*	*1.0t*	*Schmitz, 2021*
Finish Machining	*0.15*	*0.15t*	*Sun, 2021*

The BiSC components were applied, and the total CO_2 emissions reduction results were exported from Aspen and sent to MS Excel. The values were then modelled and expressed in a graph, as displayed in Figure 7-18:

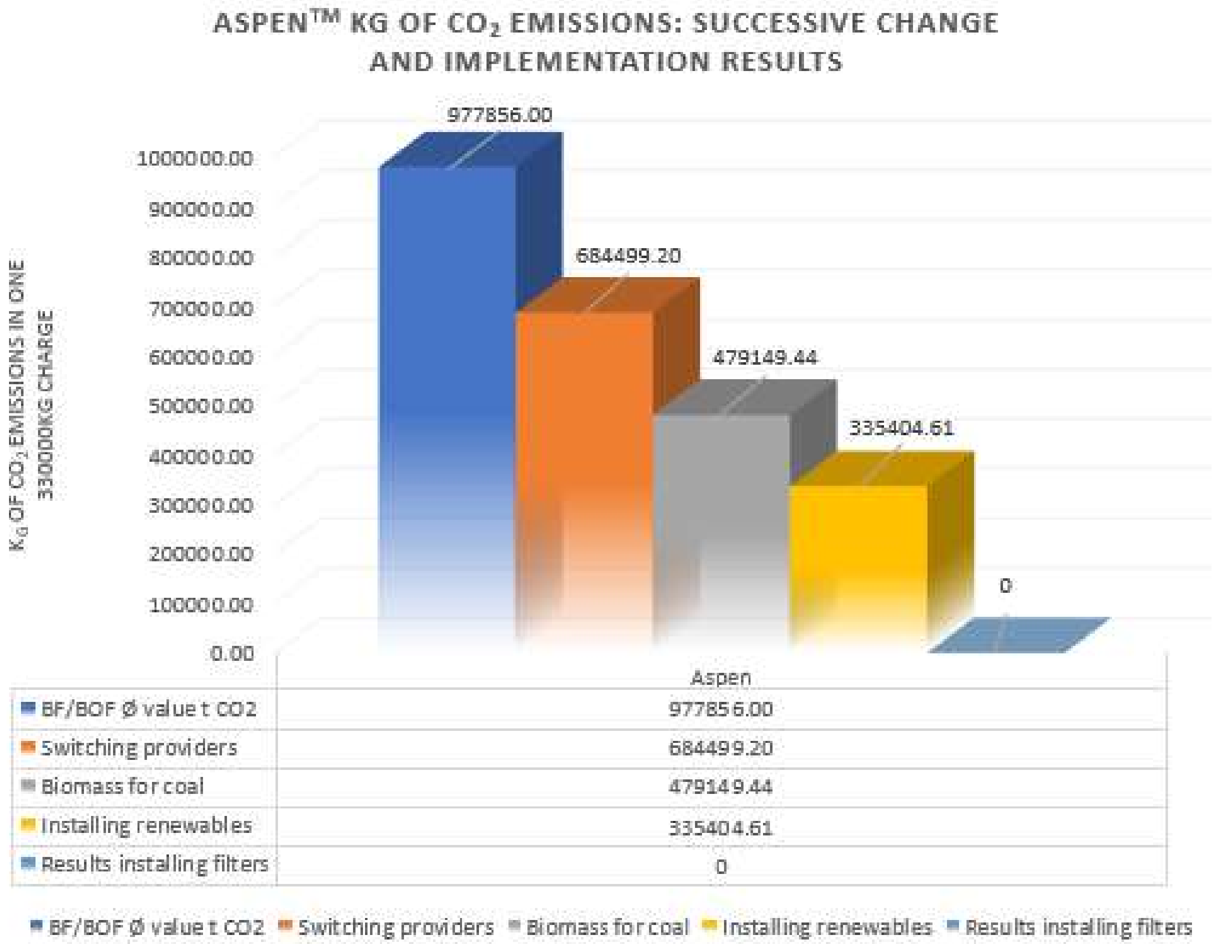


Figure 7-18: CO_2 emissions reduction results were exported from Aspen to MS Excel

Conclusively, it is safe to say that the different simulations provided proof of concept and rendered the 1 hypothesis as valid: it is possible to reduce CO_2 emissions in steel production to almost ‘0’, when the Bio Steel Cycle model and strategy is being implemented, in sections or entirely.

The CO_2 data accumulated as a result of the literature review, mathematical analysis of afore mentioned, MS Excel data compilation, evaluation, modeling and analysis, statistical validation and the process software simulations in Aspen, Simul8 and Inosim have provided congruent data and results.

Chapter 8 Knowledge contribution

8.1 PESTEL and SWOT Analysis green steel

8.1.1 Introduction

PESTEL analysis (Figure 8-1) of the UK has been carried out with attempting to add some information to answer some aspects of one of the research issues and to establish the current market situation for green steel, with a view to aligning production practice to Circular Tech Economy processes. This aims to address the framework of the political, economic, social, technological, environmental, and legal issues present in the UK today.

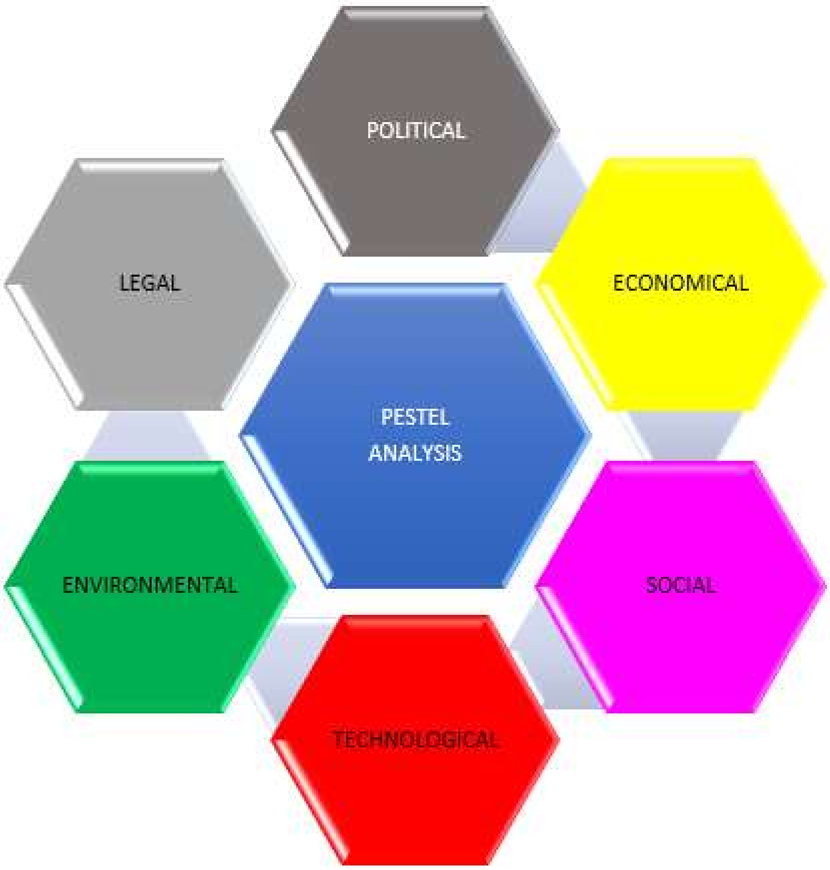


Figure 8-1: PESTEL Analysis

8.1.2 Political factors affecting the UK

The United Kingdom (UK) consists of England, Wales, Scotland and Northern Ireland, and until recently, was one of the most powerful countries in the world, with the capital London – which is still a globally powerful centre of business, finance and culture. Despite the latest controversy in political realms, it is still in theory a modern parliamentary democracy and a constitutional monarchy with the monarch being the Head of State. The Government is headed by the prime minister, who is the elected head of the government over a five-year term. The political landscape is mainly being dominated by four political parties: Labour, Conservative, Liberal Democrats and the Scottish Nationalist Party. Political stability used to be one of the great strengths of the country; however, politics of austerity, "Brexit" (the exit of the UK from the European Union framework) and the COVID-19 pandemic have created political uncertainties, cultural divide, rising unemployment, bringing the NHS (National Health Service) to the brink of collapse and caused unprecedented, partly questionable spending by the treasury – currently under investigation in the so-called "Covid-Enquiry".

Some experts (Giles, 2022) and analysts believed that Brexit would result in unimaginable devastation across the economy, although some consider Brexit an immense opportunity for the country (Tetlow and Stojanovic, 2018). The polar-opposite seems to unfold, though: the recent 25% rise in racially aggravated violence and crimes has caused serious concerns (Nandi and Luthra Reichl, 2023) and the 2022/2023 cost-of-living crisis demonstrates that Brexit has been very harmful to the UK, indeed. The UK continues to maintain good relations with the United States, and many other countries across the world, although the relations with the EU and Commonwealth countries have come under some strain in 2022. As a permanent member of the United Nations with influence on global economic, cultural, military, scientific and political affairs, the country is aiming now to realign its global position in the wake of Brexit. The so-called "Green Industrial Revolution" (HM Government UK, 2020) paper includes a 10-point plan, and all the efforts amount to a lamentable total of only 40.76% in carbon emission savings projected to have been achieved by 2030, if all measures described were to be implemented. Academic and scientific publications, governmental guidance papers and legislative frameworks influence the political landscape in any given country. In the following, Figure 8-2 shows a timeline of publications with significant influence on global politics with regard to the green agenda:

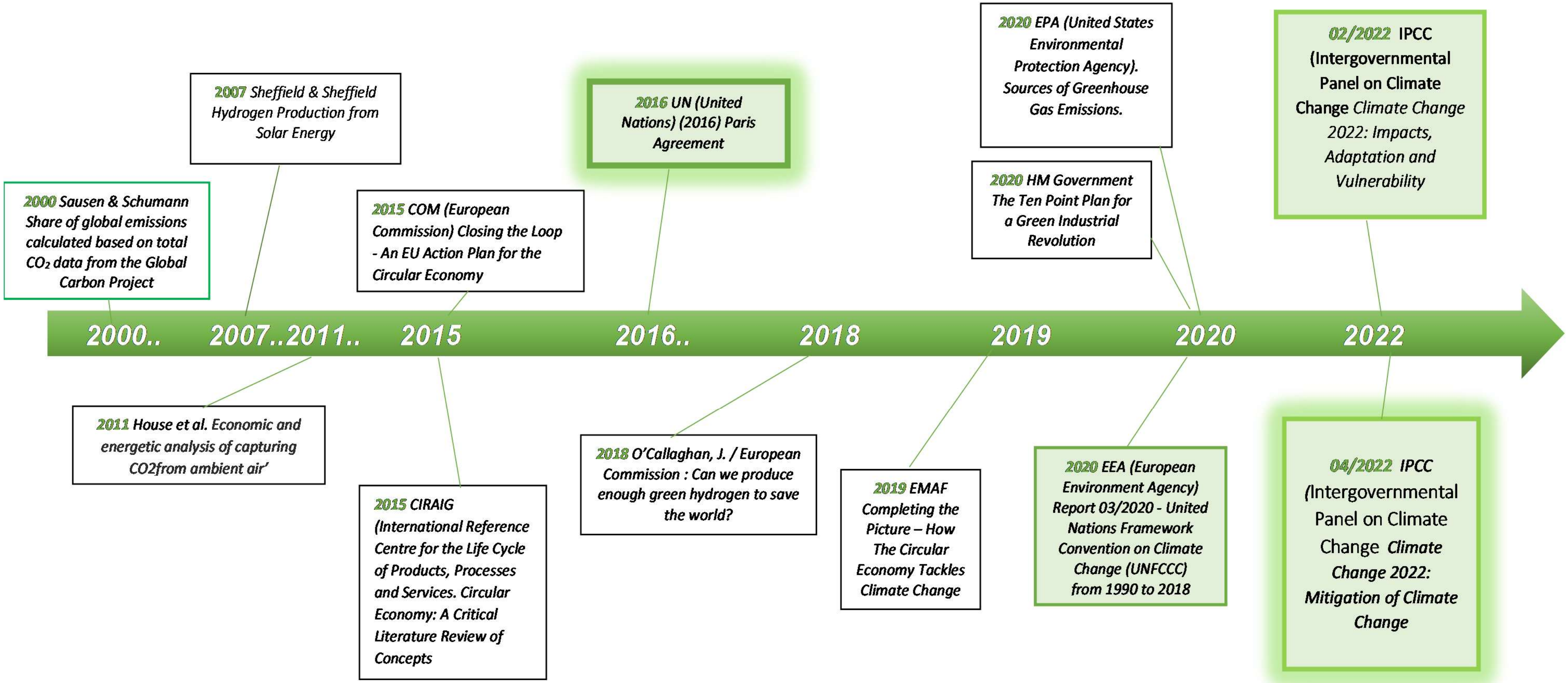


Figure 8-2 : Timeline of key publications on sustainability

The key literature influencing the political landscape in the UK with regards to sustainability, Circular Economy and Circular Tech Economy and CAT (carbon avoidance technology), CCS (carbon capture and storage) and CCUS (carbon capture, storage and utilisation) have been thoroughly reviewed. The timeline (Figure 8- 2) shows the key papers which constitute the foundation behind the thinking for creating the Bio Steel Cycle model and strategy.

Respiratory function of most living creatures is emitting carbon dioxide, for a reason: most plants require CO_2 to grow. The natural carbon emissions cycle has been perfectly designed by nature, but anthropogenic production of CO_2 emissions beyond the requirements of living things for this – initially – naturally occurring gas, has reached levels which are non-conducive to life of oxygen-dependent organisms (UN, 2016; EEA, 2020,2021; IPCC, 2021, 2021a,2022, 2023a).

The IPCC published in quick succession two critical papers in February and April 2022, sounding the climate alarm bells: despite 192 country's commitment in the Paris Agreement (UN, 2016) to do everything in their power to mitigate the impact of GHGs on our climate, industrial CO_2 emissions are at an all-time high (IPCC, 2022, 2022a, 2022).

One of the results of this inaction we are currently experiencing is the climate crisis, as our planet is heating up to unprecedented temperature levels, and frequent fires and flooding across the globe are devastating large swatches of arable land, which is incompatible with human habitation. Key guidance papers are displayed in Table 8-1:

Table 8-1: Table circular tech economy and key guidance papers

Author/Year	Title	Description/Comments
Farla and Hendriks, 1995	Carbon dioxide recovery from industrial Processes	One of the first comprehensive studies on the techno-economic performance of CO_2 capture in high-volume carbon-emitting industries for the iron and steel industry and the petrochemical sector. 1st comprehensive study CCS/CCU; Beware: in 1995, only the application of chemical absorption to capture CO_2 was considered the industry standard.
Sausen and Schumann, 2000	Estimates of the climate response to aircraft CO2 and NOx emissions scenarios	Investigated greenhouse gas (GHG) and – specifically – aviation CO2 emissions with data from the Global Carbon Project. Aviation is one of the main contributors to global GHGs and on the list of future research.
Ture, 2007	Assessment of H_2 Energy for Sustainable Development	Hydrogen Production from Solar Energy. First comprehensive analysis into green hydrogen
House *et al.*, 2011	Economic and energetic analysis of capturing CO_2 from ambient air	Investigated the opportunities of economic and energetic analysis of capturing CO2 from ambient air. In conclusion, they established that the total. DAC, energy and economics analysis; levelized cost of $80.-/MWh natural gas advanced combined cycle is the lowest total levelized energy cost. $/(tCO2 avoided), hydro power is the most cost efficient at lowest risk for humans/environment, at $748/t of CO_2 captured
COM (European Commission), 2015	Closing the Loop - An EU Action Plan for the Circular Economy	Identifying the sources of and potential ways to reduce GHG emissions. Insight into transition to minimising waste, developing a resilient, sustainable, low- CO_2, resource efficient and competitive economic model. Milestone guidance paper.
UN United Nations, 2016	Paris Agreement	It binds all signing countries to secure a sustainable global economic recovery and net-zero emissions future (all GHG and other toxic emissions are also ringfenced within this agreement). One of the main goals is: limiting global temperature rise to <1.5°C, endeavouring to avert the worst ecological, financial and economic impacts of climate change. 193 Parties (192 countries plus the European Union) out of 197 in total signed this commitment to more sustainable practice. Iran, Libya, Yemen and Eritrea have not yet ratified the agreement per June 2022.
O'Callaghan, 2018	Can we produce enough green hydrogen to save the world?	Exploration of 'Green' hydrogen – produced utilising exclusively renewable energy technologies - as an alternative to fossil fuels. Investigation of the TRLs and implementation potential.
EMAF Ellen MacArthur Foundation, 2019	Completing the Picture – How The Circular Economy Tackles Climate Change	EMAF carried out a thorough critical literature review of concepts concerning circular economic processes. EMAF have the Butterfly model – the key concept to the Circular Economy.
UNFCCC, 2020	Report 03/2020 - United Nations Framework Convention on Climate Change (UNFCCC) from 1990 to 2018	Investigating the necessary steps and issuing guidance on how to achieve sustainability in Europe. This constitutes the official inventory submission of the European Union for 2020 under the UNFCCC, as well as the Kyoto Protocol (KP), covering the years between 1990 and 2018. Key guidance paper on knowledge for transition to a sustainable Europe.
USEPA United Nations Environmental Protection Agency, 2015; 2023	Greenhouse Gas Emissions - Sources of Greenhouse Gas Emissions	Identifying the sources of and potential ways to reduce GHG emissions. US guidance papers.
IPCC (Intergovernmental Panel for Climate Change), 2022	Climate Change 2022: Impacts, Adaptation and Vulnerability	Identifies effects on the environment and those populations most at risk and how to mitigate these effects. Key report.

Going back more than 40 years, the beginnings of a change in thinking towards a more sustainable way of using our resources and the environment, has resulted in additional literature considered as direction-giving for developing more sustainable practice in the steel industry:

Aylen (1980) reviewed common steel making practice and reviewed manufacturing protocols, utilising records dating back to 1890 and to 1980, and economic reports in order to develop innovative practice, technological progress and economic performance improving concepts for the British Steel Industry. The findings pointed towards Britain being a net-steel importer, due to low labour productivity and no research and development investment towards more efficient and resource (environment) saving practices.

Farla and Hendriks (1995) compiled one of the first comprehensive studies on the techno-economic performance of CO_2 capture in high-volume carbon-emitting industries for the iron and steel industry and the petrochemical sector, although at the time only the application of chemical absorption to capture CO_2 was considered the industry standard.

Since the late 1990s, a significant number of studies focused on a broad range of industrial sectors, with one of the main contributors being the European Commission (COM) (Canadell *et al.*, 2003), where a broad variety of carbon capture methods were investigated (COM (European Commission), 2010, 2015), with the side-effect of identifying technologies which were potentially more cost-effective than the chemical absorption/adsorption method, such as the European Cement Research Academy (ECRA, 2009; WBCSD, 2017). They investigated carbon capture and storage solutions for heavy industries and the cement industry.

Over the last 20 years, climate change and its effects on the global population, the natural world and our way of using up finite resources at an accelerating rate has been investigated and researched by a range of countries and numerous specialists and in the respective fields. The researchers aim was to establish a viable, economically and ecologically sound circular tech-economic concept which could support the efforts of carbon avoidance, capture, utilisation and storage to avert the worst effects of climate change.

Sausen and Schumann (2000) had already investigated greenhouse gas (GHG) and – specifically – aviation CO_2 emissions with data from the Global Carbon Project. Lee *et al.* (2021) established how significant the impact of global aviation factually is in terms of CO_2 emissions produced, radiative forcing (RF) and effective radiative forcing (ERF) and the significant impact on climate change. The sums calculated refer to the years between 2000–2018.

Ture (2007) researched the opportunities which lie within hydrogen production from solar energy, with hydrogen being a credible alternative to using fossil fuels in industrial applications. Effectively, CO_2 emissions were removed from hydrogen production, establishing that it is both economically and practically viable to produce hydrogen using solar energy - making hydrogen a renewable energy source.

In the context of the post-Kyoto era (UNFCCC, 2005), where 192 nations signed agreement and cooperation, the European Commission and 47 industrial partners in 15 European countries, in industry and academia, supported the ULCOS (COM, 2010) project between 2004 and 2010 with the aim to develop ultra-low CO_2 steelmaking technology.

The approach was to develop:

(1) new carbon-based smelting-reduction concepts
(2) investigate the potential of new and less common reactors
(3) natural-gas-based pre-reduction reactors
(4) green hydrogen-based direct reduction using hydrogen
(5) direct steel production by electrolysis
(6) the use of biomass
(7) CCS.

The ULCOS program investigated the techno-economic viability of a vast range of low carbon iron and steelmaking technologies, including and excluding CCS, in a variety of scenarios. Some of their findings suggest that carbon capture via chemical absorption/desorption is less economical than other commercially available CO_2 capture technologies.

Most of these afore mentioned studies have been reviewed and compared in the UNIDO Industrial CCS roadmap project (UNIDO United Nations Industrial Development Organization, 2010, 2011; Zakkour and Cook, 2010), which resulted in five sectoral assessment reports: 1) Biomass, 2) high-purity CO_2 sources, 3) iron and steel, 4) refineries, and 5) cement; a technical synthesis report (DeConinck and Mikunda, 2014) and a policy brief for the 16th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCC, 2010).

House *et al.* (2011) investigated the opportunities of economic and energetic analysis of capturing CO_2 from ambient air. In conclusion, they established that the total levelized cost of $80.-/MWh natural gas advanced combined cycle is the lowest total levelized energy cost, whereas with regards to the $/(t$CO_2$ avoided), hydro power is by far the most cost efficient and bears the lowest risk for humans and the environment, at $748/t of CO_2 captured.

CIRAIG (2015) and EMAF (2019) carried out thorough critical literature review of concepts concerning circular economic processes, covering the following issues, presented in order of conceptual scale (from more to less encompassing):

- Sustainable Development
- Ecological Transition
- Green Economy
- Functional Economy
- Life Cycle Thinking
- Cradle-to-cradle thinking
- Shared Value
- Industrial Ecology
- Extended Producer Responsibility
- Eco design

In 2015, the European Commission issued a milestone guidance paper, an EU action plan for circular economic process (COM, 2015a), which is quite similar to the five years later issued United States Environmental Protection Agency (EPA) paper (Desai and Camobreco, 2020), identifying the sources of and potential ways to reduce rising GHG emissions.

One of the results of the EU countries' efforts towards averting climate disaster was the Paris Agreement, which was signed in 2016 by representatives of 192 member states of The United Nations (UN). It binds all signing countries to secure a sustainable global economic recovery and net-zero emissions future (not only zero CO_2 emissions – greenhouse gases (GHG) and other toxic emissions are also ringfenced within this agreement). Iran, Libya, Yemen and Eritrea have not yet ratified the agreement, per June 2022. One of the main goals of the Paris Agreement (UN, 2016) is to limit global temperature rise to no more than 1.5°C, as achieving this would avert the worst ecological, financial and economic impacts of climate change.

In 2018, O'Callaghan wrote for the European Commission about 'green' hydrogen – produced utilising exclusively renewable energy technologies - as an alternative to fossil fuels (O'Callaghan, 2018). Possibly inspired by this, Sunny, Mac Dowell and Shah (2020) investigated the issue of what might be needed to deliver carbon-neutral heat using hydrogen and carbon capture and storage (CCS), which led to the discovery that it is entirely possible to produce hydrogen based on using renewable energy technologies. O'Callaghan (2018) found that, currently, around 20% of all GHG emissions are produced by industries such as steel and cement. It is therefore vital to develop promising technologies and concepts in these areas. Siemens was referred to as claiming that '…Hydrogen and fuels derived … capable of reducing the CO_2 from fossil fuels … down to zero'. O'Callaghan (2018) and Sunny, Mac Dowell and Shah (2020) referred to hydrogen technology as a concept based on generating energy exclusively utilising renewable energy technologies. The opportunity for transition to minimising waste, developing a resilient, sustainable, low carbon, resource efficient and competitive economic model must be taken seriously across Europe. As a side-effect, energy will be saved and also irreversible damages avoided, which are currently caused by using up resources at an unsustainable rate, as it exceeds the Earth's capacity for renewal – as far as climate and biodiversity, air, soil and water pollution are concerned (COM, 2015a; USEPA, 2015; EEA, 2020,2021; IPCC 2021, 2022, 2022a, 2022). One of the key drivers to achieve the set objectives is a major initiative called "Horizon 2020", the purpose of which is to fund innovative projects and targeted action in areas such as plastics, food waste, construction, (critical) raw materials, industrial and mining waste, consumption and public procurement (COM, 2018). HM Government issued 'The Ten Point Plan for a Green Industrial Revolution' in 2020 (HM Government UK, 2020), covering the issue that most emissions are being produced through the burning of fossil fuels for electricity, heat, and transportation. The 6 sectors identified for being the most polluting are, as follows:

- Electricity
- Transportation
- Industry
- Commercial/ Residential
- Agriculture
- Land Use/ Forestry

Unfortunately, the efforts and plans currently in place amount to only a total achievable CO_2 reduction of a mere 40.76%, with the potential to increase these efforts, based on the roadmap for further policies, to achieve a net-zero-carbon economy by 2050.

Omoregbe *et al.* (2020) compiled a bibliometric analysis of the scientific discourse during 1998–2018, focusing on carbon capture and the three main types of technology, namely precombustion, post-combustion and oxy-fuel combustion carbon capture. The findings of the bibliometric analysis showed that post-combustion capture seems to be the most referenced carbon capture technology with ~80.9% of total publications retrieved, and oxy-fuel combustion showed the least number of publications (3.4%). The European Union was the single biggest contributor to publications relating to the development of carbon capture technology (CCT), as displayed in Figure 8-3:

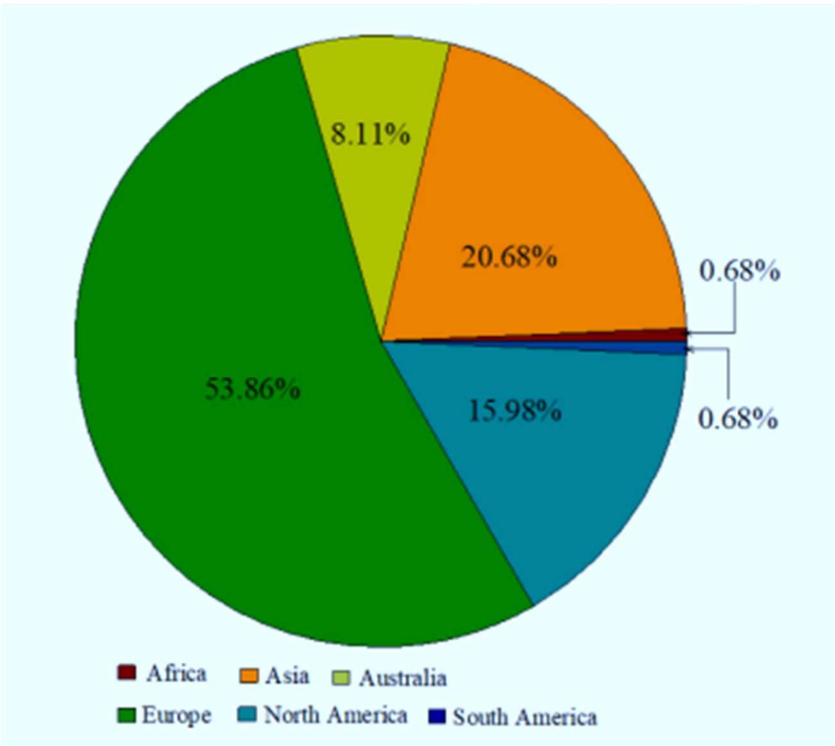
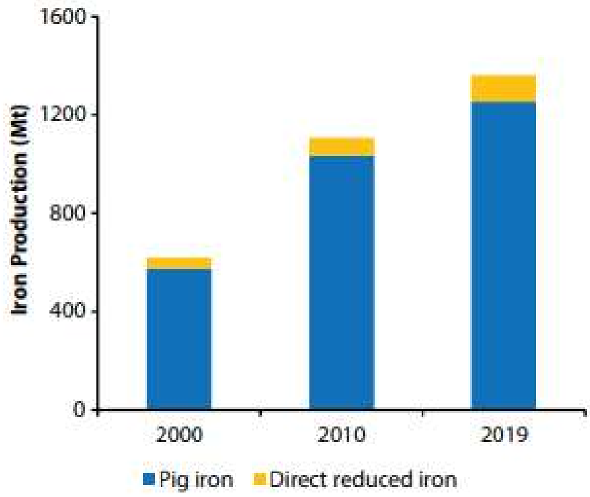


Figure 8-3: Participation of continents in CCT related research in terms of percentage of publications Omoregbe *et al.* (2020)

Although the COREX process has been the dominating smelting reduction process commercially operating worldwide, Yi *et al.* (2019) found that FINEX can be considered as having more potential for large-scale CO_2 removal, as the systematic development of the FINEX process is showing promise: energy recovery systems, binders for coal briquettes and a steel-grid system in FBR (Fluidized-Bed Reactor) achieved reductions in economic terms and the overall environmental footprint. One of the biggest advantages of the FINEX over the COREX process is that the FINEX process enables the direct use of sinter feed fine ore Yi *et al.* (2019). The scale of typical smelting reduction steelmaking plants is smaller than that of typical BF-based plants, as the graph below will show the percentage of direct reduced iron has increased decade on decade from 2000, as displayed in Figure 8-4:

Figure 8-4: Iron production 2000, 2010, 2019 (Yi et al. 2019)



The European Environment Agency Report 03/2020 constitutes the official inventory submission of the European Union for 2020 under the UNFCCC, as well as the Kyoto Protocol (KP), covering the years between1990 and 2018. The European Union (EU), party to the United Nations Framework Convention on Climate Change (UNFCCC), issues these reports on greenhouse gas (GHG) inventories annually, for emissions and removals within the area taking place within its territory. Due to the nature of this lag in reporting, the 2020 inventory report cannot yet reflect the effects which the COVID-19 pandemic might possibly have had. Although the UK left the EU in 2020, EU law still applies until the end of the transition period. Moreover, key provisions of Regulation (EU) No 525/2013 ("Mechanism for Monitoring and Reporting GHG") and of Decision No 406/2009/EC ("Effort Sharing") apply to the United Kingdom also in respect of greenhouse gases emitted during 2019 and 2020. The EU and it's agreed to a quantified emission reduction commitment, which will limit their average annual GHG emissions to 80 % of the sum of their base year emissions, reflected in the Doha Amendment.

GHG emissions decreased in the majority of sectors between 1990 and 2018, with the notable exception of transport, including international transport, and refrigeration and air conditioning. Considering the aggregate level, the highest emission reductions were achieved in manufacturing industries, construction, electricity/heat production, iron/steel production and domestic combustion.

Allegedly, contrail cirrus (the condense clouds one can observe as an air signature of a plane's flight path), consisting of linear contrails and the cirrus cloudiness arising from them, yields the most significant warming ERF, closely followed by CO_2 and NOx emissions. Interestingly, emissions of sulphate aerosol formation results in a negative (cooling) term. In conclusion, the mean contrail cirrus ERF/RF ratio of 0.42 indicated that contrail cirrus is less effective in surface and atmospheric warming than other terms. It was established that by 2018, the net aviation ERF is +100.9 milliwatts (mW) m^{-2}, meaning a 5–95% likelihood range (of 55, 145) with significant contributions from contrail cirrus (57.4 mW m^{-2}), CO_2 (34.3 mW m^{-2}) and also NOx (17.5 mW m^{-2}).

With the publications in February and April 2022, the IPCC (Intergovernmental Panel on Climate Change) sounded the climate alarm bells and had scientists and informed citizens reeling with despair: despite the Paris Agreement in 2016, where 192 out of 197 countries signed a firm commitment to doing everything to keep the global temperature rise to <1.5°C, and scientists, industry and academics rallying to find solutions to mitigate GHG emissions and reduce the impact of anthropogenic CO_2 emissions, the situation only seems to get worse. The research and study of these key papers has led the author to develop the Bio-Steel-Cycle (BiSC) and connected models and strategies. It is worth considering that every component within the circular model of the BiSC represents a cyclical model in itself, which will be explored in future research.

Furthermore, the unfortunate issue of giving planning consent for the first coal mining plant creation (BBC British Broadcasting, 2022) in 30 years and nuclear power plant creation (Watt, 2017) will be *adding* an incalculable amount of GHG and CO_2 emissions. Through construction, building and operation of required infrastructure – besides the known risks of combusting coal as one of the largest emitters of CO_2, and operating nuclear power plants, as demonstrated by the Chernobyl disaster (World Nuclear Association, no date) and the potential for illegal weaponising of by-products, such as plutonium.

Besides having issued the planning permission for a new EDF (Energy de France) nuclear power plant at Hinckley Point (Watt, 2017), the UK government has just issued a coal mine in Cumbria (BBC British Broadcasting, 2022) in December 2022, which bodes even worse for the UK's commitment to decarbonising manufacturing. However, some political manoeuvres give hope: British Steel and Tata Steel have secured government funding of £300m, each, for decarbonising steel production. under the premise that they will secure a total of 7.500 British jobs. British Steel employs ca. 4,000 people across its operations, including at the plant in Scunthorpe, and India's Tata employs 3,500 people in Port Talbot in South Wales (*BBC News*, 2023).

This bodes well for the political climate towards green steel, bringing decarbonisation of the steel industry in the UK that little bit closer to reality.

8.1.3 Economic factors affecting the UK

The economy of the United Kingdom is the 5th-largest national economy in the world (by GDP), 9th-largest by purchasing power parity (PPP), and 22nd-highest by GDP per capita, constituting 3.3% of nominal world GDP (WEF World Economic Forum, 2019). The UK has recently been overtaken by India as being the 5th-largest economy, due to 13 years of successive UK conservative government policy and dismantling of the public sector (WEF, 2023). Although the recession in 2008 hit the UK economy hard and COVID-19 is adding to these woes, the government aimed to lessen the impact of the global recession. The attempt was made by implementing adequate measures, such as quantitative easing, The Bank of England lowering bank interest rates for UK banks borrowing money, improving redundancy protection, issuing renters eviction protection during the COVID-19 crisis and setting National Minimum Wages, to safeguard the economy and the UK population against any negative economic impact Brexit and Covid-19 might cause. Unfortunately, failed policies and government intervention have led to an inflation rate rise of 10.1% in November 2022 (Francis-Devine *et al.*, 2023)

Foreign Direct Investment (FDI) by private investors and organisations from around the world have injected immense financial impetus into a variety of industries in the UK – such as sports, real estate, technology, the car industry and the grocery sector.

Although the cost-of-living-crisis and inflation were at an all-time high at 10.1% in March 2023, the economy grew by 0.3% in January 2023. The country is expected to just about escape a recession and return to the net growth in 2024 (BCC British Chamber of Commerce, 2023).

As the current corporation tax rate for company profits was 19% in 2019, the government announced a reduction to the corporation tax from 1 April 2020, and to a flat rate of 19% as of April 2021 (HM Revenue and Customs, 2022).

Considering the UK sometimes faces challenging weather conditions, millions of tourists from around the world come to visit the UK every year. Before the COVID-19 crisis, tourism was booming in the UK and contributed to approximately £127bn annually to the economy (by 2022) (VisitBritain, 2023).

8.1.4 Social factors affecting the UK

The Office for National Statistics released data in March 2021 stating that the strong consumer market in the UK held a population of 59.5 million (Office for National Statistics, 2021a), down from 66.4 million in 2018 (Office for National Statistics, 2021b), partly due to EU citizens leaving the UK politically hostile environment. Allegedly, births continued to outnumber deaths, resulting in the population expected to reach 74 million by 2039. However, the COVID-19 and Brexit fallout had not yet been taken into consideration and future data will cast a better-informed light on the actual situation. In terms of demographics, it needs to be noted that the UK population is getting older, in comparison with our European neighbours, due to advancements in medicine, care provision and increased living standards. With young people staying longer in education, According to the ONS, in 2016, 18% of people were aged 65 and over, while 2.4% were aged 85 and over, with implications on the labour market, the health and care system and the wider economy. Interestingly, this poses a lot of opportunities for organisations, enabling these to cater for the needs of an older population. Industry sectors such as real estate, holiday, insurance, health care and many others have already benefitted from this shift within the population.

Historically, the UK has been strongly influenced by the concept of social class – where people now have to adjust their way of thinking, due to an increasingly multicultural population. Owing to this increased demographic variety, companies have developed a variety of strategies to accommodate these variants, providing new products and markets to cater for the needs of different races, cultures and religions.

Ernst and Young, 2023 have issued a bleak report for the UK, stating that the cost-of-living pressures are set to intensify the UK's regional economic divide.

8.1.5 Technological factors affecting the UK

Overall, the UK is seen to be one of the most technologically advanced countries in the world, with the capital London being a focal point for technological, financial and real estate-based institutions, it offers entrepreneurs from all business pathways immense opportunities to develop their business in the UK.

The technology sector in business terms, in education and the manufacturing sector, is a major contributor to the UK GDP. FDI (Foreign Direct Investment), talented individuals and interested non-governmental organisations are moving into the sector, which attracted £28bn in technology investment since 2011, compared to £11bn in France and £9.3bn in Germany. Despite all efforts, the Brexit referendum, the COVID-19 crisis and the fallout of the UK leaving the EU has the UK falling behind the US and Asia-Pacific states in technological development. According to the Office for National Statistics (2023):

- The value of the UK's *inward* FDI stock (position) (£1,929.2 billion) was higher than that of the outward position (£1,660.9 billion) in 2020.
- Inner London West was the International Territorial Level 2 (ITL2) sub-region with the highest inward FDI stock value in 2020 (£529.2 billion); the sub-region with the lowest inward value was Cornwall and Isles of Scilly (£2.1 billion).
- UK manufacturing companies with foreign parent companies (inward FDI), accounted for the highest stock values in 18 of the 41 sub-regions in 2020; these were mainly located in Wales and the English Midlands.
- Financial and insurance companies in the UK that have companies abroad (outward FDI) accounted for the highest stock values in 19 of the 41 sub-regions in 2020; these were mainly located in the east of the UK, including Eastern Scotland, East Yorkshire and North Lincolnshire, East Anglia and London.

Despite FDI increase, the UK is in danger of falling behind that its European and global counterparts in technological advancement, as the manufacturing sector is increasingly lacking the technical expertise of its workforce, due to skilled workers taking early retirement or being otherwise economically inactive as one of the effects of the Covid-19 pandemic, and EU citizens have left in droves after Brexit and less young people joining the manufacturing workforce. Investment in people, 'green' skills, and innovative and renewable energy technologies, can be a once-in-a-generation opportunity for the UK to innovate itself out of the economic and technological downturn. As the examples of British Steel, Tata Steel and the newest hydropower project by SSE (Appendix 6) are demonstrating: the willingness to decarbonise production and transform into a green industry is abundant, it now requires the political powers at be to provide the legal framework, grants and incentives to the technical and manufacturing sector to transform this opportunity into a reality.

8.1.6 Environmental factors affecting the UK

Economic activities have a direct impact on ecological systems, like the natural environment. Although the UK has made efforts in reducing the negative impact of economic activity, vouching for "Zero Net Carbon" by 2050 (HM Government UK, 2020), local councils, newspapers and some charities have taken a variety of initiatives to create environmental awareness and reduce the negative impact of economic growth on the environment. Unfortunately, these efforts seem not to have yielded the desired effects, as per autumn 2022, 85% of UK rivers are heavily polluted by a "chemical cocktail" of sewage, agriculture and road pollution. This has been identified to be the result of repeated breaches of environmental regulations on an industrial scale by water companies and farms alike (UK Parliament, 2022).

Interestingly, at first glance, it so seems as if the three most polluting sectors in the UK are not sufficiently focused on within the UK Green Industrial Revolution Agenda, with most CO_2 saving opportunities in transport/aviation, residential dwellings almost and (animal) agriculture completely being left out. It was found that animal agriculture, such as beef production, accounts for 25% of global land use, land-use change and forestry emissions - and these issues do not appear to have been factored into the UK 10-Point Agenda (EEA, 2020,2021; Nix, 2020, 2023; WWF, 2023).

There appears to be a political willingness to implement the principles of circular economic processes, which promote circular economic production cycles – as opposed to linear production cycles, which have been in place since long even before the Industrial Revolution. Linear production processes and manufacturing have led to the destruction of almost 40% of flora and fauna, globally, but the efforts in the UK to create the framework for adequate environmental protection, rewilding and reforestation-action to follow are inadequate.

8.1.7 Legal factors affecting the UK

The UK legal landscape follows Common Law principles, which have been adopted, besides the UK, in the US and Commonwealth countries. England and Wales operate a common law system which combines the passing of legislation with the creation of precedents via case law. The laws are established by the passing of legislation by Parliament. This consists of the Monarch (King or Queen), the House of Commons and the House of Lords (the University of Oxford, no date). A detailed discussion of the UK legal environment would be beyond the boundaries of this analysis. Overall, following thoughts in the section discussing political factors, the UK follows democratic principles and has a framework of laws and policies in place, which are currently still aligned with The Human Rights Act 1998.

Nonetheless, at this point, it needs to suffice to mention The Employment Act 1996, which protects the rights of employees. There are laws and regulations in place regarding maternity and paternity leave, minimum wage, holiday pay, sick pay, and other legally protected provisions. Likewise, the Equality Act 2010 protects people from any discrimination.

8.1.8 Conclusions

The PESTEL landscape of the UK suggests it lends itself to host future generations of workers with “green” skills. Steel manufacturing has been one of the early industries to establish itself in the UK and has been an industry mainstay since the days of the industrial revolution, since 1740. The evolved legal and political framework in the UK, geared towards industry, could make the UK the hub of decarbonised steel production and the accelerator for producing green steel and decarbonised production in heavy industries. The recent IPCC (2023) report issued a clear warning and called for immediate action, so as not to lose any more time to decarbonise production and limit the overall - and not just the industrial - CO_2 emissions drastically, immediately.

8.2 SWOT analysis of the UK

8.2.1 Introduction

This SWOT (Strengths / Weaknesses / Opportunities / Threats) analysis of the UK explores some of the key aspects in the respective areas, which – given the gravity of their impact – were explored in more detail throughout the PhD project, as appropriate.

8.2.2 Strengths of the UK

Despite the latest controversy in political realms, it is still in theory a modern parliamentary democracy and a constitutional monarchy with the monarch (currently Queen Elizabeth II) being the Head of State - hence it can be argued that the UK is a country of political stability.

The Government is headed by the prime minister, who is the elected head of the government over a five-year term. The political landscape is mainly being dominated by four political parties: Labour, Conservative, Liberal Democrats and the Scottish Nationalist Party.

The UK is a founding member and one of the five permanent members of the UN (United Nations). Not only is the UK a key ally of the USA, but there are also good connections with the Commonwealth of Nations – therefore playing a significant role in world politics.

The UK is the 5th largest economy in the world and the UK's GDP in 2019 was 2.827 trillion US dollars (WEF, 2019). Although the recession in 2008 hit the UK economy hard and COVID-19 is adding to these woes, the government aimed to lessen the impact of the global recession by implementing adequate measures, such as quantitative easing, The Bank of England lowering bank interest rates (currently at 0.1%) for UK banks borrowing money, improving redundancy protection, issuing renters eviction protection during the COVID-19 crisis and setting National Minimum Wages. The minimum wage as of April 2019 for people aged 25 or over is £8.21 per hour which is likely to increase in near future.

The UK is home to some of the greatest and global companies in the world: Shell, GlaxoSmithKline (GSK), BP, Vodafone, BAE Systems, ASOS, Lloyd's, Aviva, AstraZeneca, Unilever and Tesco some of the brand names which are contributing vastly to the annual GDP and are forerunners for research and development leading the way in everything from tech and manufacturing, infrastructure to food, pharmaceuticals and fashion.

Healthcare in the UK is provided by The National Health Service (NHS), which is the publicly funded healthcare system of the UK and is universally free at the point of delivery.

Geographically, the UK is a European country with a temperate climate – although, with its insular location, the coastal areas are exposed to the elements – which can be experienced in local weather phenomena. An extraordinary island with several world heritage sites, sites of special scientific interest (SSSI), national parks, iconic landmarks, quaint villages, vibrant coastlines, scenic countryside, castles and palaces, events and festivals, filming locations, and many more. Although the UK sometimes faces challenging weather conditions, millions of tourists from around the world come to visit the UK every year. Before the COVID-19 crisis, tourism was booming in the UK and contributed to approximately £127bn annually to the economy (VisitBritain, 2023). The Office for National Statistics (2023) stated that the strong consumer market in the UK held a population of 59 million in 2022. Allegedly, births continued to outnumber deaths, resulting in the population expected to reach 74 million by 2039. The UK is also home to some of the best higher education institutions, such as St Andrews, Oxford and Cambridge University. Historically, many scientists, historians, inventors, laureates and intellectuals with international acclaim are British – such as Mary Currie, Elisabeth Townsend, Alfred Turing and Alexander Fleming, to name just a few.

8.2.3 Weaknesses of the UK

The UK seems on the surface to be one of the top destinations for foreign direct investment (FDI), confirmed by the value of the UK's inward FDI stock (position) (£1,929.2 billion) being higher than that of the outward position (£1,660.9 billion) in 2020 (ONS Office for National Statistics, 2023). However, some experts argue that this current situation is one of the negative aspects of Brexit, as even some of the British household brand names, such as Dyson, have moved their production abroad. The number of UK businesses exporting goods to the EU fell by 33% to 18,357 (2021), from 27,321 (2020). , according to data provided by the Office for National Statistics (2023).

Additionally, in the international context, the UK is one of the most expensive countries to live in. In order to provide a realistic and relatable example: the average monthly net rent (without services) for a one-bedroom flat even in poorer areas of the capital London may cost around £1000. Due to FDI, the housing market is extremely buoyant, and it forces native Londoners and young people out of the city, as it is very difficult for a first-time buyer to buy a property. Furthermore, generally, the cost of living – i.e. to buy food, clothing and consumables is very expensive in the country, particularly in London.

Nevertheless, the UK is one of the richest countries in the world, with a classical North/ and South divide, as more employment opportunities have been created in southern cities than elsewhere across the UK. This has led to regional wealth inequality and the richest 10% of UK households owned 45% of the UK's national wealth in 2020, and the UK wealth of the richest 1% of households was on average more than £3.6 million, compared with £15,400 or less for the least wealthy 10% of the population (ONS, 2023).

Another area of concern is the lack of investment in research and development. Only recently, as an effect of Brexit, the UK has lost access to the international space research program "Galileo", which has not yet been replaced with an equivalent in the UK. Additionally, access to European academics has been cut off, with the Erasmus programme not having been negotiated to continue and high-achieving university graduates seeking employment elsewhere instead of in the UK. As a growing concern, the UK has been falling behind many advanced nations as far as spending on research and development as a proportion of GDP is concerned (Rhodes, Hutton and Ward, 2023).

8.2.4 Opportunities for the UK

Every literate person in the UK will by now have understood that Brexit has created great uncertainties and the sheer expanse of negative impact on the UK GDP is not yet fully known. However, the UK has been a leading industrial power and global player before joining the EU in 1974 and there is therefore every chance that – although it may take some time, given that COVID-19 has added to UK's woes – the UK will be seen as a leader and economically strong once more. Freed from the binding powers of the EU membership, new doors to new possibilities have been opened. There is every chance that the UK can now build bilateral and free-trade relations with nations worldwide, which will in their own right create opportunities for British companies to expand. It is too early to say if access to the EU single market can be maintained. However, as 41% of the UK's export flows directly into Europe, countries and companies are all interested in continuing this positive relationship and access to the EU single market might yet be secured. Being steeped in history has made the UK a very desirable location which draws talents from all over the world. It is now key to attracting highly skilled talents, increasing productivity, investing in research and development, meeting domestic demands and increasing the influence in global affairs.

8.2.5 Threats to the UK

With the old-world order changing and the BRIC (Brazil, Russia, India, China) economies advancing, many competitors are challenging the UK in a variety of sectors and adding significant competitive pressures on the UK. Additionally, owning and running businesses in the UK is a very expensive undertaking, depending on the sector, prohibitively expensive to the extent that often especially small businesses find them unbearable. But even household names, big businesses such as Dyson, have moved abroad, as the running cost in the UK were just in no positive relation to the potential profit and resulted in yet another big player taking their money elsewhere. The UK government is under great pressure to restart the economy and change these unfavourable conditions, as otherwise many businesses may go bust, resulting in a wave of unemployment and subsequently, decreased GDP.

8.2.6 Conclusions

On the surface, the commercial environment and the current Conservative Governments' drive to cut "red tape" seem to be geared towards economic growth and a greener economy. Unfortunately, a decade of underinvestment in infrastructure and public service, the 2020-2023 COVID-19 pandemic and the 2022/2023 ongoing cost-of-living-crisis, along with a high inflation rate of 14.6% per the 20th of June 2023, have left businesses and the population reeling with the aftermath of the afore mentioned situations. One of the consequences is an ailing economy and currently 40% of businesses are said to be failing as a result of BREXIT and the increase in energy prices. The country is on its knees at time of writing, but this also provides considerable opportunity for improvement. The negative and positive impact factors are known – all that is required now is political willingness to make the change for a technical green industrial revolution with the effect of decarbonisation of production and environmental rehabilitation happen with an adequate legal and political framework.

8.3 CO_2 emissions for the entire steel production process

To date, there is no comprehensive overview of all CO_2 emissions associated with steelmaking published in the public domain. It has been common practice to merely account for the emissions produced during the iron making (BF) and steelmaking processes (BOF) or EAF operations. However, it makes logical sense that all processes involved, for all resources associated with the production of steel, need to be included in the determination of total emissions. Although there are currently six main greenhouse gases resulting from anthropological activity, this study focused on CO_2 emissions only - for the time being. Figure 8-5 will give an overview of most CO_2 emissions levels at the different stages and quantities required for the respective resources. The investigations, calculations and process simulations, based on 330000t capacity BF/BOF, have resulted in the findings that 4,270,655t of CO_2 are being emitted per steel production cycle and thus resulting in <u>12.94t of CO_2 per t of steel produced</u> – with all production stages from mining to finish machining considered.

8.4 BiSC – steel production decarbonisation model and strategy

With designing a viable model and strategy, the main aims and objectives have been achieved. The Bio Steel Cycle model contains components which are classed as being at TRL 6-9 and can be readily implemented. Following the 7-steps strategy to achieving net zero carbon emissions steel production, zero carbon emissions steel production can be achieved, in the short-term. There are 59 projects underway, worldwide (Appendix 6), which are individually investigating and operating the technology mentioned above, so the viability of the model has indirectly been vindicated by the operation of the selected technologies.

8.5 Higher degree of energy independence

Tata Steel having set up a cooperation in Ijmuiden directly next to the Nort Sea shores, gives hope to the scenario that hydrogen-based technologies will be implemented in the near future, in heavy industry. Implementing renewable energy technologies will not only support the decarbonisation of the steel industry but the mechanisms are transferrable to most heavy industries. The currently available UK grants, subsidies and tax incentives make this move to greener production and a higher degree of energy independence a viable solution.

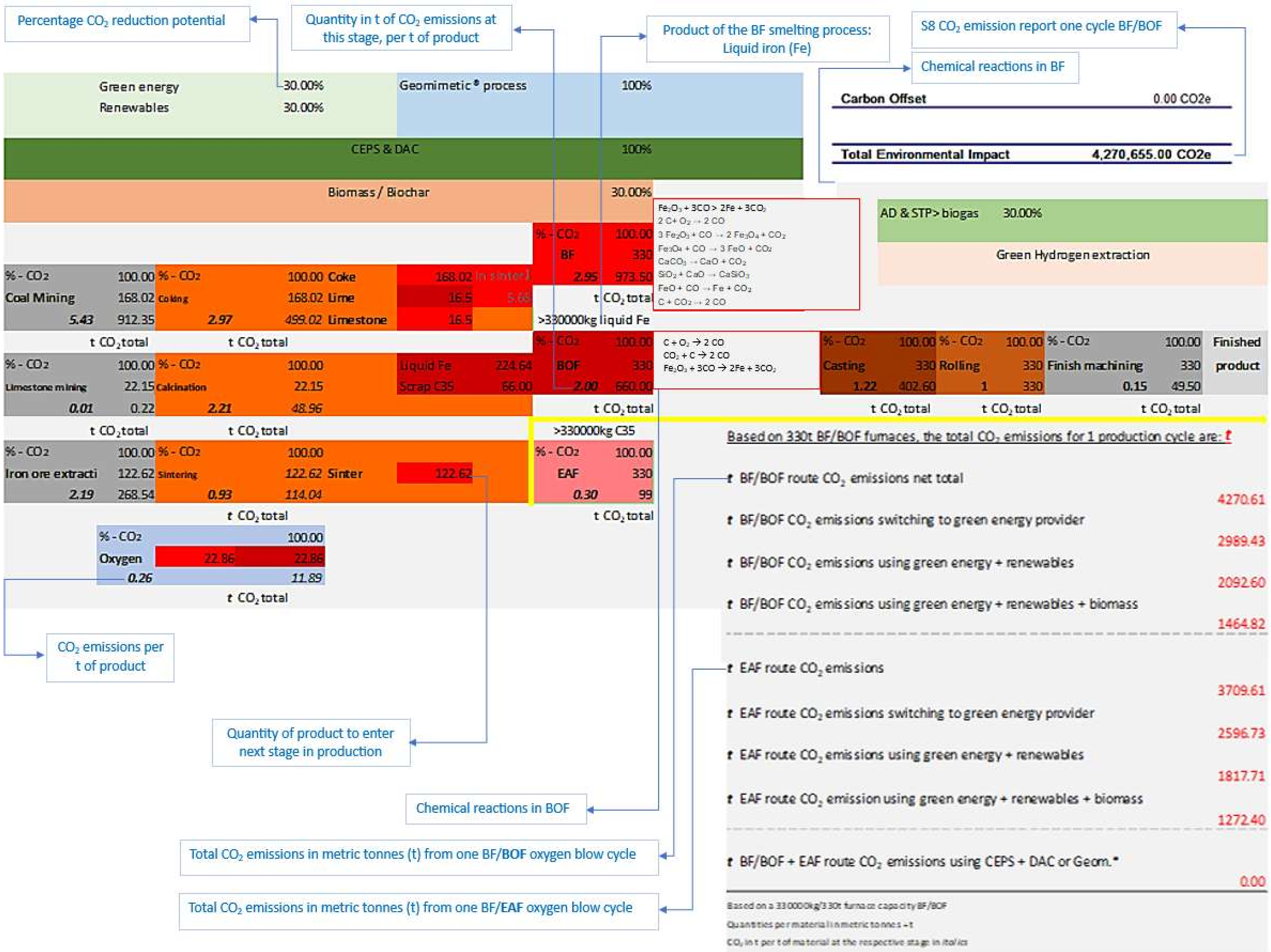


Figure 8-5: Overview Ms Excel spreadsheet accumulated data on CO_2 emissions along the steelmaking process in a 330t BF/BOF furnace operation with data from Aspen Plus, Inosim and a report excerpt from Simul8

8.6 Knowledge contribution summary

8.6.1 Introduction

Conducting this research, the following research questions needed answers, as detailed in the image below (Figure 8-4):

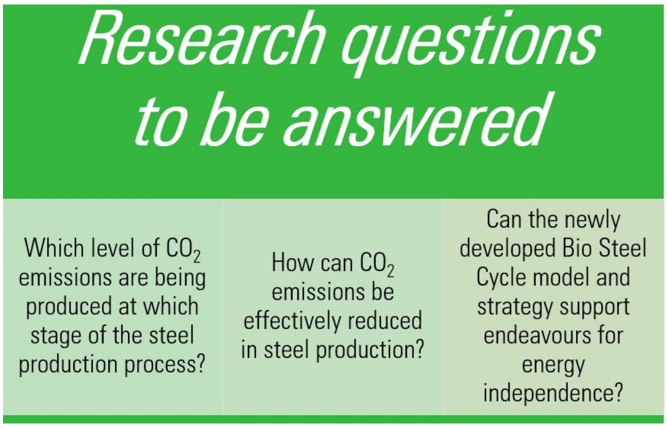


Figure 8-6: The research questions to be answered by this work

This thesis provides answers to the set research questions (Figure 8-4) in a range of knowledge contributions, which are described in the following text. In section 1.4, the aims of this research were set out, as described below in Aim 1 and Aim 2, and how these were met are described in detail in section 8.6.2. The objectives were set out in section 1.5 and the results of this work and how these were met are detailed in section 8.6.3.

8.6.2 Knowledge contribution

8.6.2.1 Knowledge contribution

The novel knowledge contribution of this research requires clarification and outlining what knowledge the author found which has not already been available in the literature. Additionally, how this aligns with the research gap which was used to shape the research aim.

The knowledge base in the academic literature has been enriched by this project and subsequent results and is demonstrated by the following points:

- The CO_2 emissions produced at the *respective stage* of the steelmaking process have been established in metric tonnes of *product* as follows:

Table 8-2: CO_2 emissions at the different stages of material preparation and the steelmaking process

Steel production stage	*CO_2 / t product*	*Values applied in simulations*	*Literature Reference*
Oxygen	*0.26t*	*0.26t*	*Variny 2021*
Limestone	*0.035t-2.31t*	*0.035t*	*Kittipongvises 2017*
Iron ore	*2.19-6.4t*	*2.19t*	*BHP 2019*
Coal	*5.43-12.31t*	*5.43t*	*BHP 2019*
Coking	*2.97-3.14t*	*2.59t*	*Chen et al. 2018 (SEC) Li Zhu 2014*
Calcification	*2.21-2.32t*	*2.21t*	*Chen et al. 2018 (SEC) Li Zhu 2014*
Iron ore pelletising	*0.035-0.45t*	*0.035t*	*RftF 2022*
Sintering	*0.04 – 0.97t*	*0.93t*	*Ecofys 2009 Riesbeck et al. 2013*
Blast Furnace	*2.1-3.2t*	*2.95t*	*Suer 2022*
Basic Oxygen Furnace	*1.6-3.13t*	*2.0t*	*IEA 2000 Tian 2022*
Casting	*0.2 -1.22t*	*1.22t*	*Wänerholm 2016*
Rolling	*0.26-1.0t*	*1.0t*	*Schmitz 2021*
Finish Machining	*0.15*	*0.15t*	*Sun 2021*

- The CO_2 emissions total per metric tonne of steel produced was determined to be **12.94t of CO_2 per t of steel produced**.

- A novel concept and aligned strategy for the production of steel has been developed, called "**The Bio Steel Cycle**".

- The newly developed model and concept "**The Bio Steel Cycle**" was found to yield opportunities for industry to achieve a **higher degree of energy independence**.

As far as the author is aware, this is the first time the attempt has been made to gather all the information publicly available for the steelmaking and ancillary processes and the CO_2 emissions at every stage, and per metric tonne of steel produced.

8.6.2.2 Knowledge contribution – achievements and meeting set aims

The *research questions* (*below)* were the basis to set aims and objectives:

1) Which level of CO_2 emissions are being produced at which stage of the steel production process?

2) How can CO_2 emissions be effectively reduced in steel production?

3) Can the newly developed Bio Steel Cycle framework support energy independence?

The set *aims* as a result of establishing the research questions are, as follows:

1) Creating a universally applicable model and subsequent strategy which have the potential to reduce the CO_2 emissions effectively and sustainably in steel production.

2) Defining the afore mentioned model and strategy in line with circular economic principles.

3) Providing evidence to prove that the newly developed Bio Steel Cycle model and strategy support endeavours for energy independence.

The whole project was carried out with a practical approach in mind, in response to the authors knowledge of the industry. The author has worked in a professional capacity in multi-metal manufacturing and renewable energy technology manufacturers and has therefore an invaluable insight into the internal and external mechanisms which have driven the iron and steel industry into the current situation, which is unsustainable in the long-term (Price *et al.*, 2002; Muslemani *et al.*, 2021; Bhaskar *et al.*, 2022a; Kiessling, Gohari Darabkhani and Soliman, 2024).

Achievements:

The publications as a result of the research project and which research questions these refer to:

Research question 1):

- ✓ The Bio Steel Cycle establishes a sustainable, circular economic blueprint for steel producers how to manufacture near CO_2-emissions-free steel.

Research question 2):

- ✓ 'The Bio Steel Cycle: 7 Steps to Net-Zero CO_2 Emissions Steel Production' (Kiessling, Darabkhani and Soliman, 2022).

Research question 3):

- ✓ 'Greater Energy Independence with Sustainable Steel Production' (Kiessling, Gohari Darabkhani and Soliman, 2024) offer a sustainable, circular economic strategy for main and ancillary businesses involved in steel production which details how the implementation of the different components of the Bio Steel Cycle along every step of all stages of the steel production process can be improved to be more sustainable and support almost '0' CO_2 emissions steel production.

8.6.3 Knowledge contribution – meeting set objectives

The objectives set out in section 1.5 are listed below, and how they were subsequently met by the results of this research.

All developed research questions and set aims and objectives were met by the research and subsequent dissemination of results. Detailed evaluation of the various technologies with regards to their efficiency or defining the best in class was not subject of this research.

Table 8-3: Set objectives and how they were met by this research

Objectives	Objectives met by the work detailed in these sections
Conducting a literature review, covering the 'Carbon life cycle'	Chapter 3: Literature Review; Section 3.2; Chapter 7: Results
Resources for and stages in steel production	Chapter 3: Literature Review; Section 3.3 and 3.4; Chapter 7: Results
Biomass as alternative fuels	Chapter 3: Literature Review; Section 3.5; Chapter 7: Results
Steel production CO_2 emissions	Chapter 3: Literature Review; Section 3.6; Chapter 7: Results
Energy and Exergy analysis	Chapter 3: Literature Review; Section 3.7 and 3.7.2; Chapter 7: Results
Energy, emissions and cost	Chapter 3: Literature Review; Section 3.7.1; Chapter 7: Results
Decarbonisation of the steel industry and selected case studies	Chapter 3: Literature Review; Section 3.8; Chapter 7: Results
Carbon Capture, utilisation and storage	Chapter 3: Literature Review; Section 3.8.25; Chapter 7: Results
Evaluation HM Government "The Ten Point Plan for a Green Industrial Revolution"	Appendix 3 – Evaluation
Identifying the gaps in knowledge and understanding regarding the CO_2 emissions for the entire steel production processes and stages, within the afore mentioned areas of specialism	Chapters 3-7
Investigating existing steel production processes with regards to greenhouse gas emissions, and particularly, CO_2 emissions	Chapter 3: Literature Review; Section 3.3, 3.4 and 3.7.1; Chapter 7: Results
Developing a universally applicable model, suitable for the iron and steel industry	Chapters 3, 4 and 5
Designing an ecologically and technically sound strategy, based on the afore mentioned model	Chapters 3 - 7
Establishing hypotheses and investigating these against standard mathematical principles	Chapter 7; Section 7.4
Providing proof of viability and replicability by creating process simulations in suitable software applications.	Chapters 6 and 7

The findings of this work and the Bio Steel Cycle model and strategy can be applied for decarbonisation purposes throughout the iron and steel industry, in line with site parameters and insofar as suitable, but also in a wide range of other heavy industry sectors.

Chapter 9 Conclusions and further research

9.1 Introduction

This research was driven by finding answers to a contemporary issue: to compile an overview of CO_2 emissions in steelmaking, as there is seemingly only incomplete assessment of emissions from the iron and steel industry. Furthermore, the need to create a model and strategy for reducing emissions in the iron and steel industry and how this strategy can simultaneously support efforts to achieving a higher degree of energy independence.

9.2 Conclusions

This research was driven by finding answers to a contemporary issue: to compile an overview of CO2 emissions in steelmaking, as there is seemingly only incomplete assessment of greenhouse gas emissions from iron and steel manufacturing along the various stages and processes available. The ensuing literature review of the steel industry to identify said emissions resulted in the formation of three research questions:

1) Which level of CO_2 emissions are being produced at which stage of the steel production process?
2) How can CO_2 emissions be effectively reduced in steel production?
3) Can the newly developed Bio Steel Cycle model and strategy support energy independence?

The literature review resulted in a substantial data volume, which was organised in an MS Excel database, followed up by evaluation, calculation and modelling in MS Excel, validation via standard mathematical procedure and creation of process simulations in three different simulation software packages: Simul8, Aspen+ and Inosim, for verification and replicability purposes.

The overall CO_2 emissions identification in steelmaking along the entire process, starting with extraction and ending with issue of the finished product, resulted in the finding that between 39 and 47 metric tonnes of CO_2 emissions are one of the co-products of producing one metric tonne of crude steel.

A vast array of technological advancement and solutions for carbon avoidance, capture, utility and storage, at TRL6-9 have been identified. The development of circular (tech-) economic processes has been the researcher's main interest, as the increased scarcity of materials and the price development of steel production resources had been reliably on an upwards trajectory. The findings of this study led to the creation of a model and strategy called "The Bio Steel Cycle" (BiSC).

Numerous challenges lay in the way of compiling an informed CO_2 emissions assessment of the production practices in the iron and steel industry, and lack of standardised legal reporting frameworks and standards, as well as the diversity in (production) practices, resulted in an accumulation of directly incomparable data, which had to be mathematically standardised, to be relatable to one metric tonne of crude steel produced, to be able to compare and utilise the insights gained.

The apparent lack of reliable data, and inconsistency and diversity of reporting structures, makes an assessment of process emission mitigation potential with a high confidence level at global or regional scale extremely difficult. The enormous variety of processes and technologies adds to the complexity of any assessment attempt.

It is my understanding, that the findings of this study point to the possibility of drastic changes in conceptualisation of steel plants within refurbishment and new builds, and even only partial implementation of the BiSC, would lead to CO_2 savings or avoidance in the region of between 30 and 60% - and possibly - even up to 100% (UNIDO, 2011), with greater energy independence achievable by the same percentages. Interestingly, as part of the UK governments efforts to achieve a net zero carbon economy by 2030 (Chapter 5 and appendices 2 and 3), a number of incentives, grants and support schemes are now readily available for private individuals and businesses alike, making the switch to greener energy generation, in independence from commercial energy providers, which in the UK still mostly rely on generating energy via fossil fuel combustion, a technically and economically viable option.

Some technologies as process components of the BiSC had been in development in recent years in the EU (European Union), but with the exit of the UK (United Kingdom) from the EU on the 1st of February 2020, the UK government does no longer have access or right to obtain data and information regarding possible developments from ULCOS or NER-400 to reduce CO_2-emissions in the UK steel industry and advancements in carbon capture and storage technology. Companies involved in ULCOS, such as Tata Steel and Rio Tinto, are privately owned companies and therefore under no obligation at present to share - or develop data for – governmental departments anywhere. Therefore, access to process data from active production sites remains difficult.

Nonetheless, it is my understanding that the implementation of the Bio Steel Cycle concept seems universally applicable and would not only have the potential to reduce CO_2 emissions. It also provides potential for restoring former wasteland or brownfield sites to commercially viable woodlands, opportunity for habitat creation and increased biodiversity and provide an opening for an integrated approach to – not only - steel production. Meaning: by having a great proportion of the resources produced on site (Biomass, Biogas) and recycling plants (anaerobic digester, Biochar plant, recycling plant, hydrogen extraction site) required for steel production on site or close-by, greater independence from international imports (coal, coke, wood, gas) would be achieved.

Additionally, it was found that the creation of woodlands could produce sizeable profits and create up-skilling, training and employment opportunities – as would the integration of anaerobic digester, Biochar plant, recycling plant, and the hydrogen extraction site. Woodland management, soil management, plant operations and maintenance are all opportunities to create employment in the so called "green economy".

To emphasise the hypothesis stated and prove the Bio-Steel Cycle 7 steps to net-zero carbon emissions steel production a viable and technically implementable model, the European Commission's and steel industry leaders' technical and process improvement developments have been taken into consideration, as their innovations are likely to be implemented within the next 5 years and will achieve a reduction in CO_2 emissions in the order of +50%. These are:

- HIsarna smelting (eliminates the need for sintering)
- ULCOS (ULCOS top gas recycling blast furnace process (TGRBF) recycling the remaining CO and H_2 in blast furnace top gas back into the process, lowering the coke consumption. CO and H_2 are recovered with CO_2 separation BF)
- ULCORED (direct reduction)
- ULCOWIN (electrolysis at low temperatures)
- Athos (Carbon Capture and Utilisation)
- ReclaMet (Waste resource recovery)

9.3 Future research

During the evaluation of the various opportunities for CO_2 avoidance, utilisation and reduction, another major factor was identified, which could play a significant role – not only in CO_2

reduction, but energy independence – in most industrial production processes: exergy analysis, or energy loss identification. The findings were that at least 30% of the energy sent into the production cycle, linear or not, will be lost using the current production facilities and infrastructures. Future research could provide valuable insights into:

- ✓ exergy analysis
- ✓ the loss-points and
- ✓ processes reducing or eliminating entirely any energy lost in the system.

The energy lost is negatively productive costs, which reduce profitability. Also, energy bought in at great cost, momentarily still produced mainly using fossil fuels, could be reduced if the loss points were identified. The energy saved can be actively used and the 30% momentarily thought to be lost could be saving businesses cost and CO_2 emissions in the region of 30%. Given the vulnerability of businesses to energy price volatility, there is urgent need to further research into this direction. Furthermore, capturing carbon for carbon enrichment in plant stimulation (CEPS) and the mechanisms and processes involved pose an interesting direction for further research. At present, Zeolite 13X is a promising candidate for CEPS, but the investigation of a) more economical solutions than using Zeolite 13X and b) investigating in more detail exactly how the CO_2 capture for the temperature swing adsorption has taken place, could yield promising solutions for carbon capture not yet thought about. One element seems to be an interesting direction for research: limestone, or burnt lime, to be precise. The calcination of limestone produces lime, which is "hungry" for CO_2, as this has been removed during the calcination process. Meaning: when lime is being exposed to industrial flue stack off-gases, the lime molecules will inevitably try to bind to the CO_2 molecules. Which leads to an additional line of thought: CO_2 capture, filtering and cost in various industries: Steel, Concrete, Chemical (Solutions, Oil, Gas) and Waste Recycling. At present, not many industrial providers seem to be considering this a business proposition, as only businesses in Asia seem to offer solutions in this direction. This could be another opportunity for the UK economy to create employment and training opportunities, as it has yet to be identified which CO_2 capture technology is the most effective for which industry: active coal filters (Framework flexibility-driven CO_2 adsorption on a zeolite), air locks, chemical absorption, phyto-absorption, and hydro absorption (i.e. CO_2 Capture in wet and dry superbase ionic liquids). Furthermore, application of the research processes within the BSC to other industries: Transport / Aviation, Concrete, Glass, Chemical (Solutions, Oil, Gas) and Waste Recycling.

- BiSC heat recovery and utilisation technologies.
- Investigate and monitor process development of ArcelorMittal, Tata and others, with focus on physical trials, data evaluation and technical/economic viability assessment of decarbonisation
- Investigating CO_2 emissions natural decomposition vs. combustion.

Additionally, during the course of the 3.5 years of research, it has come to light that suitable commercially viable carbon filters don't seem to be available. The author has therefore compiled a research proposal to that effect. Currently, there are efforts underway to secure funding from either industry or external funding sources such as UKRI or the UK Research Councils.

It is evident that there are manifold directions of further research that, if followed, could provide an impressive array of prospects potentially leading to commercially viable projects. These, in turn, could provide additional training, upskilling and employment opportunities and could give positive impetus to the drive for the UK being the hub of the green skills market.

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Appendices

Appendix 1 Ethics approval form

RESEARCH ETHICS

Proportionate Review Form

The Proportionate Review process may be used where the proposed research raises only minimal ethical risk. This research must: focus on minimally sensitive topics; entail minimal intrusion or disruption to others; and involve participants who would not be considered vulnerable in the context of the research.

PART A: TO BE COMPLETED BY RESEARCHER

Name of Researcher:	Sandra Kiessling
School	School of Digital, Technologies & Arts

Student/Course Details (If Applicable)			
Student ID Number:			11000225
Name of Supervisor(s)/Module Tutor:			Prof H. G. Darabkhani and Prof A-H. Soliman
PhD/MPhil project:	☒		
Taught Postgraduate Project/Assignment:	☐	Award Title:	MPhil/PhD Electrical/Electronic Engineering
Undergraduate Project/Assignment:	☐	Module Title:	

Project Title:	CIRCULAR TECH ECONOMY Reducing carbon emissions in the UK Steel industry
Project Outline:	This research investigates the manufacturing cycle of steel and all components within for assessing greenhouse gas (GHG) emissions and energy usage. Additionally, this work aims to provide a range of sustainable solutions with newly developed theories, a critical literature review and a comprehensive technical database, aligned with circular techneconomic models. One of the objectives is to identify technical solutions of and opportunity for improvement of existing heavy industrial production and manufacturing mechanisms, while at the same time making considerable effort to reduce emissions and increase efficiency of the steel production cycle. All these key elements are aiming to support achieving the objectives set within the Paris Agreement (UN, 2016), and are transferable to heavy industries. At this stage of the research activities, it was already been established that the commonly applied figure of 1.9t of CO2/t of steel is actually closer to 31t of CO2/t of steel, all Scope 1 and 2 process emissions from mining, over coking to sintering and finish machining considered. The researcher has had some correspondence with academics and industry leaders, who are more than happy to share their information: such as Kevin Kung of Takachar , Blue Planet, Prof Paul Dastoor (Director, Centre for Organic Electronics, Department of Physics, University of Newcastle Callaghan, NSW 2308) and Johan Rockström (Director of the Potsdam Institute for Climate Impact Research). All these efforts will be resulting in a comprehensive overview of GHG emissions within the steel production processes, including detailed process

	flow charts, and will provide a solution to achieve zero carbon emission steel production: presented by the author with the newly developed 'Bio-Steel Cycle' (BSC). The Bio-Steel cycle includes all the possible scenarios in the steel manufacturing industry, including using renewable energy technologies, recycling waste and capturing pollution where necessary. The research has provided information on the level of CO2 emissions at different steps of the steel manufacturing cycle in a comprehensive database, informed by literature, calculations, and modelling. As a solution, implementing the Bio-Steel cycle model will show how the current CO2 emissions could be reduced to achieve net-zero CO2 emissions in this industry. To emphasise the hypothesis stated and prove the Bio-Steel Cycle a viable and technically implementable model, developments for greenhouse gas avoidance and carbon saving technologies have been taken into consideration and implemented within the Bio-Steel cycle as short-term and long-term solutions. The BSC circular production method can be transferred to other heavy industries including cement, glass, and chemical industries. The methodology used in this research includes an objective oriented literature review with Excel spreadsheet-based calculations for the emission of all processes in the steel industry, SCOPE 1-3 emissions, energy consumption and possible ways to avoid or capture CO2 emissions and to utilize these within the BSC. Implementing the Bio-Steel Cycle production model shows that net-zero steel production is possible – today.		
Give a brief description of participants and procedure (methods, tests etc.)	- Literature Review and Technoeconomic Assessment - Emission calculation and Excel based spreadsheet database development - Utilising MATLAB®, Inventor® and Autodesk®/AutoCAD® software for investigating existing process CO2 emissions, savings potential, and energy usage		
Expected Start Date:	01/03/2020	Expected End Date:	02/06/2023

Relevant professional body ethical guidelines should be consulted when completing this form.

Please seek guidance from the School Ethics Coordinator if you are uncertain about any ethical issues arising from this application.

There is an obligation on the researcher and supervisor (where applicable) to bring to the attention of the School Ethics Coordinator any issues with ethical implications not identified by this form.

Researcher Declaration

I consider that this project has no significant ethical implications requiring full ethical review	☒

I confirm that:		
1.	The research will **NOT** involve members of vulnerable groups. Vulnerable groups include but are not limited to: children and young people (under 18 years of age), those with a learning disability or cognitive impairment, patients, people in custody, people engaged in illegal activities (e.g. drug taking), or individuals in a dependent or unequal relationship.	☒
2.	The research will **NOT** involve sensitive topics. Sensitive topics include, but are not limited to: participants' sexual behaviour, their illegal or political behaviour, their experience of violence, their abuse or exploitation, their mental health, their gender or ethnic status. The research must not involve groups where	☒

	permission of a gatekeeper is normally required for initial access to members, for example, ethnic or cultural groups, native peoples or indigenous communities.	
3.	The research will **NOT** deliberately mislead participants in any way.	☒
4.	The research will **NOT** involve access to records of personal or confidential information, including genetic or other biological information, concerning identifiable individuals.	☒
5.	The research will **NOT** induce psychological stress, anxiety or humiliation, cause more than minimal pain, or involve intrusive interventions. This includes, but is not limited to: the administration of drugs or other substances, vigorous physical exercise, or techniques such as hypnotherapy which may cause participants to reveal information which could cause concern, in the course of their everyday life.	☒
6.	The research **WILL** be conducted with participants' full and informed consent at the time the study is carried out: • The main procedure will be explained to participants in advance, so that they are informed about what to expect. ☐ • Participants will be told their involvement in the research is voluntary. ☐ • Written consent will be obtained from participants. *(This is not required for self-completion questionnaires as submission of the completed questionnaire implies consent to participate).* ☐ • Participants will be informed about how they may withdraw from the research at any time and for any reason. ☐ • For questionnaires and interviews: Participants will be given the option of omitting questions they do not want to answer. ☐ • Participants will be told that their data will be treated with full confidentiality and that, if published, every effort will be made to ensure it will not be identifiable as theirs. ☐ • Participants will be given the opportunity to be debriefed i.e. to find out more about the study and its results. ☐	YES ☒ N/A ☒
7.	A risk assessment has been completed for this research project	YES ☐ N/A ☒

If you are unable to confirm any of the above statements, please complete a **Full Ethical Review Form**. If the research will include participants that are **patients,** please complete the Independent Peer Review process.

8. Information and Data Please provide answers to the following questions regarding the handling and storage of information and data:
a) How will research data be stored (manually or electronically)? Mainly electronically, on encrypted devices. Handwritten notes are kept in a secure location.

b) How is protection given to the participants (e.g. by being made anonymous through coding and with a participant identifier code being kept separately and securely)?
Participants providing information, such as industry leaders, have given consent to and encouraged the researcher to publish the findings.
c) What assurance will be given to the participant about the confidentiality of this data and the security of its storage?
N/A, as the literature review is the main tool for research, leading to the compilation of the database and subsequent findings & recommendations.
d) Is assurance given to the participant that they cannot be identified from any publication or dissemination of the results of the project?
N/A.
e) Who will have access to this data, and for what purposes?
Only the researcher and the supervisory team.
f) How will the data be stored, for how long, and how will it be discarded?
The data will be stored for the duration of the project and kept in encrypted, secure locations for the time being, as these are publicly available sources of information.

Supporting Documentation

All key documents e.g. consent form, information sheet, questionnaire/interview schedule are appended to this application.	☒

Signature of Researcher:	Sandra Kiessling	Date:	26/01/2022

NB: If the research departs from the protocol which provides the basis for this proportionate review, then further review will be required and the applicant and supervisor(s) should consider whether or not the proportionate review remains appropriate. If it is no longer appropriate a full ethical review form **MUST** be submitted for consideration by the School Ethics Coordinator .

Next Step:

STUDENTS: Please submit this form (and supporting documentation) for consideration by your Supervisor/ Module Tutor.

STAFF: Please submit this form to your Head of Department or a Senior Researcher in your School. Once they have reviewed the form, this should be forwarded to the Research Administrators in RIIS (ethics@staffs.ac.uk) who will arrange for it to be considered by an independent member of the School's College of Reviewers .

PART B: TO BE COMPLETED BY SUPERVISOR/MODULE TUTOR (If student) OR Head of Department/ Senior Researcher (if staff)

I consider that this project has no significant ethical implications requiring full ethical review by the Faculty Research Ethics Committee.	☒
I have checked and approved the key documents required for this proposal (e.g. consent	☒

form, information sheet, questionnaire, interview schedule).	

Signature of Supervisor/ Head of Department/ Senior Researcher:	Hamidreza G. Darabkhani	Date:	28/02/2022

Next Step: Please forward this form to the Research Administrators in RIIS (ethics@staffs.ac.uk) who will arrange for it to be considered by an independent member of the School's College of Ethical Reviewers , having no direct connection with the researcher or his/her programme of study.

PART C: TO BE COMPLETED BY A MEMBER OF THE SCHOOL'S COLLEGE OF ETHICAL REVIEWERS

This research proposal has been considered using agreed University Procedures and is now approved.	☐
Or	
This research proposal has not been approved due to the reasons given below.	☐
Recommendation (delete as appropriate): Approve/ Amendments required/ Reject	

Name of Reviewer:		Date:	
Signature:			

Signed (School Ethical Coordinator)		Date:	

Appendix 2 Circular Tech-Economy and the Agenda 2030 – Sustainable Development Goals

Circular Tech-Economy and the Agenda 2030 – Sustainable Development Goals

Our planet's resources are finite and in order to sustain the currently achieved lifestyle, sustainable frameworks of meeting human needs, producing food and maintaining clean water and managing waste responsibly is the highest priority to secure our species' survival, as it was found that there is currently neither business models nor consumers outlined as enablers of the circular economy. (Frosch and Gallopoulos, 1989, Arcadis and Triple E, 2015). Charter (2018) cited in EllenMacArthur-Foundation (EMAF) (2018) when stating that Circular Economy (CE) defines restorative and regenerative practice by design, whilst keeping components and materials at their highest quality during their biological and technical life cycles. CE is often visualised with a focus on circular flow charts of product life cycles. One of the most cited illustrations of the EMAF is the butterfly, displayed in Figure A2-1, which distinguishes between technical and biological material life cycles (EMAF 2019):

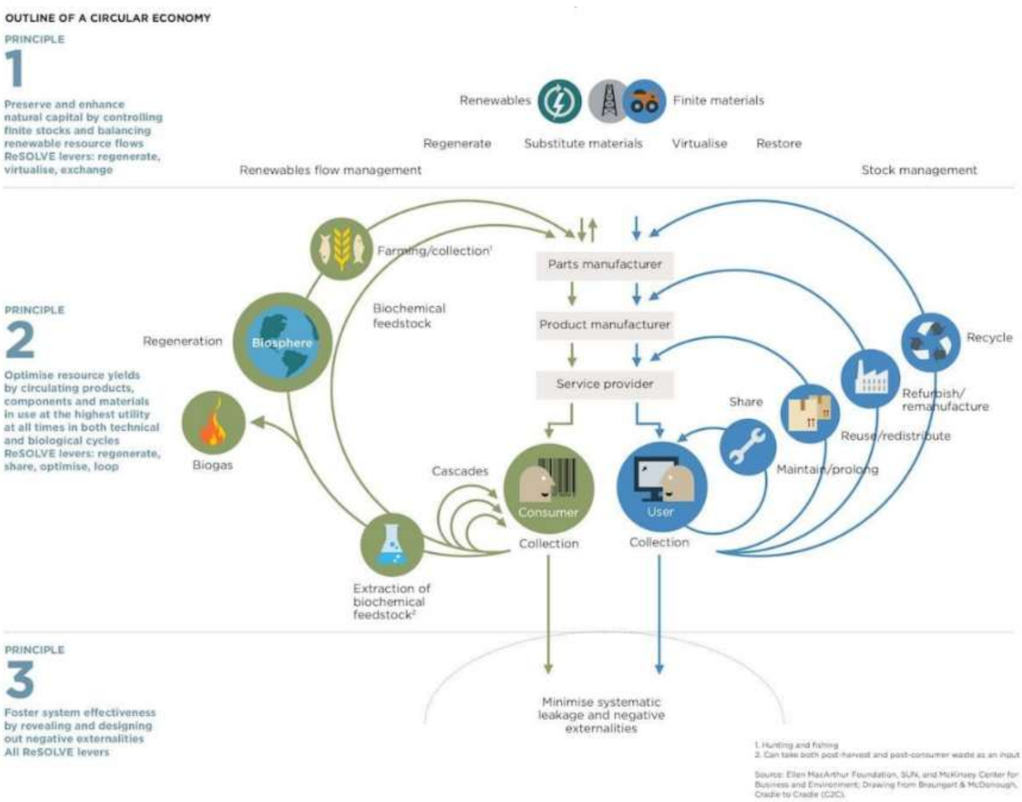

Figure A2-1: The EMAF Butterfly Model 1 (EMAF, 2019)

Braungart, McDonough and Bollinger (2007), McDonough and Braungart's (2002), and McDonough, and Braungart's (2002) work is widely acknowledged the most important environmental manifestos of our time, as the authors present an integration of design and science that provides long-lasting benefits for society from safe materials, water and energy in circular economies and reverses the concept of waste into perpetual resource production. Lacy and Rutqvist (2015) and Perchard (2017) seem to believe that circular economy is one of the view viable and ultimately inevitable models for overcoming the current economic and ecologic challenges against the backdrop of increased scarcity of resources, as demonstrated in the following Figure A2-2 : 10 Steps To Circular Economy 1 (Perchard, 2017):

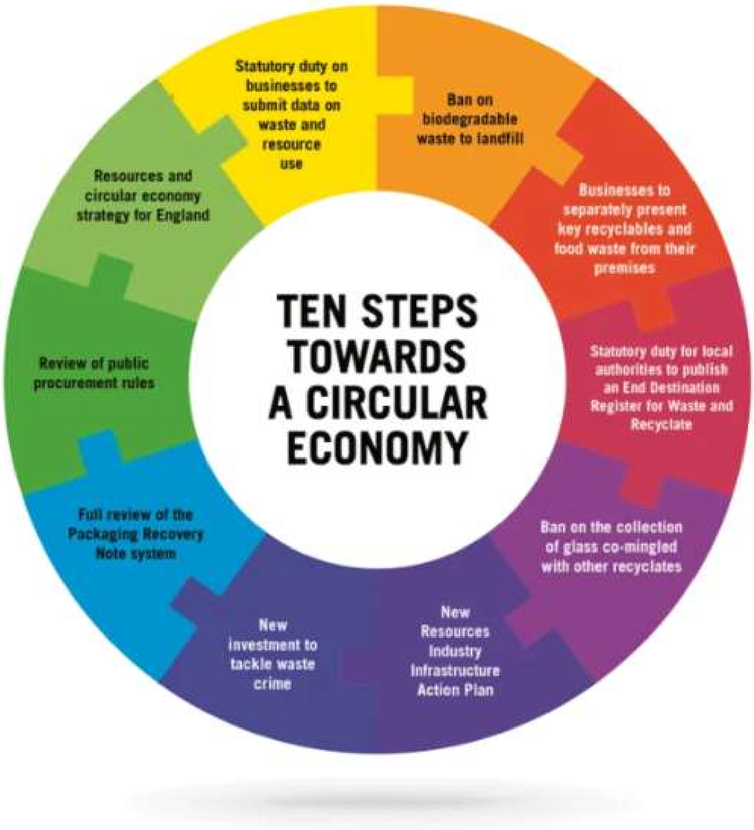

Figure A2-2 : 10 Steps To Circular Economy 1 (Perchard, 2017)

EMAF (2019) aimed to identify the effective contributions of Circular Economy (CE) to the development of sustainability. Within their studies it has emerged, that endeavours to achieve sustainability were positive, but not sufficient to combat the emerging challenges of increased prices and scarcity of raw materials and the prevention of ecological and economic issues as a result of abusing natural resources.

Appendix 3 The UK government's Green Industrial Revolution

The UK Government's Green Industrial Revolution

Carbon Dioxides (CO_2) are the so-called greenhouse gases, which trap heat by building a gaseous barrier between the Earth's atmosphere and space and the subsequently trapped heat makes the planet warmer (EEA, 2020,2021). EPA (2020) was investigated the same principles and found that human activities can be considered solely responsible for the increased greenhouse gases in the atmosphere for the timespan of the last 170 years. EPA (2020) and EEA (2020,2021) both stated clearly that the largest source of greenhouse gas emissions is the direct result of human activities from burning fossil fuels for producing electricity, heat, and transportation.

As EPA (2020) and HM Government (2020) found, most emissions are being produced through the burning of fossil fuels for electricity, heat, and transportation. The 6 sectors identified for being the most polluting are, as follows:

- Electricity
- Transportation
- Industry
- Commercial/ Residential
- Agriculture
- Land Use/ Forestry

The UK government seems to be proactively trying to reduce greenhouse gas emissions by issuing suitable guidance papers and policies, such as the "Ten Point Plan for a Green Industrial Revolution" (HM Government, 2020). The ten points in

question are dealing with significant issues, which will be discussed in detail.

In addition to these efforts, a multitude of projects and policies are currently being created, which the roadmap ahead, in Figure A3-1, will demonstrate:

Figure A3-1: UK roadmap of forthcoming announcements (HM Government, 2020)

<u>Offshore wind</u>

Quadrupling offshore production to achieve 40GW of electric power by 2030 and powering every residential building whilst additionally supporting up to 60,000 jobs. Planned investment of £160 million into modern ports and manufacturing infrastructure, with the delivery of 60% UK content in offshore wind projects. 5% reduction in carbon emissions.

Hydrogen

Aiming to generate 5GW of low carbon hydrogen produced electricity capacity by 2030 for industrial and residential application and having the first town heated entirely by hydrogen power by the end of the decade. This is being supported by a £240 million Net Zero Hydrogen Fund, whilst encouraging private sector investment and endeavour to create 8,000 jobs across all industries. 9% reduction in carbon emissions.

Nuclear

Developing the next generation of small and advanced clean energy reactors, potentially supporting up to 10,000 jobs. £385 million already set aside in the Advanced Nuclear Fund, with £215 million investment already earmarked for the development of Small Modular Reactors, whilst relying on unlocking up to £300 million private sector match-funding. Increasing carbon emissions by building nuclear infrastructure.

Electric vehicles

Backing car manufacturers in the UK to accelerate the transition to electric vehicles and transforming the national infrastructure to support electric vehicles. Up to £1 billion committed to support the electrification of UK vehicle-supply chains, with the first £500 million of investment being announced within the lifetime of this Parliament to drive the electrification of the UK automotive sector. Provision of £582 million to extend the Plug-in Car, Van, Taxi and Motorcycle grants to 2022–23. Investment of £20 million next year in freight trials to pioneer zero emission lorries. Endeavour to save 5MtCO_2 emissions by 2032. 1.1% reduction in carbon emissions.

Public Transport

Investment in zero-emission public transport and promoting cycling and walking. £4.2 billion have been set aside for city public transport and £5 billion on buses and encourage cycling, whilst also electrify more railway lines. Investment of £120 million in 2021 to begin the introduction of at least 4,000 more British built zero emission buses. 0.44% reduction in carbon savings.

Jet Zero

Supporting difficult-to-decarbonise industries through *research projects* for zero-emission planes and ships. £15 million set aside for FlyZero, a 12-month *study*, into the strategic, technical and commercial issues in designing future zero-emission aircraft and currently running a £15 million *competition* to support the production of Sustainable Aviation Fuels (SAF) in the UK. 0.22% reduction in CO_2 emissions.

Greener buildings

Providing £1 billion to install 600,000 heat pumps every year by 2028, creating 50,000 jobs by 2030 and to making residential buildings, schools and hospitals more energy efficient. The Green Homes Grant will be extended into 2022, homeowners can apply for the Homes Upgrade Grant and funding for the Social Housing Decarbonisation and Public Sector Decarbonisation Scheme will be provided. 16% reduction in carbon emissions.

Carbon capture

Becoming a world-leader in carbon capture and storage with a target to remove 10MT of CO_2 by 2030. The £1billion CCUS (Carbon Capture, Utilisation and Storage) Infrastructure Fund will provide industry with the certainty required to deploy CCUS at pace and at scale. 9% reduction in carbon emissions.

Nature

Protecting and restoring the natural environment and planting 30,000 hectares of trees every year, whilst creating and retaining thousands of jobs. The Green Recovery Challenge Fund has been increased to £80 million over 100 nature projects are delivered over the next 2 years, with an additional 1.5% of AONB natural land in England, contributing to achieving the target of protecting 30% of UK land by 2030.

Green Finance and Innovation

Developing the technologies to make the City of London the global centre of green finance. The first phase of a £100 million investment has already been launched, applying state-of-the-art Greenhouse Gas Removal technology, such as Direct Air Capture. Additionally, £100 million will be provided for Energy Storage and Flexibility innovation challenges. Additionally, the commercialisation of fusion energy technology is being supported, by providing £222 million for the visionary STEP programme (Spherical Tokamak for Energy Production), on grid in the UK by 2040, and £184 million for new fusion facilities, infrastructure and apprenticeships to lay the foundations of a global hub for fusion-related innovation in the UK.

Findings

The 10-point-plan and all the efforts within amount to a total of only 40.76% in carbon emission savings projected to have been achieved by 2030, notwithstanding the unfortunate issue that nuclear power plant creation will actually be *adding* an incalculable amount of GHG and CO_2 emissions, through construction, building and operation of required infrastructure – besides the known risks of operating nuclear power plants, as demonstrated by the Chernobyl disaster (WNA, 2024) and the potential for illegal weaponizing of by-products, such as plutonium.

On first glance, it so seems as if the three most polluting sectors in the UK are not sufficiently focused on within the UK Green Industrial Revolution Agenda, with most CO_2 saving opportunities in transport/aviation, residential dwellings almost and (animal) agriculture completely being left out? As Nix (2020), EPA (2020), EEA (2020,2021), and WWF (2023) found, animal agriculture, such as beef production, accounts for 25% of global land use, land-use change and forestry emissions - and these issues do not appear to have been factored into the 10-Point Agenda.

Especially for residential dwellings, there are various concepts available, which could contribute to significant CO_2 savings: with the German "Passivhaus"(Passive House Institure 2024, 2024), CO_2 could possibly be reduced by more than 85%.

As far as agriculture is concerned, the implementation of robust guidance and financial incentives for sustainable farming could revolutionise UK farming within the next 5 years:

- Making it compulsory for every meat and dairy producer to be assigned to the "Good-farming-protocol" (Kiessling, 2021) to have an anaerobic digester plant (adp) on site for recycling organic waste. Support farmers efforts with grants to build adp's and support them with mentoring, i.e., technical support, to build the infrastructure on site to utilise the biogas as by-product of anaerobic digestion (HM Government, 2020a).

Farm effluents such as slurry and organic waste would then not just be disposed of on existing farmland, endangering the fresh-water table and increasing the nitrogen levels in natural water courses, but could be utilised as biomass and a valuable resource for energy production.

The required technical support and expertise would create long-term, sustainable jobs for workers who have so far been employed in industries, which have been heavily relying on fossil fuels.

With regards to point nine of the UK Green Industrial Nature - forests and green spaces: a massive opportunity has been missed: a hard wood tree (such as oak, beech, elm) (Nix, 2020) sequesters up to 1t/CO_2 in a 40-year-lifetime (EPA, 2020).

Interestingly, the UK governments Forest Research group (2021) found, that currently only 13% of available land has tree cover in the UK, estimated to be 3.21 million hectares. This represents 10% in England, 15% in Wales, 19% in Scotland and 9% in Northern Ireland. Interestingly, most of the UK direct continental neighbours have an average tree cover of 37% (Van der Zee, 2013). We can rebuild natural forests as carbon sinks very easily by paying farmers to do so during environmental stewardship schemes (Nix, 2020).

Additionally, there are multiple errors in thinking behind the UK Green Industrial Revolution agenda, which will be demonstrated in the following:

Hydrogen

Rapier (2020) is clearly demonstrating that there is at present no need to produce hydrogen, which is being produced using 100% fossil fuels, and 9.3 kg CO_2 are being produced per kg of hydrogen. Hydrogen has just the same destructive energy balance as combustion engine fuel, which produces 9.1 kg of CO_2 per 5 litres, when combusted (Rapier, 2020).

However, solar and wind energy are the most abundantly available forms of energy and here is the opportunity: hydrogen produced using solar energy could potentially be a more sustainable, future-proof solution (Ture, 2007; Sunny, MacDowell and Shah,2020), which marks out the need for further research into this direction.

Nuclear

Besides the negative CO_2 balance, the threat of nuclear catastrophe is real, as Chernobyl has taught us (World Nuclear Association, no date). Additionally, problematic by-products, such as weapon-worthy plutonium, could be obtained and used for illegal purposes (Maerli, Schaper and Barnaby, 2003). Solar, wind and hydro-power energy is abundantly available in the UK and an additional nuclear power plant is neither in keeping with efforts to reduce carbon emissions, renewable energy currently being achieved and potential for achieving 100% renewable energy within the next 4 years nor fulfilling any governments duty to keep their citizens safe.

Electric vehicles

Besides the fact that the new agenda only saves 1.1% in carbon emissions, the most pressing issues have not been addressed, such as the fact that *road transport* equates to 75% of the overall CO_2 emissions and drastic action is urgently required (WWF, 2023). If the pandemic has taught us one thing, it is the fact that we are driving and flying too much, we have too many old technology road vehicles and aeroplanes in service which are emitting a toxic level and mixture of greenhouse gases.

Public Transport

Road transport is one of the fastest-growing sources of GHG emissions and is driving global climate change at an accelerating pace (WWF, 2023). A change in thinking is required: meetings can easily be conducted online, via MS Teams, ZOOM and other means. Even teaching is possible online, i.e., via Google classroom, we do not HAVE to commute unsociable distances on a daily basis, gathering with people we are forced to socialise with, which we would not choose to do given half the chance. The aviation is one of the biggest polluters in existence and drastic measures are required: driving and flying less means improving public transport infrastructure, reducing road traffic, reducing the number of airlines and training airline staff to work in green industries, as set out by the UK government. Figure 71 displays the aviation-related CO_2 emissions, which accounts only for 2.5% of global CO_2 emissions (EPA, 2020). Unfortunately, besides a drive to further develop hydrogen-based public transport (with hydrogen production largely based on using fossil fuels) and more environmentally friendly aviation fuels studies and conceptualisations, the UK Green Industrial Revolution agenda falls short of proposing real change. Information to this effect as displayed in Figure A3-2.

Research Gap:

What really needs to happen is a lifestyle change, a change in attitude: attend meetings and educational events online wherever possible, cut down on commuting for workers across all industries and eradicate the use of combustion engines within the next 5 years. This change could happen easily if fossil fuel subsidies were being diverted to incentivise drivers to switch to electric vehicles and planes with environmentally-friendly jet engines, and radically subject public transport, the iron and steel industry and all other heavy industries (cement/concrete, glass, paper, chemicals, building) to a green overhaul – away from fossil fuels, using renewable energy technology only.

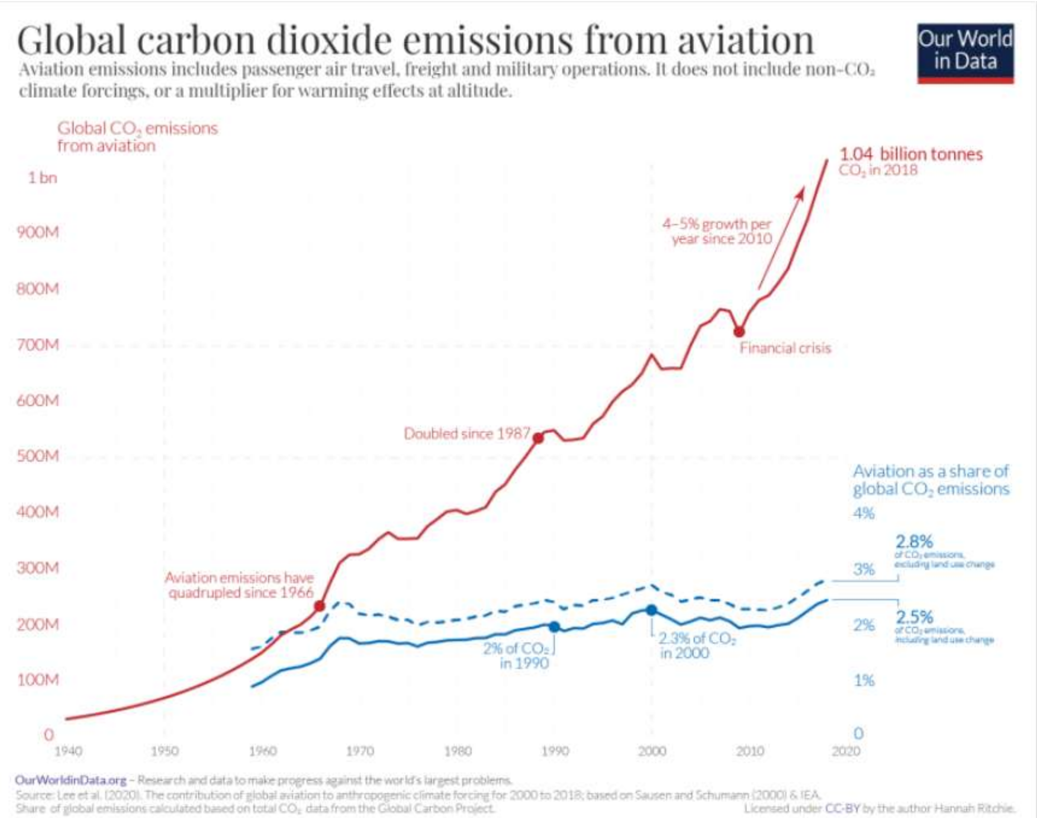

Figure A3-2: GHG from aviation (Lee et al., 2021)

Appendix 4 Green energy providers at time of writing

Energy provider	UK Headquarters address	Renewable sources	Green electricity	Green gas	Carbon offsetting
Octopus Energy, 2023	UK House, 5th floor, 164-182 Oxford Street, London, W1D 1NN https://octopus.energy/	Anaerobic digestion, solar, wind, hydro	100%	0%	Yes

Green Energy UK, 2023	Green Energy (UK) plc Black Swan House, 23 Baldock Street Ware, Herts, SG12 9DH https://www.greenenergyuk.com	Hydro, solar, wind	100%	100%	No
OUTFOX The Market, 2023	16 North Mills, Frog Island, Leicester, Leicestershire, LE3 5DL https://www.outfoxthemarket.co.uk/	Wind	100%	0%	No
Ecotricity, 2023	Lion House, Rowcroft, Stroud, Gloucestershire, GL5 3BY https://www.ecotricity.co.uk/our-green-energy/green-electricity	Wind (98%), solar (0.12%) and hydro (0.7%)	100%	Yes	Yes
OVO Energy, 2023	1 Rivergate Temple Quay Bristol BS1 6ED https://www.ovoenergy.com/	Anaerobic digestion 49%, solar 32%, wind 18%, hydro 1%	100%	15%	Yes
Good Energy UK, 2023	Monkton Park Offices, Monkton Park Chippenham SN15 1GH https://www.goodenergy.co.uk/	49.41% = Wind. 32.71% = Bio generation. 13.60% = Solar. 4.28% = Hydro	100%	No	Yes
SSE Energy Solutions, 2023	Inveralmond House, 200 Dunkeld Road, Perth PH1 3AQ https://www.sseenergysolutions.co.uk/business-energy/our-renewable-electricity	Hydro plants and wind farms	100%	No	Yes
CERES Power, 2022	Viking House, Foundry Lane, Horsham, West Sussex, RH13 5PX https://www.ceres.tech/technology/steelcell/	Fuel-flexible SteelCell® from natural gas and biogas, ethanol or hydrogen	Yes	No	No

Appendix 5 https://www.mdpi.com/1996-1073/15/23/8880

The Bio Steel Cycle: 7 Steps to Net-Zero CO_2 Emissions Steel Production

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(This article belongs to the Special Issue **Challenges and Development on Carbon Capture and Storage**)

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Abstract

CO_2 emissions have been identified as the main driver for climate change, with devastating consequences for the global natural environment. The steel industry is responsible for ~7–11% of global CO_2 emissions, due to high fossil-fuel and energy consumption. The onus is therefore on industry to remedy the environmental damage caused and to decarbonise production. This desk research report explores the Bio Steel Cycle (BiSC) and proposes a seven-step-strategy to overcome the emission challenges within the iron and steel industry. The true levels of combined CO_2 emissions from the blast-furnace and basic-oxygen-furnace operation, at 4.61 t of CO_2 emissions/t of steel produced, are calculated in detail. The BiSC includes CO_2 capture, implementing renewable energy sources (solar, wind, green H_2) and plantation for CO_2 absorption and provision of biomass. The 7-step-implementation-strategy starts with replacing energy sources, develops over process improvement and installation of flue gas carbon capture, and concludes with utilising biogas-derived hydrogen, as a product from anaerobic digestion of the grown agrifood in the cycle. In the past, CO_2 emissions have been seemingly underreported and underestimated in the heavy industries, and implementing the BiSC, using the provided seven-steps-strategy will potentially result in achieving net-zero CO_2 emissions in steel manufacturing by 2030.

Keywords: net-zero steel; CO_2 emissions; Bio Steel Cycle (BiSC); CAT; CCUS; flue stack gas scrubbing

1. Introduction

The requirement to drastically reduce GHG emissions, and particularly CO_2 emissions, has never been greater than today. The Kyoto Protocol, the Paris Agreement, and recent 2022 reports from the IPCC have clearly set out the impact that the highest-ever recorded anthropogenic CO_2 emissions are having on our environment and climate. With the iron and steel industry being responsible for at least between 7% and 11% of global CO_2 emissions [1,2,3,4,5,6,7,8,9,10] and China being responsible for 50% of these GHGs [2], the factual level of CO_2 emissions for every t of steel produced currently stands at more than 4.6 t of CO_2 emissions [11]. The onus is therefore on industry to remedy the environmental damage caused in the past two centuries [11,12,13,14,15,16]. The anthropogenic carbon emissions are at an all-time-high with reported ~65.6 Gt CO_2-equivalent in 2019 [11,12,13,14,15,16]. The 64 steel producing countries reported 1.9 Gt of steel produced between January and December 2021 [17,18,19,20,21], and—based on the current findings—are likely resulting in 8,806,211,400 t or ~8.8 Gt CO_2-equivalent of CO_2 emissions as a result of the current linear steel manufacturing.

The importance to significantly reduce GHGs and eliminate fossil fuel combustion and usage has never been greater, and fast, practical solutions—on a global scale—are needed. Already in 1912, it was recognised that coal consumption is an environmental hazard and incompatible with keeping global temperatures at a balanced level to sustain life. Industrial processes have for more than 200 years polluted the air we breathe, and this was already recognised in 1912 [22].

It is worth pointing out that in this article [22], merely the in-furnace-coal-combustion process is mentioned in connection with carbon emissions. CO_2 emissions from energy consumption, mining, pelletising, coking, sintering, steel smelting, casting, rolling, annealing, finish machining and surface treatment and related processes were not considered at that time. These authors have already, more than a hundred years ago, established the emission factor as being 3.5: as 7,000,000,000/CO_2 emissions./.2,000,000,000 t of steel equates to 3.5 t of CO_2 emissions in the blast furnace operations per tonnes of steel. These assumptions and calculations were possibly based on the carbon content of coal (78–95%) [5,23,24] and the release of CO_2 into the atmosphere as a result of combustion processes. Although the steelmaking process has undergone significant improvements, the basic oxygen furnace (BOF) operation alone still stands at CO_2 emissions of between 2.2 t and 1.6 t/CO_2/t of steel produced. This begs the question why this knowledge has not been used to establish the true CO_2 emissions of the steelmaking process over the past 2 centuries. Why has the iron and steel industry not reacted immediately after having been made aware in 1912 of the devastating environmental consequences of their operations?

The current state of the decarbonisation of the iron and steel industry has been carefully reviewed and key publications have been identified. A direction-giving quality can be attributed to Bataille et al.'s (2018/2021) publications [25,26], as this provided key components to develop the BiSC model and strategy and set the foundations to establish the seven steps to net-zero carbon steelmaking. Invaluable insights were provided regarding decarbonisation of the iron and steel industry, "green" steel in particular and the mechanisms and processes necessary to achieve sustainable and carbon-free iron and steel production. Setting the scene, Muslemani et al. (2021) [27] worked on identifying the opportunities and challenges for decarbonising steel production by creating markets for "green" steel products. Their in-depth investigation provides valuable insight into potential markets for green steel products and their manufacturers and to make the economic case for sustainable production. Arens, Åhman, and Vogl (2021) [28] researched which countries are factually prepared to "green" their coal-based steel industry with electricity and reviewed respective climate and energy policy. They subsequently published policy guidance by country for "green" steelmaking. One of the key papers to provide the technical insight into the vital components of sustainable steel is Wang et al.'s (2022) and Wang's (2022) [29,30] investigations of the opportunities for technology-driven decarbonisation and green steel for Australia. They carried out economic modelling of a green steel value chain with wider implications for the second- and third-tier small-to-medium enterprises and heavy industry. Models, pathways, and roadmaps are guiding the industry on the path to decarbonisation, and therefore Bataille, Nilsson, and Jotzo's (2021) [26] study was considered a key paper. They provided some components for the BiSC (Bio Steel Cycle) model [10] when they looked at the iron and steel industry in a net-zero emissions world. They identified new mitigation pathways, new supply chains, modelling needs, and policy implications. Their mitigation pathways investigation towards decarbonisation of steelmaking provided invaluable analysis and insight into supply chains and policy needs. Liu et al.'s (2022) and Liu et al.'s (2020) [31,32] work created a technological roadmap towards optimal decarbonisation development of China's iron and steel industry. They developed policy guidance exploring the deep decarbonisation pathways. Richardson-Barlow et al. (2022) [33] identified policy and pricing barriers to steel industry decarbonisation during their case study of the UK iron and steel industry. They issued a guidance paper, exploring the decarbonisation pathways. One of the paths towards decarbonisation of the iron and steel industry is using hydrogen, and particularly hydrogen direct reduction. The discussion around H_2 has gained more momentum again, and Öhman, Karakaya, and Urban (2021) [34] researched the transition potential into a fossil-free steel sector and identified the necessary conditions for technology transfer to hydrogen-based steelmaking in Europe. Toktarova et al. (2020) [35] investigated the low-carbon steel industry interactions between the H_2DR of steel and the electricity system via a Swedish case study. Toktarova (2021) [36] created a cost-optimal design of the steelmaking industry and electricity system with close to "0" CO_2 and produced another key paper towards the creation of the BiSC model. Matino and Colla (2021) [37] took a slightly different approach when they endeavoured to issue a guidance paper and overview of the state of the art, recent developments, and future trends regarding a hydrogen route for a green steelmaking process. In their opinion, steel production based on hydrogen is one of the key factors to improve the carbon footprint of the steel industry. A more global perspective was taken by García-Herrero, Tagliapietra, and Vorsatz (2021) [38], within their development of hydrogen development strategies. They see hydrogen as a candidate to fully decarbonise European steelmaking, global aviation, and maritime transport. Grasa et al. (2022) [39] investigated the blast furnace gas decarbonisation through calcium-assisted steel-mill off-gas hydrogen production. They took an experimental and modelling approach to the calcium-assisted steel-mill off-gas H_2 production process (CASOH) in integrated steelmaking plants. Devlin and Yang (2022) [40], however, focused more on regional issues when researching supply chain implications and their potential for decarbonising steel. Their focus was energy efficiency and green premium mitigation, green hydrogen-based iron ore reduction, and renewable electricity-based steelmaking. Case studies, such as Gosens, Turnbull, and Jotzo's (2021) [41] work concentrated on a highly granular model of China's coal production, transport, and consumption system. Their work shows how its decarbonisation and energy security plans will affect coal production and the effect of decarbonisation on coal imports. Griffin and Hammond (2019/2021) [42,43], however, cast the net wider with the focus on global transitions and investigation into making UK steel production more environmentally benign whilst advancing decarbonisation of the iron and steel sector. Lu et al. (2022) [44] also provided insight into China's iron and steel industry decarbonisation options, based on a 3-dimensional analysis. Whereas Steenbrink (2022) [45] focused on the impact of the Carbon Border Adjustment Mechanism and conducted an economic and geopolitical assessment of the German–Chinese aluminium trade flows. That paper provides a thorough assessment on how best to incentivise non-EU trade partners, and to adopt measures comparable to the EU's and—simultaneously—assessment of yield revenue to reuse in accelerating decarbonisation of steelmaking. In terms of carbon avoidance, capture and utilisation, Kempken et al. (2021) [46] identified possible decarbonisation barriers (Deliverable 1.5). The isolation of major barriers to the decarbonisation process of the EU iron and steel industry provides valuable insights into the reasons why the industry seems quite reluctant to decarbonise its existing production and facilities. Williams et al. (2021) [47] conducted a case study, during which they focused on CO_2 capture and storage (CCS) and presented the results of focus group discussions in a Welsh steelmaking community. The topic of decarbonisation of steel production by switching to renewable sources was welcomed during the local focus group discussions and showed widespread support in the community for the company's efforts in this direction. Tanzer, Blok, and Ramirez (2021) [48] went one step further by focusing their research on integration of biomass when they investigated the decarbonisation opportunities via BECCS: promising sectors, challenges, and techno–economic limits of negative emissions and BECCS in the iron and steel industry. Sarić, Dijkstra, and Van Delft (2021) [49] considered CO_2 abatement in the steel industry through carbon recycle and electrification by means of advanced polymer membranes. For this, a conceptual process design and assessment was performed for a process that is a combination of carbon recycling and electrification of the steelmaking process. Wang (2022) [30] focused more on energy saving technologies and optimisation of energy use for a decarbonised iron and steel industry. A valuable guidance paper was issued in which suitable decarbonisation technologies are categorised. A different approach was taken by Singh et al. (2022) [50], as they researched the opportunities of decarbonisation of steel-mill gases in an energy-neutral chemical looping process, providing the technical elements for carbon enrichment for plant stimulation (CEPS), which is based on flue-stack gas scrubbing. In addition to CAT, CCUS, and BECCS, waste recycling is a vital part of the decarbonisation process. Jacob, Sergeev, and Müller (2021) [51] provided a thorough review when they investigated the potential of valorisation of waste materials for high temperature thermal storage. An overview of the decarbonisation process was presented, of both the electricity and steelmaking industry. Sun (2022) [52] seemed to have worked along the same lines and developed a concept for the decarbonisation of the iron and steel sector for a 2° C target, using inherent waste streams. Furthermore, other aspects of decarbonisation need to be considered, as Antonazzo et al. (2021) [53] pointed out: A key component of the transition process to decarbonisation is the need for meeting green-skills needs for a sustainable steel industry. They identified the skills required for a steel industry in transition to sustainability. Zhiming et al. (2021) [54] researched material-based decarbonisation implications and how lime quality affected metallurgical steel quality and the value in use of lime in the BOF steelmaking process. Garvey, Norman, and Barrett (2022) [55], however, focused on technology and material efficiency scenarios for net-zero emissions in the UK steel sector. Their assessment included steel-plant retrofitting and grid electricity decarbonisation.

So far, high asset cost and long amortisation periods (in excess of 25 years) of capital equipment are making it difficult for steel manufacturers to honour their obligation to decarbonise and clean up their production processes. However, even if only parts of the BiSC and 7-steps strategy are being implemented, carbon neutrality can be achieved in the short-term: Switching energy suppliers to those who derive their energy from renewable sources can achieve a 30% reduction in emissions. Adding filter and Geomimetic® systems would capture the remaining CO_2.

The objectives of this multi-disciplinary and multi-industry overarching study are to identify the most efficient implementation opportunities of the chosen processes and technologies to reduce the current BF–BOF route 4.6 t CO_2 emissions/t of steel produced to factual "0". These are ordered in seven easy steps, from short-term to long-term solution implementation. This work appears to be one of the first of its kind (to date), as it so seems that neither in academia, nor industry, nor politics have suitable models, strategies or guidance papers been published to explain how net-zero steelmaking can be achieved. If only individual steps are being implemented, such as switching to renewable energy suppliers, a 30% reduction of GHG emissions can be achieved.

2. Materials and Methods

The research used global steel data and literature on sustainability, decarbonisation, and CAT, CCS, and CCUS technology. The main reason underpinning this choice and course of research is that, as suggested by the Steel Yearbook 2018/2019 [17,19] the global iron and steel industry is still heavily reliant on coal and is responsible for at least between 7% and 11% of global CO_2 emissions [1,2,3,4,5,6,7,8,9,10,56], and China is responsible for 50% of these GHGs [2].

The impact of different technologies [35] on the processes at all stages in the steelmaking process [43], decarbonisation of the iron and steel manufacturing [1,2,3,4,5,6,7,8,9,10,17,18,19,20,21,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55], and related databases and corresponding literature [56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137,138,139,140,141,142,143,144,145] were investigated. Additionally, literature regarding CAT, CCS, and CCUS and the circular economy, sustainability, and decarbonisation of the steel industry were categorised for ease of implementation, from easy to more challenging and

An Excel database was used for data collection, modelling, and key calculations. The parameters were defined as t of CO_2 per t of steel produced, although further parameters for future research are being allowed. The research works with metric tonnes only. Formulae were developed and adjusted [57,58], as follows:

(1) $CO_2E_{total} = \sum$(emissions per ton of steel) × Ω (output tons produced)
(2) 1 charge (400 tons in 40 min)

$$CO_2E_{total,1c} = \sum(CO_2RE_{coal} + CO_2RE_{ore} + CO_2RE_{oxy} + CO_2PT_{coal} + CO_2PT_{lime} + CO_2ST_{sint} + CO_{2Smelt} + CO_2BF + CO_2BOF + CO_2C + CO_2M + CO_2FM) \times (CapBF \times t)$$

In order to determine the BF/BOF-route CO_2 emissions, the formula had to be adjusted, accordingly, to [65,66,119]:

(3) $CO_2E_{total} = \sum(CO_2BF + CO_2BOF)$
CO_2E_{total} = Total CO_2 emissions
CO_2RE_{coal} = CO_2 emissions resource extraction coal
CO_2RE_{ore} = CO_2 emissions resource extraction iron ore
CO_2RE_{oxy} = CO_2 emissions resource extraction oxygen
CO_2PT_{coal} = CO_2 emissions primary resource transformation coal> coke
CO_2PT_{lime} = CO_2 emissions primary resource transformation limestone> lime
CO_2ST_{sint} = CO_2 emissions secondary resource transformation coke/iron ore> sinter
CO_{2Smelt} = CO_2 emissions smelting
CO_2BF = CO_2 emissions blast furnace
CO_2BOF = CO_2 emissions basic oxygen furnace
CO_2C = CO_2 emissions casting
CO_2M = CO_2 emissions milling
CO_2FM = CO_2 emissions finish machining
CapBF = Capacity blast furnace / basic oxygen furnace
t = time (charges per day) 400 tonnes per charge every 40 min,
Ø of 10,000 tonnes/day

Additionally, engineering simulation software was used, such as Simul8 and Aspen Plus V11. The Simul8 and Aspen Plus V11 models are being adjusted continuously to meet the different applications of carbon avoidance, carbon saving, and carbon utilisation technologies, in accordance with the strategy flowchart in **Figure 1**:

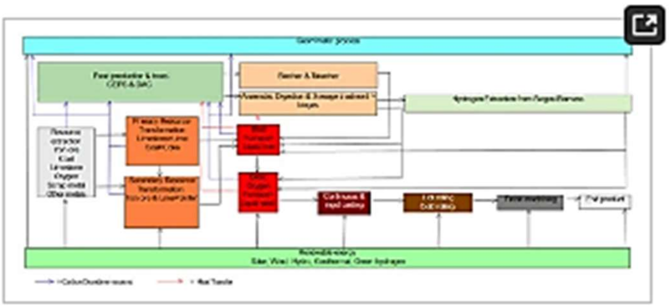

Figure 1. Simul8 steel linear production configuration. The colour-coding within **Figure 1** is identical to the master database (Excel), which has been created to gather and display findings, facts, and figures, and is supposed to signify the energy intensity and heat development at the different stages of the steelmaking process in °C.

3. The Bio Steel Cycle Components and 7-Steps Principles

The conventional linear steel manufacturing process, including all processes such as coal, iron ore, and limestone extraction, crushing, pelletising, sintering, smelting, casting, rolling, and finish machining, was investigated and resulted in establishing that the BF/BOF route alone produces ~4.6 t of CO_2 emissions, which are one of the undesired by-products of every metric t of steel produced. The results to date of research into the CO_2 emissions at the various stages of the steelmaking process and related sub-processes have been established, and the findings of the BF/BOF route are displayed in Appendix 5. CO_2 emissions as a direct result of steel manufacture increased by 1.6% or 8.7 Gt/CO_2 in 2020, although in the Net-Zero-Emissions-by-2050 scenario, industry emissions are estimated to decrease by 2.3% annually at 6.9 Gt/CO_2 by 2030, despite expected industrial production growth [4]. Improved material and energy efficiency, the increased utilisation of renewable energy technologies, and development and deployment of low-carbon process routes (including CCS and hydrogen) are considered to have an emission-reduction effect of individually between 12 and 30%. Fossil-fuel-derived energy generation and combustion of fossil fuels for transport (including aviation) are the two biggest sources of CO_2 emissions, worldwide [3,4,5,13,35,56,59]. Steel production is in close third place, followed by cement production and the chemical and glass industries [3,4,5,13,35,56,59].

One possible solution to combat this issue is the Bio Steel Cycle (BiSC) as a model, based on the circular tech economical principle. Steel scrap is considered a resource, and similar to recycling waste and by-products, is an integral part of the circular production process. Off-gases (CO_2 and other GHGs) are being captured and reutilised, and alongside implementation of steelmaking process improvements, furnace heat capture and utilisation, CAT, CCS, and CCUS technologies and processes, and multi-disciplinary external components, are closing the circle [14,15,25,26,35,59,60].

Suitable literature was thoroughly investigated in regard to applied and innovative steelmaking procedures, CAT, CCS, and CCUS processes, and improved management systems such as industry 4.0 (I4.0) [61,62]. The literature investigating the most efficient and effective technologies, process improvement suggestions, and technologies at suitable technical readiness levels (TRL 6–9) was analysed, and the conclusions derived led to the creation of the components within the Bio Steel Cycle and the 7-stepsstrategy to net-zero steel manufacturing.

The most likely scenarios were considered, and the principles of the Bio Steel Cycle model are applicable to most heavy industries, such as cement, chemical, glass, paper, and transport. It includes using renewable energy technologies, avoiding CO_2 emissions by incorporating process improvement technologies, recycling waste and by-products, and capturing post-combustion emissions where possible [14,15,25,26,35,59,60], as displayed in **Figure 2**:

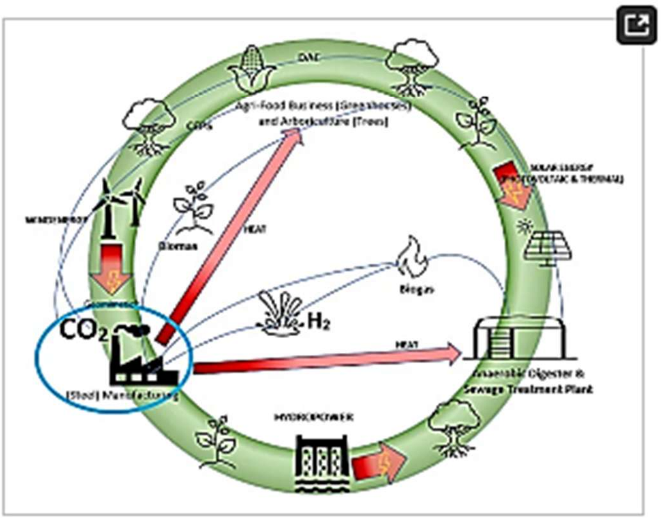

Figure 2. The Bio Steel Cycle concept and cyclical resource utilisation flow.

Analyses of the technical and economical long-term potential of novel steel production technologies CAT, CCS, and CCUS and in the UK [63,64,65,66], Germany [67] and beyond used techno–economic models to model three research-stage [35,43,59,64] ore-based steelmaking routes versus the BF–BOF route [68]. It was concluded that in comparison, the BF with CCS1 (BFCCS) [6,7,8,9,67], hydrogen direct reduction (H-DR) [6,7,8,9], and iron ore electrolysis (EW) [35,36], energy and raw material efficiency is significantly higher for H-DR and EW [6,7,8,9,67,68,69,70] and the 80% reduction target by 2050 [71] was thought to be perfectly achievable in the scenario, as per Tata Steel's Zeremis vision much sooner, by 2045 [72]. It was found that there are a sufficient number of viable CAT, CCS, and CCUS technologies, methods, and strategies at TRL 7–9 available for immediate BiSC implementation and achieving short- to medium-term significant reduction of CO_2 emissions in steelmaking. The urgency for sufficient prioritisation throughout all industries and political willingness (subsidies) cannot be emphasised enough [14,15,71]: the need to create a viable commercial environment, due to the required high capital investment and a significant dependency on electricity prices [35,56,73,74].

The following key components within the Bio Steel Cycle are based on a circular production process and are functioning in an interactive manner. The basis for this system is the BF/BOF route and involves the aforementioned CAT, CCS, and CCUS and process improvements where possible. Innovative technologies such as Hisarna [70] and GrInHy [75] and hydrogen direct reduction (HDR) have CO_2 saving potential in their own right, as explained in more detail, as follows. By removing coal as a primary energy source or using hydrogen direct reduction, an immediate 30% CO_2 emissions reduction is possible, and therefore [31,35,64,76,77,78], replacing coal with biomass or hydrogen would reduce the CO_2 emissions from steelmaking potentially by the same percentage. According to Siemens (2022) [79], a 50% carbon emissions reduction is immediately possible via utilisation of green hydrogen direct reduction. The standard steel production (SSP) process in combination with the currently operational newly developed technologies [35,69,70,72] also achieves a reduction of more than 50% with successive implementation to less than three metric tonnes/t of steel produced. By incorporating the BiSC components of CAT, CCS, and CCUS into existing steel production sites, an almost 100% CO_2 emission reduction can be achieved, immediately.

The post-combustion capture of CO_2 (CCS) and other GHGs and the exploration of carbon scrubbing of flue gases were explored. There are several possible technologies and processes to be considered for post-combustion carbon capture:

- Mechanical capture;
- Compression and dehydration;
- Membrane installation;
- Guiding off-gas through troughs of physical solvents/solid sorbents (such as Zeolite13X) and chemical solvents;
- Utilising metal-/organic frameworks [25,26,43,59,80].

Renewable energy technologies are one of the key components within the Bio Steel Cycle, as CO_2 emissions in steelmaking could be reduced by more than 30% [81] if commercial entities in iron and steel production [25,26,82] were to simply switch their energy providers [59] to those that supply energy which was derived using 100% renewable energy technology and produce their own energy by retrofitting their plants with renewable energy technologies (wind, solar PV). The same applies to greenhouses, as there is a vast amount of roof space available, which has to date not been utilised. The static requirements would obviously have to be considered, but as the cost and weight of solar energy and solar PV has decreased significantly over recent years (Dastoor, 2021) [92] to less than GBP 3/m^2 and to a foil body in appearance, it can be considered an unmissable opportunity.

In the spirit of innovative, multi-disciplinary approaches to solving contemporary CO_2 emission issues, the positive effects of DAC (Direct Air Capture) and utilisation of woodlands for carbon capture cannot be emphasised enough. As one of the critical components of the BiSC, woodlands/trees for DAC would even be a profitable side-line for steel producers, as illustrated in the following Figure 3:

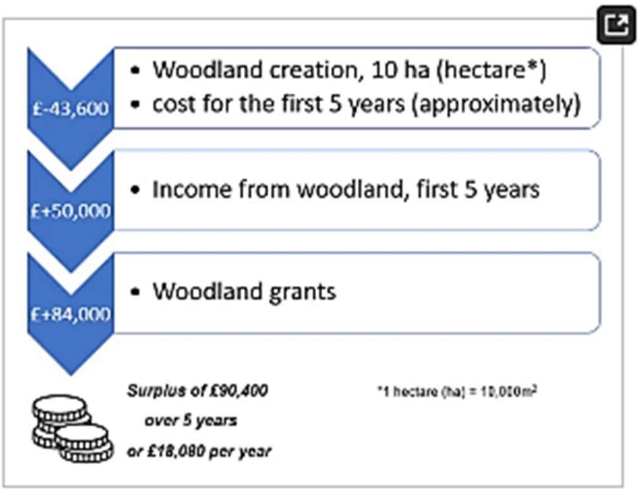

Figure 3. Woodland creation graph.

Trees and vegetation as natural carbon sinks should ideally be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC) [83,84,85], whilst at the same time, the plant matter could feed the anaerobic digester, biochar plants or be directly used at selected quality in iron and steelmaking as readily available biomass. In this respect, bamboo beats deciduous native plants with its carbon sequestration capacities: on average, one hectare of bamboo stand absorbs ~17 tonnes of carbon per year [86]. Native deciduous and non-deciduous trees have a carbon sequestration capacity of on average 9 t of CO_2/ha of tree plantation [6,7,8,9,83,84,85]. Planting a sufficient number of trees should be considered in the planning for the updating of existing steel production plants and for any new development in order to meet the UK government's zero emissions targets. The UK tree cover stands at 13.2% (3.2 million ha, 66.65 m people = 0.048 ha per capita) [83,84], which is the lowest in the Northern hemisphere. In comparison, forests, and wooded land cover over 182 million hectares in the EU, which is about 42% of the EU's total land area. This equates to 0.36 hectares of forest per capita in the EU in comparison [6]. Woodlands not only capture post-combustion CO_2 and create biomass for anaerobic digestion, but they also may create recreation and employment opportunities and additional sources of commercial activity. Additionally, they offer a low-cost opportunity for carbon-offsetting, which could be seen as a commercial opportunity in itself.

Food production in greenhouses, anaerobic digestion, and sewage treatment plants require a stable ambient temperature throughout the year, which requires a conventional source of heating. Re-using heat from the steelmaking process, the expenditure of installing heating systems and using fuel and energy is simply not required, as the air has already been heated. Although the installation of a suitable infrastructure would have to be considered, the economical case must be further investigated, and the financial viability, such as the cost of ducts and pipework against the installation of a heating and cooling system including energy requirements, need to be solid to make a case for re-utilising flue-stack off-heat. The flue-stack heat can be as high as 1650 °C and would have to cool down, i.e., via travelling through adequately sized pipework, ducts, and possibly turbines (which in their own right would possibly be able to generate electricity, via convection, baffle systems or plate-heat exchangers). The energy saved on heating food production facilities is deserving of further investigation, as this will effectively contribute to achieving net-zero carbon emissions in steel production.

Additionally, incorporating the CEPS (Carbon Enrichment for Plant Stimulation) process into the BiSC-based circular steelmaking process [30,80] involves CCUS by means of driving CO_2-enriched flue-stack off-gas from combustion processes into CEPS units. Subsequently, this at almost 100% carbon enriched air is then directed into greenhouses to stimulate plant growth. The chosen CEPS model is deemed scalable and has the capacity to provide 85 tonnes of CO_2 p.a. in its current configuration [80]: concentrating CO_2 from ambient air (400 ppm) into an enriched product stream at 1000 ppm CO_2. Locating the source of CO_2, i.e., flue gases from production in steel, cement [87] or energy production and greenhouses in proximity of each other eliminates costs associated with filtering, deactivation, compression, transportation, handling, distribution, and storage entirely. Every successfully installed CEPS unit/greenhouse infrastructure is effectively a CO_2 sequestration station, and the economic feasibility is based on 1 kWh = 3600 kWs = 3.6 MJ [88], costs between GBP 0.11–0.21/kWh and 17.8 kJ/mol CO_2 = 17.8 kJ/44 g CO_2 [89,90] for pure CO_2 versus 8.5 kJ/mol CO_2 = 8.5 kJ/44 g CO_2 for enriched, 1000 ppm CO_2, costing effectively between USD15 and USD309/t CO_2. The efficiency, technical, and economic viability are making the case for temperature-swing absorption/desorption flue-gas carbon capture.

The anaerobic digester and sewage treatment facility are vital components within in the BiSC and would be ideally integrated into the steel mill or quite possibly be independent businesses in their own right, conveniently located on site of the steel production facility. These units would be able to accommodate debris from nearby woodland management and additional biomass from surrounding residential and commercial entities. Steelmaking by-products, such as brown water, can be treated at the sewage treatment facility. The cleared sewage can subsequently be utilised to fertilise the food production units. The anaerobic digestion process in itself produces biogas, which can be used in steel production, but it also provides the base for extraction of hydrogen. The green hydrogen produced at or nearby the anaerobic digestion facility can then be used in (steel) production within the hydrogen direct reduction (HDR) process. As this has been derived from biogas as a result of anaerobic digestions, this can therefore be considered green hydrogen. Hydrogen direct reduction (HDR) has been piloted over recent years and has been shown to have great CO_2 avoidance potential, and green hydrogen technologies are currently being developed by a number of significant industry leaders, such as Mannesmann Salzgitter [75], in cooperation with the European Commission and Tata Steel. Green HDR in blast furnace and electric-arc furnace application is considered as having a significant impact on reducing CO_2 emissions in steel manufacturing, as this process uses 3.48 MWh of electricity per ton of steel product and emits only 2.8% of blast furnace CO_2. However, as the prices of fossil-fuel-derived energy have increased significantly, it is imperative to replace fossil-fuel-derived energy with renewable energy technologies and biomass [35,36]. Technologies such as ReclaMet (waste resource recovery, post-combustion) [69] electrolysis projects, i.e., GrInHy and H2Future [6,7,8,9,75] (direct water splitting: biomass > hydrogen, pre-combustion) all have an impact in the magnitude of between 12% and 25%, although further research is required to establish not only the most effective technology in terms of environmental impact, but also which technology can be deployed the fastest and be the most cost-efficient.

A further key component of the BiSC is the Geomimetic® process [91], as these units are effectively recycling facilities for the recycling of reclaimed concrete and the reutilisation of CO_2, filters, dust, sludge, and slack from (steel) production. These units have the capacity to reduce post-combustion CO_2 emission to effectively zero and should be on site of any (steel) production plant. The workings of the Geomimetic® process are in its essence carbon utilisation and sequestration processes at the same time, as these recycle CO_2 from flue gases and recycled concrete into synthetic limestone and aggregate in cement production, with the potential of absorbing 100% of the CO_2 emissions produced. This is a technique suitable to be applied in any industrial production setting: energy, steel, concrete, chemical industry, glass industry, paper, and transport, to name a few.

4. The 7 Steps to Net-Zero Carbon Emission Steel Manufacturing

The newly introduced concept "Bio Steel Cycle" (BiSC) [10] provided the elements with which net-zero carbon emissions steel production can be made a reality, in the short-term. The following key components within the Bio Steel Cycle are based on a circular production process and are functioning in an interactive manner. The basis for this system is the BF/BOF route and involves the aforementioned CAT, CCS, and CCUS, and process improvements where possible. Innovative technologies such as Hisarna and GrInHy and hydrogen direct reduction (HDR) have CO_2 saving potential in their own right. Removing coal as primary energy source or using hydrogen direct reduction, an immediate 30% CO_2 emissions reduction is possible [31,35,64,76,77,78], and therefore, replacing coal with biomass or hydrogen would reduce the CO_2 emissions from steelmaking potentially by the same percentage. According to Siemens (2022) [79], a 50% carbon emissions reduction is immediately possible via utilisation of green hydrogen direct reduction. The standard steel production (SSP) process in combination with the currently operational newly developed technologies can also achieve a reduction of more than 50% with successive implementation to less than 3 metric tonnes per ton of steel produced. By incorporating the BiSC components of CAT, CCS, and CCUS into existing steel production sites, an almost 100% CO_2 emission reduction can be achieved, immediately.

The post-combustion capture of CO_2 (CCS) and other GHGs and the exploration of carbon scrubbing of flue gases were explored. Several possible technologies and processes to be considered for post-combustion carbon capture were considered [25,26,42,43,59,80], such as mechanical capture, compression and dehydration, membrane installation, off-gas flow through physical solvents/solid sorbents (such as Zeolite13X) troughs and chemical solvents and utilising metal-/organic frameworks.

Renewable energy technologies as one of the key components within the Bio Steel Cycle, can reduce CO_2 emissions in steelmaking by more than 30% [81] if commercial entities in iron and steel production [25,26,82] were to simply switch their energy providers [59] to those who are deriving their energy based on 100% renewable energy technology. Retrofitting existing plants to produce their own energy (wind, solar, PV) is the next logical step. The same applies to greenhouses, as there is a vast amount of roof space available, which has to date not been utilised. The static requirements would obviously have to be considered, but as the cost of solar energy and solar PV has decreased significantly over recent years [92] to less than GBP3/m^2, it can be considered an unmissable opportunity. **Figure 4** demonstrates the steps, built on the components within the BiSC, that should be taken with the aim to achieve net-zero carbon emission steel production.

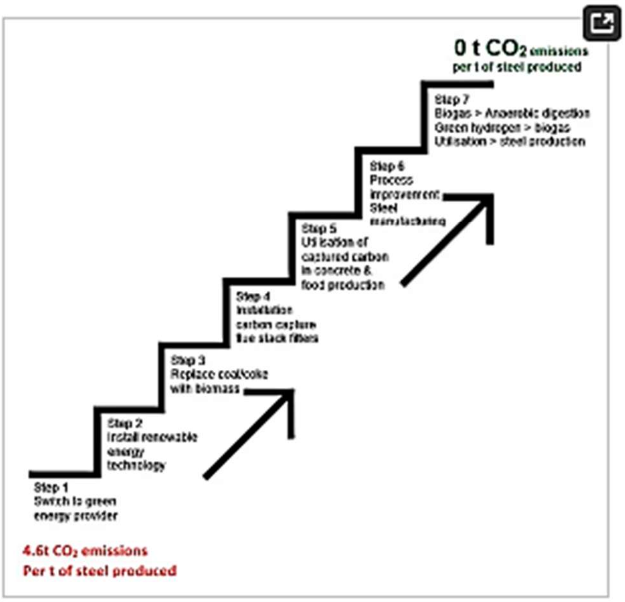

Figure 4. The seven steps to achieving net-zero carbon emissions steel production.

Steps 1–7 were introduced based on the level of ease of implementation and from short-term to long-term project duration, starting with Step 1 by switching energy providers and arriving at Step 7 with producing biogas as a result of full implementation of all elements of the Bio Steel Cycle (BiSC), splitting green hydrogen from this biogas and using thus gained hydrogen in steel manufacturing for hydrogen direct reduction (HDR).

There are a range of energy providers, which claim to produce energy exclusively based on renewable energy technologies. The image in **Figure 5** demonstrates the flow of the seven steps in some detail:

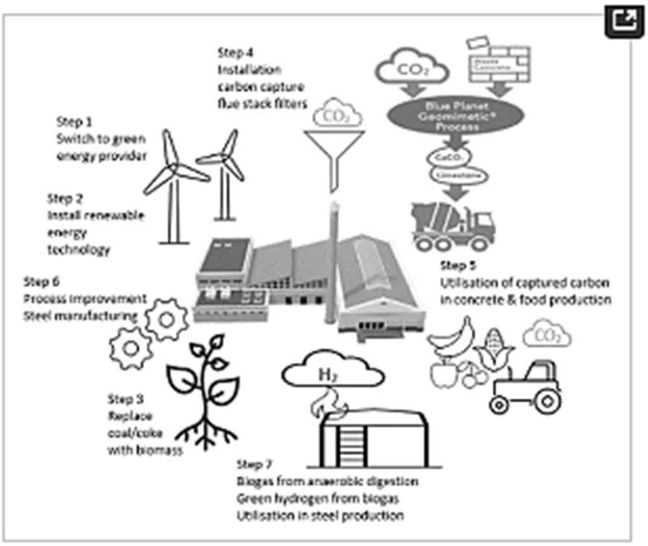

Figure 5. The seven steps to net-zero steel production.

Step 1: Switching to a green energy provider is probably the easiest to achieve. Any steel producer will just have to make an informed choice to switch its energy contract to an energy provider that produces energy solely relying on renewable energy technologies, and not—as it has been up to now—the companies that agree to the best deal, regardless of the consequences for the environment.

Step 2: Installing renewable energy technology. This requires surveying of existing steel plants, regarding static performance of buildings, ground parameters, and structures in situ. Selection of the most suitable product from a range of technologies and producers is the most time-consuming step after surveying the locations.

Toktarova et al. (2020) [35] identified a 30% CO_2 emissions savings potential by replacing fossil-fuel-derived electricity with renewable-energy-derived. Most industrial structures well-maintained under British Standards are suitable to accommodate the installation of the mature technology solar energy panels, either as solar thermal (hot water production) or photovoltaic panels (PV) (electricity). There is such a very wide range of solar and PV systems available that it would be beyond the scope of this paper to list these in their entirety. It may suffice at this point to mention that there are suitable systems available for every type of setting, from on-roof, over to in-roof and wall-covering solar panels and even foils, which can be retrofitted to provide a reliable source of energy all year round. Even windows may consist of solar panels, as the newest known development are semi-transparent solar cells. Researchers at the University of Michigan have developed a technique to manufacture highly efficient, semi-transparent solar cells at scale, which use micron-scale electrical connections between individual cells that constitute the solar modules [93].

Wind energy pylons are—besides solar—another effective way to produce electricity from a natural source (wind). This technology is mature and widely used, Again, there is a wide range of products on the market, and the site parameters will determine which system would be suitable for the location in question.

At sites where solar or wind energy systems are unsuitable, open- and closed-loop hydro energy systems might have their place to provide energy for industrial processes. In the United States, this technology is widely used, where creating closed-loop systems using pairs of existing or artificial lakes or reservoirs instead of rivers would avoid the need for new dams. There are currently projects underway, where in Bell County, Kentucky, for example, an old coal strip mine is being re-used [94]. As Wales in the UK has a vast array of those locations, it should be practical to install these. **Figure 6** provides some details (not to scale) for the principles of this technology:

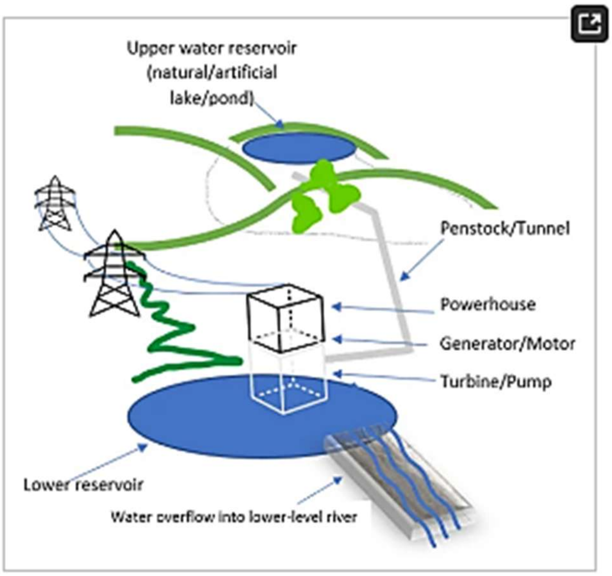

Figure 6. Pumped-storage hydropower, open loop.

Step 3: Replacing coal and coke with biomass. Coal and energy derived from combustion of fossil fuels is the biggest emitter of CO_2 emissions [2] and replacing coal with biomass in steel production would quite easily achieve a 30% reduction in carbon emissions, which is the reason why renewable energy technologies and replacing coal and coke with biomass are cornerstones in the Bio Steel Cycle. Replacing pre-combustion fossil fuels with biomass [6,7,8,9,35,59,67,95] and operating (green) hydrogen direct reduction (HDR) as well as capturing post-combustion CO_2 emissions with the Geomimetic® process [91] are efforts which have the potential to reduce the CO_2 emissions in steel production to almost "0". There is considerable outreach into other industries, such as the application of the Geomimetic® [91] process, which produces aggregates from CO_2 emissions and recycled concrete to producing new concrete and utilisation of BOF slacks for road building.

Step 4: Installation of carbon-capture flue-stack filters (CCUS). These technologies are wide ranging, and every production site has its own parameters and challenges to overcome. Thorough surveying of the sites and greenhouse gas emission (GHG) points need to be identified, and depending on the situation, a suitable GHG capturing system can be installed. There are companies such as Yurcent® [146], which provide Xeolite rotors (disc-like wheels that are working on the absorption/desorption principle). These types of filters consist of aluminosilicate crystals with average pores measuring 9 angstrom (0.9 nm) and can be adapted to fit almost any industrial flu stack or off-gas outlet and are part of the CEPS (carbon enrichment for plant stimulation) system [25,26,42,43,59,80,146].

Step 5: Utilisation of captured carbon in concrete and food production. Blue Planet [91] is using the so-called "Geomimetic® process", in which recycled concrete and captured carbon are being re-formed to make new concrete and aggregate. In combination with manufacturing post-combustion flue-stack carbon capture, the utilisation of the hereby captured carbon is subsequently utilised in making new concrete (carbon sequestration). This process has the capability to reduce the carbon emissions from steel production by almost 100%.

Step 6: Process improvement in steel manufacturing. Greater material and energy efficiency, and deployment of low-carbon process routes are all critical. The steel production process has been thoroughly investigated in every aspect from mining to recycling, and it can be said that there is currently a global effort underway for developing more environmentally friendly and resource-saving technologies in steel production, such as TGRBF (top gas recycling blast furnace operation, coal mine methane recovery [25,26,35,60,64,65,66,69,70,72,96] and HISARNA [20,69,70,78,89,90,95,97], which eliminates the need for the sintering process entirely. HISARNA, implemented individually, has the potential to reduce CO_2 emissions from steel production by at least 30%.

Step 7: Biogas from anaerobic digestion—Green hydrogen from biogas—Utilisation in steel production. Trees are natural carbon sinks [83,84,85] and ideally, woodlands would be planted around steel production plants to absorb the remaining CO_2 emissions via direct air capture (DAC)—while simultaneously, the trees would provide some of the material for producing biochar and organic matter to be fed into the anaerobic digester, alongside agricultural businesses.

Planting a sufficient number of trees [6,7,8,9,83,84,85] and both anaerobic digester and biochar plants [6,7,8,9] are vital components within the Bio Steel Cycle and instrumental to meet the UK government's zero emissions target. They should be considered in the planning for the updating of existing steel production plants and for any new steel plant development or refurbishment. As the UK tree cover stands at 13.2% (3.2 million ha, 66.65 m people = 0.048

ha per capita) [83,84], it is fair to say that this is the lowest percentage in the Northern hemisphere. EU forests and wooded land cover over 182 million hectares (42%) of the EU's total land area [83,84].

Biochar [98] can easily be used as a direct replacement for coke or coal. Biogas and biomass also are an alternative to commercial gases and fossil fuels [6,7,8,9,35,62,81], as their properties allow for 1:1 replacement. Using biochar instead of coke in (steel) production could reduce the CO_2 emissions by 30%.

Additionally, "green" hydrogen extraction from biogas, naturally produced by anaerobic digestion, offers additional carbon avoidance opportunities. Hydrogen direct reduction (HDR) has been piloted over recent years and has been shown to have great CO_2 avoidance potential. (Green hydrogen technologies are currently developed by a number of significant industry leaders, such as Mannesmann Salzgitter [75], in cooperation with the European Commission and others [6,7,8,9]). Green hydrogen implies hydrogen production using energy from renewable resources only, which is where the Bio Steel Cycle comes to full circle: Biomass from trees used for DAC is converted to biogas in the anaerobic digester, which produces biogas. The hydrogen is then extracted from the biogas, using renewable energy technologies exclusively.

5. Results and Discussion

The results of this study are the identified levels of CO_2 emissions during the BF/BOF route in steelmaking, as per **Table 1**:

Table 1. CO_2 emissions BF/BOF route.

The sum total of identified levels of CO_2 emissions at ~4.61/CO_2/t steel is the result of thorough investigation of research into every process step along the linear steelmaking BF/BOF route, to date.

The individual seven steps towards "0" carbon steel production have a different effect, based on the way they are being implemented, either individually or in sequence (successive), as displayed in **Table 2** and **Figure 7**:

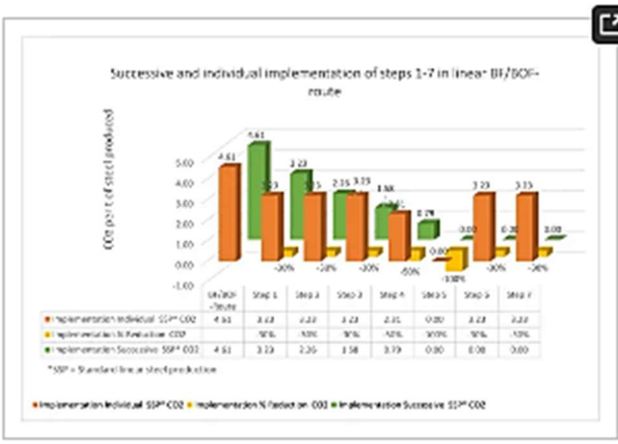

Figure 7. Individual and successive implementation of Steps 1–7.

Table 2. Individual/successive implementation of the seven steps to 0-carbon steel.

Notably, during the sequential implementation of the seven steps to "0" carbon steel production—already with step 5–100% carbon reduction has been achieved.

This would logically render Steps 6 and 7 obsolete, with successive implementation, but the technical application of flue-stack scrubbing technology, processes or material is quite challenging, and the efficiency is dependent on site factors and the quality of the installation, as well as the execution.

The industrialisation processes have for more than 200 years caused significant damage to the natural environment. Although the current UK government seems to have abandoned their commitments to reducing carbon emissions in the UK and are instead issuing licences for natural gas exploration (Shell/Jackdaw) [99] and new coal mines (Cumbria) [100], industry seems to have understood the severity of the climate crisis we find ourselves in. In 2018, Tata Steel announced a partnership with chemicals company Nourvon with the aim of producing hydrogen and oxygen at Tata Steel Europe B.V.'s Ijmuiden plant in the Netherlands. Using water electrolysis, this effort is part of the company's drive to be a carbon-neutral steel manufacturer by 2050. As they are using electricity generated by using renewable energy technologies, the plant is set to save up to 350,000 t/p.a. of CO_2. The aim is to use the hydrogen as a reductant in the direct reduced iron steelmaking process [70]. Tata Steel have requested financial support to the tune of GBP1.5bn to fund its transition to greener production from the UK government for investing in sustainable technologies at their Port Talbot (Wales/UK) plant, which employs more than 4000 people at present [72]. With the 2020 UK Government "UK Green Industrial Revolution" paper still fresh in everyone's mind [101], this might possibly come to pass.

Industry leaders have already recognised that the current linear steel production process is detrimental for our environment [145], and they have taken already considerable action by investing in R&D into production process improvement and infrastructure improvement towards sustainable and carbon-neutral steel production. The governments in the respective countries might be inclined within their "green" agendas to award green loans at favourable terms to enable businesses to reach their sustainability goals sooner rather than later. Legal frameworks require adaptation to accommodate an attractive solution for businesses—in the form of tax incentives and subsidies, possibly re-directed from nuclear and fossil fuel subsidies—and to apportion a set percentage of gross profits to drastically change their business models to sustainable, circular production processes. Despite global pressure, making steel—even in the UK—is still a very attractive business and it can be done sustainably.

Previous aforementioned studies have focused on the assessment of policy needs, skills needs, supply-chain pressures on a regional and global scale, and the requirement for models, strategies, and guidance papers, and investigated the technical solutions for the decarbonisation of the iron and steel industry. This paper is the first of its kind to (a) assess sustainability guidelines, (b) assess technical progress and viability of technical and process solutions for CAT and CCUS, (c) identify the factual CO_2 emissions of the BF/BOF route of steelmaking, and (d) offer a multi-disciplinary model and strategy to achieve factual "0" carbon emissions steel manufacturing in one research report.

The individual or successive implementation of the detailed BiSC components, accompanied by steel production process improvements and following the "7 steps to net-zero carbon emissions steel production" strategy is quite possibly the mechanism which is set to achieve between 50% and 100% CO_2 emissions reduction, immediately.

The authors' work on the decarbonisation of the steel industry and further investigation of the CO_2 emissions along the whole steelmaking process, starting with coal and iron ore extraction, are currently under way.

6. Conclusions

The 7 steps to net-zero carbon emissions steel production and the Bio Steel Cycle components are providing a feasible strategy to reach net-zero carbon emissions steel production in the short- to medium-term. Even if only sections of the BiSC or 7-steps strategy are being implemented, at least 30% carbon emission reduction can be achieved in the short-term. The BiSC seven steps to take for reaching net-zero carbon emission steel production seem to be technically possible and practically implementable in the short-term. The global anthropogenic ~65.6 Gt CO_2-equivalent emissions in 2019, reported by the 64 steel-producing countries and documented 1.9 Gt of steel produced between January and December 2021, are set to be resulting in 8.8 Gt CO_2-equivalent of CO_2 emissions. This volume as the product of the current linear steel manufacturing process leads to the conclusion that the iron and steel industry's emissions might have possibly in the past been heavily underestimated and underreported. One example is the issue that there are contradictory publications that do not seem to agree with the percentage of global share in CO_2 emissions, as they range from at least 7% to 11%. Suitable literature has been identified, but the level and range of discrepancy just demonstrates and emphasises the point of uncertainty, and possible underreporting of emissions in the iron and steel industry.

Industry leaders have already recognised that the current linear steel production process is detrimental for our environment, and they have taken considerable action by investing in R&D into production process improvement and infrastructure improvement towards sustainable and carbon-neutral steel production. The governments in the respective countries might be inclined within their "green" agendas to award green loans at favourable terms to enable businesses to reach their sustainability goals sooner rather than later. Legal frameworks require adaptation to accommodate an attractive solution for businesses—in the form of tax incentives and subsidies, possibly re-directed from nuclear and fossil fuel subsidies—and to apportion a set percentage of gross profits to drastically change their business models to sustainable, circular production processes.

Despite global pressure, making steel—even in the UK—is still a very attractive business and it can be done sustainably. This research has proposed a sustainable solution to avoid and remove carbon emissions from the iron and steel industry by implementing the Bio Steel Cycle in seven steps to achieve net-zero steelmaking, at the latest by 2050. A road map needs to be prepared to show the correct direction and required actions for government, policy makers, and steel manufacturers.

Author Contributions

Conceptualization, S.K.; methodology, S.K., H.G.D. and A.-H.S.; software, S.K.; validation, H.G.D. and A.-H.S.; formal analysis, S.K.; investigation, S.K.; resources, S.K., H.G.D. and A.-H.S.; data curation, S.K.; writing—original draft preparation, S.K.; writing—review and editing, H.G.D. and A.-H.S.; visualization, S.K.; supervision, H.G.D. and A.-H.S.; project administration, A.-H.S.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) Staffordshire University (date of approval: 28 January 2022).

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix 6 Green Steel Tracker (Leadit, 2023)

2	1. Steel decarbonisation projects							
3	**About**	Title of the project i	Official project website	ID number of proje	stated company climat	Stated company climate target for 2050		
4	Company	Project name (if applicable)	Project website	GEM Project ID	2030 climate target	2050 climate target	Climate target [ref]	Country (in which
5	Salzgitter	GrInHy2.0 (Green In	https://www.green-indu	SDE00004	50% reduction (baselin	95% reduction by 2050 (ba	https://salcos.salzg	Germany
6	ArcelorMittal	SIDERWIN	https://www.siderwin-sp	TBD	35% reduction in Europ	carbon neutrality	https://corporate-m	France
7	POSCO	TBD	N/A	TBD	20% reduction (baselin	carbon neutrality	https://newsroom.p	South Korea
8	SSAB	FFS - Towards Fos	N/A	TBD	26% reduction (baselin	N/A (fossil-free by 2045)	https://www.ssab.co	Finland
9	Baowu	N/A	N/A	N/A	Not stated	carbon neutrality	https://www.reuters.	China
10	HBIS	N/A	N/A	N/A	30% reduction (baselin	carbon neutrality	https://www.worldst	China
11	JFE	N/A	N/A	N/A	20% reduction (baselin	carbon neutral soon after	https://www.jfe-hold	Japan
12	Salzgitter	μDRAL	https://salcos.salzgitte	SDE00004	50% reduction (baselin	95% reduction by 2050 (ba	https://salcos.salzg	Germany
13	Voestalpine	H2Future	https://www.h2future-pr	SAT00001	30% reduction (baselin	carbon neutrality	https://www.voestal	Austria
14	ArcelorMittal	3D	https://3d-ccus.com/	SFR00001	35% reduction in Europ	carbon neutrality	https://corporate-m	France
15	Baowu	N/A	N/A	N/A	Not stated	carbon neutrality	https://www.reuters.	China
16	ArcelorMittal	N/A	N/A	TBD	35% reduction in Europ	carbon neutrality	https://corporate-m	Spain
17	Salzgitter	WindH2	https://www.windh2.de/	SDE00004	50% reduction (baselin	95% reduction by 2050 (ba	https://salcos.salzg	Germany
18	Boston Metal	Series B (newest fu	https://www.bostonmet	TBD	N/A	N/A	https://www.boston	USA
19	ArcelorMittal	Hamburg H2	https://future.hamburg/	SDE00007	35% reduction in Europ	carbon neutrality	https://corporate-m	Germany
20	Tata Steel	HIsarna	https://www.tatasteeleu	SNL00001	30% reduction (baselin	carbon neutrality	https://www.tataste	Netherlands
21	British Steel	Zero Carbon Humb	https://www.equinor.co	SGB00002	Not stated	carbon neutrality	https://britishsteel.c	United Kingdom
22	SSAB	HYBRIT	https://www.hybritdevel	SSE00002	26% reduction (baselin	N/A (fossil-free by 2045)	https://www.ssab.co	Sweden
23	Algoma Steel	N/A	N/A	TBD	Not stated	carbon neutrality	https://www.sootod	Canada
24	Metalloinvest	N/A	N/A	N/A	Not stated	carbon neutrality	https://www.metallo	Russia
25	Thyssenkrupp	HydrOxy Hub Walsu	https://www.steag.com	SDE00001	30% reduction (baselin	climate neutral	https://www.thyssen	Germany
26	Liberty Steel	Whyalla Transform	https://www.gfgalliance	SAU00002	carbon neutrality	N/A (see 2030 target)	https://libertysteelg	Australia
27	SSAB	HYBRIT	https://www.hybritdevel	TBD	26% reduction (baselin	N/A (fossil-free by 2045)	https://www.ssab.co	Sweden
28	ArcelorMittal	N/A	N/A	TBD	35% reduction in Europ	carbon neutrality	https://corporate-m	Spain
29	ArcelorMittal	N/A	N/A	TBD	35% reduction in Europ	carbon neutrality	https://corporate-m	Belgium
30	ArcelorMittal	N/A	N/A	TBD	25% reduction (baselin	carbon neutrality	https://corporate-m	Canada
31	H2 Green Steel	H2 Green Steel (H2	https://www.h2greenste	TBD	N/A	N/A	https://www.h2greer	Sweden
32	POSCO	TBD	TBD	TBD	20% reduction (baselin	carbon neutrality	https://newsroom.p	South Korea
33	LKAB	TBD	TBD	TBD	Not stated	N/A (carbon neutrality by	https://www.lkab.co	Sweden
34	Stahl Holding Saar GmbH	TBD	TBD	TBD	Not stated	80-95% reduction by 2050	https://www.saarsta	Canada
35	Salzgitter	N/A	N/A	TBD	50% reduction (baselin	95% reduction by 2050 (ba	https://salcos.salzg	Germany
36	Nippon Steel	N/A	N/A	N/A	30% reduction (baselin	carbon neutrality	https://www.nippons	Japan
37	Bluescope	N/A	N/A	TBD	30% reduction (baselin	carbon neutrality	https://www.bluesco	Australia
38	Fortescue Metals	N/A	N/A	TBD	carbon neutrality	N/A (see 2030 target)	https://www.fmgl.co	Australia
39	POSCO	N/A	N/A	N/A	20% reduction (baselin	carbon neutrality	https://newsroom.p	Australia
40	Voestalpine	TBD	TBD	SAT00002	30% reduction (baselin	carbon neutrality	https://www.voestal	Austria
41	Voestalpine	SuSteel	https://www.k1-met.con	SAT00002	30% reduction (baselin	carbon neutrality	https://www.voestal	Austria
42	Aço Verde do Brasil (AVB)	N/A	https://avb.com.br/	TBD	N/A	N/A	https://avb.com.br/	Brazil
43	Compañía Siderúrgica Huachipato SA	N/A	https://www.capacero.c	SCL00001	Not stated	Not stated	https://www.capace	Chile
44	HBIS	Paradigm project	N/A	TBD	30% reduction (baselin	carbon neutrality	https://www.worldst	China
45	SSAB	HYBRIT	https://www.hybritdevel	TBD	26% reduction (baselin	N/A (fossil-free by 2045)	https://www.ssab.co	Finland
46	ArcelorMittal	N/A		SFR00001	35% reduction in Europ	carbon neutrality	https://corporate-m	France
47	Liberty Steel	TBD	TBD	N/A	carbon neutrality	N/A (see 2030 target)	https://libertysteelg	France
48	ArcelorMittal	HyBit - Hydrogen fo	N/A	SDE00006	35% reduction in Europ	carbon neutrality	https://corporate-m	Germany
49	ArcelorMittal	N/A	https://germany.arcelor	SDE00005	35% reduction in Europ	carbon neutrality	https://corporate-m	Germany
50	ArcelorMittal	N/A	https://germany.arcelor	SDE00006	35% reduction in Europ	carbon neutrality	https://corporate-m	Germany
51	Thyssenkrupp	H2morrow	https://oge.net/en/us/p	N/A	30% reduction (baselin	climate neutral	https://www.thyssen	Germany
52	Thyssenkrupp	Blast Furnace 2.0	N/A	SDE00001	30% reduction (baselin	climate neutral	https://www.thyssen	Germany
53	Tenaris	Dalmine Zero Emis	N/A	TBD	N/A	N/A	https://www.tenaris.	Italy
54	ArcelorMittal	SeaH2Land	https://seah2land.nl/en	SBE00001	35% reduction in Europ	carbon neutrality	https://corporate-m	Netherlands
55	Tata Steel	N/A	N/A	TBD	30% reduction (baselin	carbon neutrality	https://www.tataste	Netherlands
56	Tata Steel	Project H2ermes	https://www.portofams	SNL00001	30% reduction (baselin	carbon neutrality	https://www.tataste	Netherlands
57	Liberty Steel	TBD	TBD	SRO00001	carbon neutrality	N/A (see 2030 target)	https://libertysteelg	Romania
58	POSCO	TBD	TBD	TBD	20% reduction (baselin	carbon neutrality	https://newsroom.p	South Korea
59	POSCO	TBD	N/A	TBD	20% reduction (baselin	carbon neutrality	https://newsroom.p	South Korea
60	Enagas	Green Crane (forme	https://www.h2v.eu/hyd	SES00001	N/A	N/A	https://www.h2v.eu/	Spain
61	FerroSilva	FerroSilva	https://www.ferrosilva.c	N/A	N/A	N/A	https://www.ferrosil	Sweden
62	SSAB	HYBRIT	https://www.hybritdevel	SSE00001	26% reduction (baselin	N/A (fossil-free by 2045)	https://www.ssab.co	Sweden
63	US Steel	N/A	N/A	TBD	20% reduction (baselin	carbon neutrality	https://www.ussteel	USA

Appendix 7 Energy, exergy and entropy

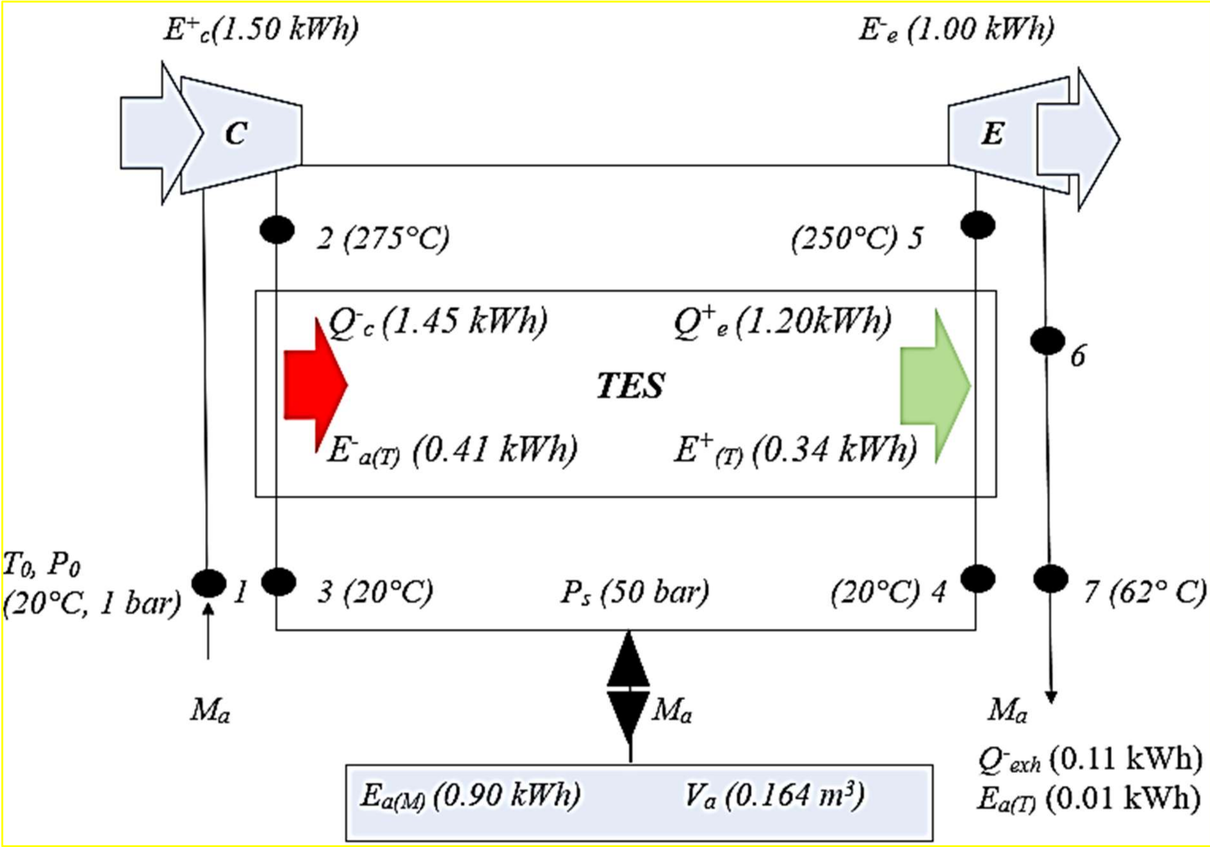
Siefert, Narburgh and Chen (2016) provided an equation to demonstrate the first law of thermodynamics, as displayed in Equation 7-1:

Equation A7-1

Equation (1): First Law of Thermodynamics for a steady-state control volume solving for thermal energy transfer to the environment.

$$\dot{Q}_{env} = \sum_{i=inlet} \dot{n}_i \hat{h}_i - \sum_{o=outlet} \dot{n}_o \hat{h}_o - \dot{W} - \sum \dot{Q}_j$$

Furthermore, already in 2007, Demirel describes exergy with – what he classed as - a unifying concept of various forms of energy. Within, heat, mechanical processes, chemical energy and the maximum amount of work theoretically available were thought to bring a resource into equilibrium with its environment through a reversible process – entropy. In Figure 7-1, the function of entropy is explained in detail:



Entropy function abbreviations explained:
E = Energy (in kWh) + = input - = output E_a = remainder
V = Volume (in m^3) a = remainder
C = Constant
T = Temperature
S = Entropy
P = Pressure
Q = Quantity - = input + = output

Figure A7-1: : Entropy, function (Adapted from Demirel, 2007)

Thus, exergy constitutes a function, consisting of the physical resource properties and its surrounding environment. In practical terms, it means that exergy *loss* means exergy *transfer*. The work loss in a continuous process is the difference in the exergy before and after the process. Available energy, A = H − T0S, or exergy is a measure of the departure from the ambient or dead state.

During the practical trials to establish the feasibility and viability of carbon capture and storage processes for steel components (Moran and Sciubba, 1994; Siefert, Narburgh and Chen, 2016), exergy analysis was considered a useful tool to establish the efficiency of implemented measures. Particularly, as the environmental and monetary benefits require to be shown to grow proportionately with input, in order to result in a) behaviour change in the steel component manufacturing companies involved and b) demonstrate the potential for remanufacturing processes and carbon capture and storage to be a transferrable process with applications in a vast variety of metal working industries.

For steel production, this is an additional element to consider – meaning: researching energy *consumption*. This entails establishing if exergy loss can be minimised or harvested, or if the energy required for the steel production process can be reduced (Johansson and Söderström, 2011; Waugh *et al.*, 2013; Tata Steel Europe, 2020, 2023, 2024; Schmitz *et al.*, 2021; USEPA, 2023), as a proportion can be harvested from the production processes within. Therefore, this core principle is one of the elements of the Bio-Steel cycle, where heat emitted during the production process is being harvested and used elsewhere. However, there were some attempts with helpful outcomes, showing the different levels of exergy analysis and results. The approach to establishing a framework applicable to all industries, and the energy input for the various industrial sectors had been established and utilised as the starting point. As displayed in Figure A7-2:

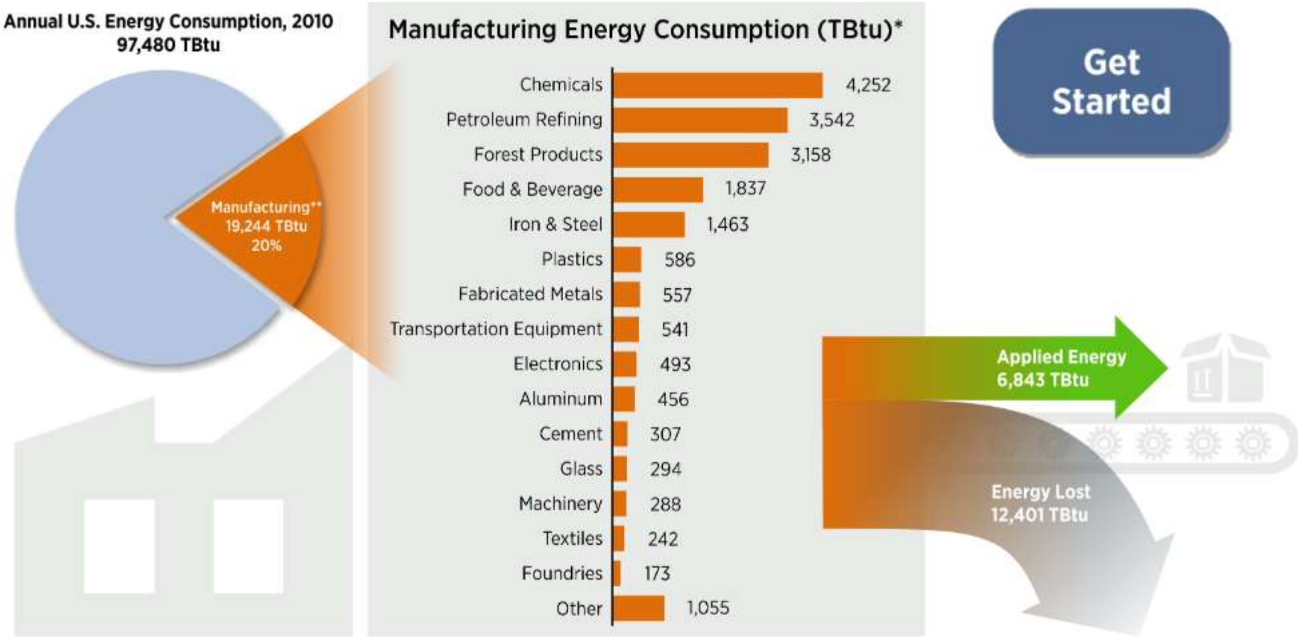


Figure A7-2: : Manufacturing Energy Flows (EERE, 2010)

The (US) Office of Energy efficiency and renewable energy (EERE, 2010) created a dynamic Sankey diagram to demonstrate manufacturing energy flows. Herein, the line widths indicate the volume of energy which flows to the main energy end users in manufacturing, with the line colours indicating fuel, steam, electricity and applied or lost energy. Users are able to modify the display to explore the flow of energy use at the macro scale or even compare the energy consumption across the chosen manufacturing subsectors. This methodology (EERE, 2010) provided us with the conclusion that, in the US, the best part of 20% of all US energy combined produced is being used to provide energy to the manufacturing sector. They established a new factor within exergy analysis, namely *efficiency loss.* They concluded, that of the energy volume being made available to the manufacturing sector, approximately 20% is being lost due to inefficiencies, both on-site and within the infrastructure, with some losses being unavoidable due to technological constraints. The manifold opportunities within exergy analysis to determine energy reclamation potential have been recognised very early, and simultaneously, the opportunity to determine CO_2 emissions from energy expenditure. In 2018, EERE published a detailed overview of the energy expenditure and CO_2 emissions (EERE, 2018), based on the most recent overall manufacturing energy and carbon footprints, using the U.S. Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS) data and contemporary estimations. Within the manufacturing energy and carbon footprints map, the assumed flow of energy as supply stream, demand curve, and losses within the production processes were mapped. Additionally, greenhouse gas emissions (GHG) were estimated, based on energy derived from fossil fuel combustion. The flows demonstrate how energy is used and where it is most likely lost in manufacturing, alongside the estimated simultaneously produced GHG emissions from combustion processes. Each footprint details the flow of energy, described as either fuel, electricity, or steam, to the main factor components in manufacturing. This includes boilers, combined heat and power generation, process heaters, process coolers, machine-driven equipment, facility air conditioning. The estimated GHG emissions associated with energy generation, based on fossil fuel combustion, were also mapped. It needs to be said that a great proportion of these figures are estimated, as there are no binding policies or legal requirements for businesses in the US of any description to report their GHG emissions, and thus there are no devices in place to record, mitigate or decarbonise production of the factual GHG emissions from industry. However, sensible estimates have been incorporated in Figure A7-3, to visualise an educated estimate of the current situation in the US:

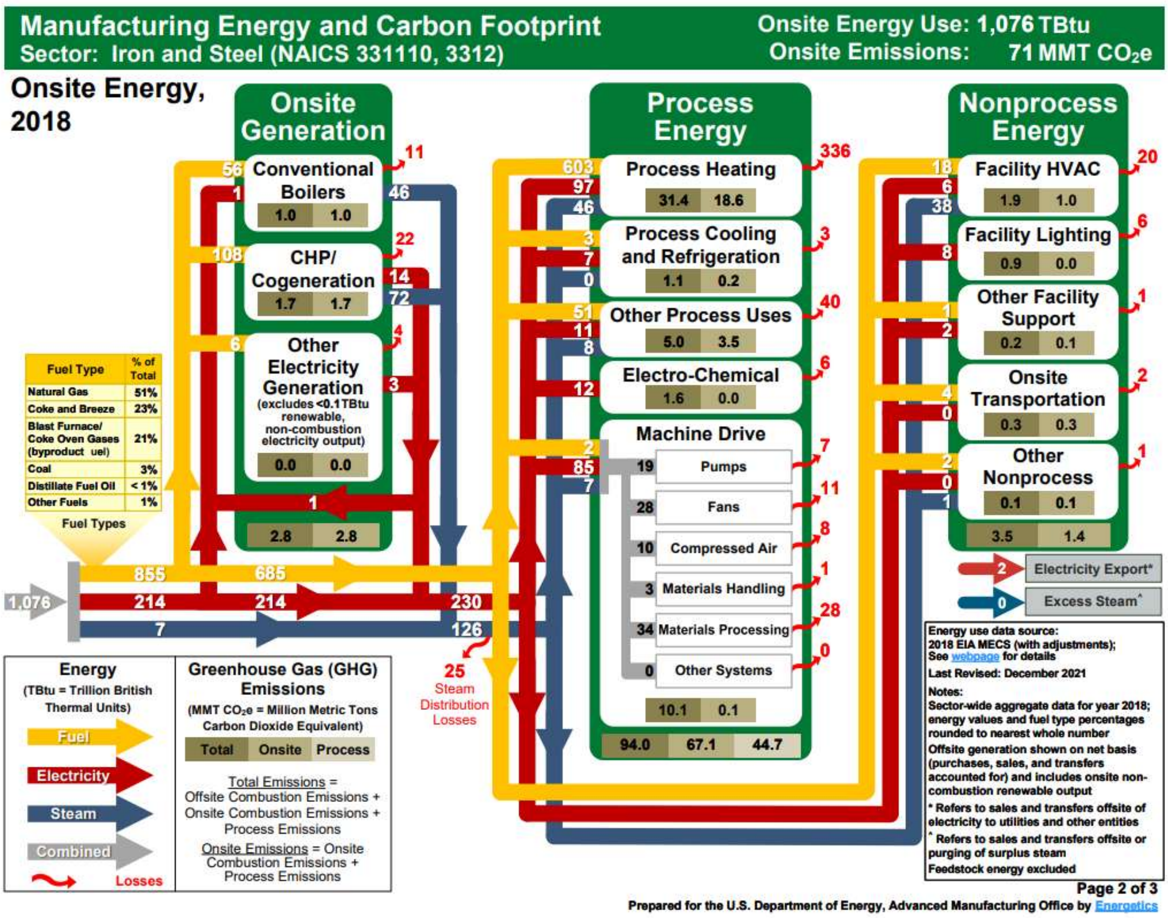


Figure A7-3: US Manufacturing Energy Consumption Survey (MECS) 2018 data

Based on Demirel's (2007), Moran and Sciubba's (1994), EERE's (2010, 2018), and Brockett's (2017) work, it can be extrapolated that:

- 70% of all energy input is productively applied during manufacturing processes and
- 30% of all energy input is lost to infrastructural and procedural inefficiencies.

The individual industrial processes need to be investigated for their harvestable energy and heat losses, to be re-invested in the circular production process, and possibly even for external uses. There are plenty of opportunities for avoiding and decarbonising manufacturing, by harvesting energy, capturing and reutilising heat and off-gases within the steel manufacturing industry, from mining through to finish machining, which is explained in some detail in Chapter 4: The Bio Steel Cycle.