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The Bio Steel Cycle: 7 Steps to Net-Zero CO_2 Emissions Steel Production

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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

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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 [1–10] 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 [11–16]. The anthropogenic carbon emissions are at an all-time-high with reported ~65.6 Gt CO_2-equivalent in 2019 [11–16]. The 64 steel producing countries reported 1.9 Gt of steel produced between January and December 2021 [17–21], 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 [1–10,56], 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 [1–10,17–21,23–55], and related databases and corresponding literature [56–145] 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 depending on duration.

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) $CO_2E_{total} = \sum(\text{emissions per ton of steel}) \times \Omega$ (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:

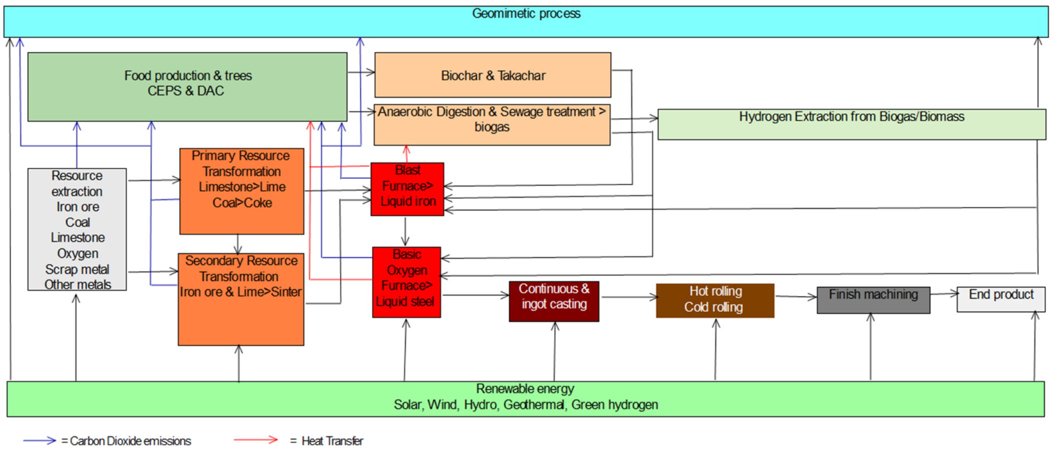

Figure 1. Simul8 steel linear production configuration. The colour-coding within Figure 1 is identical to the master database (Excel), which has been created to gather and display findings, facts, and figures, and is supposed to signify the energy intensity and heat development at the different stages 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 [3–5,13,35,56,59]. Steel production is in close third place, followed by cement production and the chemical and glass industries [3–5,13,35,56,59].

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:

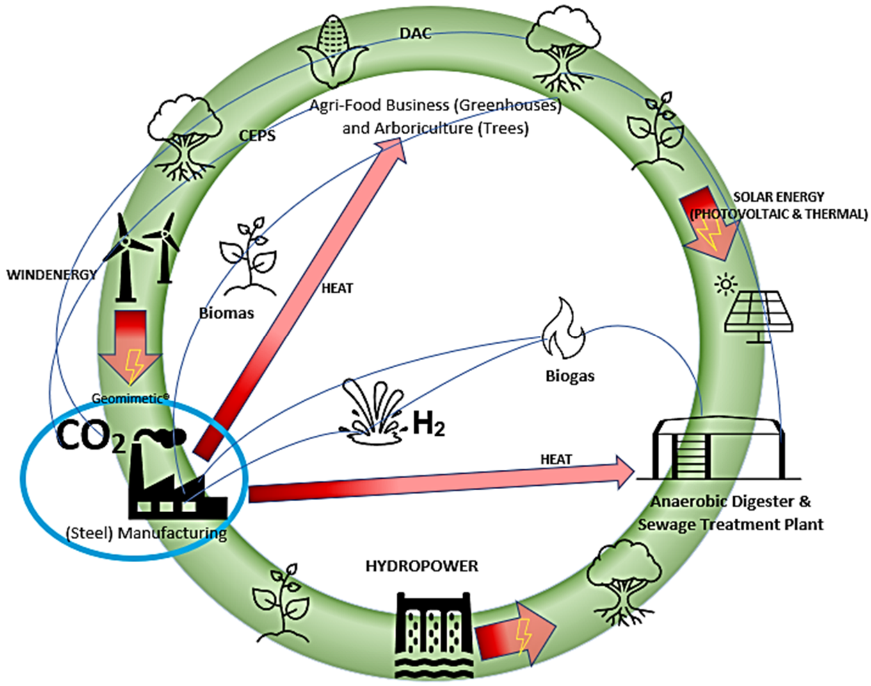

Figure 2. The Bio Steel Cycle concept and cyclical resource utilisation flow.

Analyses of the technical and economical long-term potential of novel steel production technologies CAT, CCS, and CCUS and in the UK [63–66], 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) [6–9,67], hydrogen direct reduction (H-DR) [6–9], and iron ore electrolysis (EW) [35,36], energy and raw material efficiency is significantly higher for H-DR and EW [6–9,67–70] 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 [31,35,64,76–78], 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:

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) [83–85], 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 [6–9,83–85]. 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.

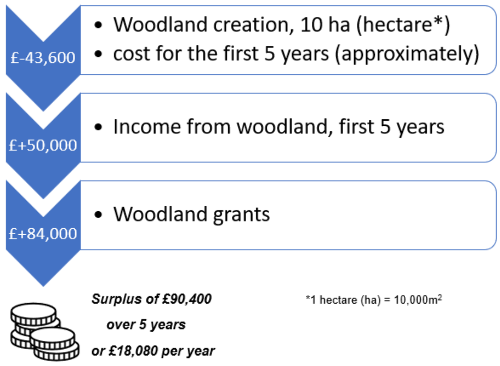

Figure 3. Woodland creation graph.

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 [6–9,75] (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 [31,35,64,76–78], 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.

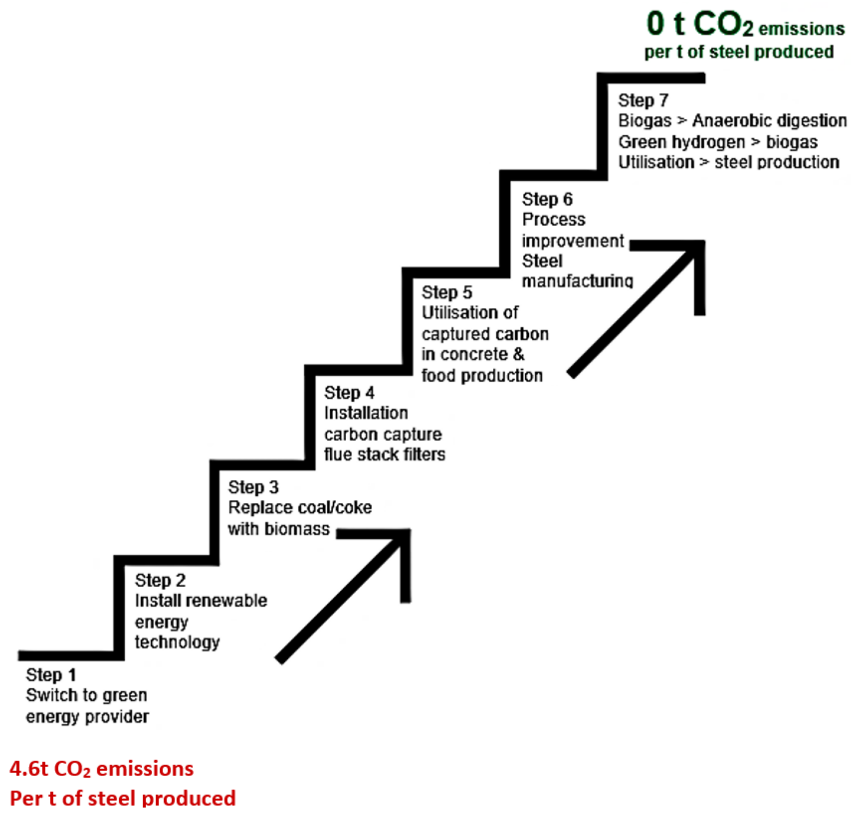

Figure 4. The seven steps to achieving net-zero carbon emissions steel production.

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:

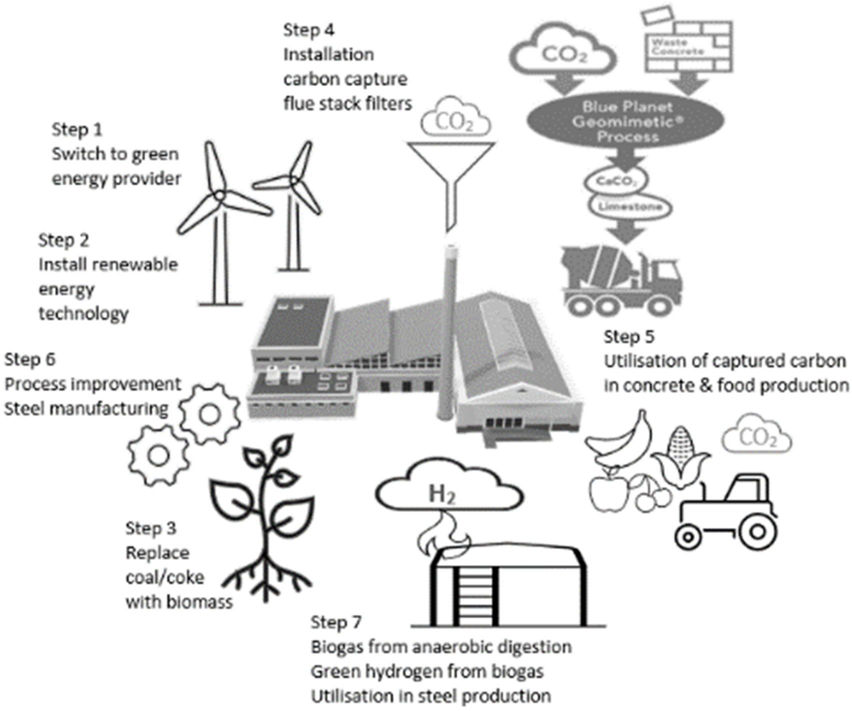

Figure 5. The seven steps to net-zero steel production.

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:

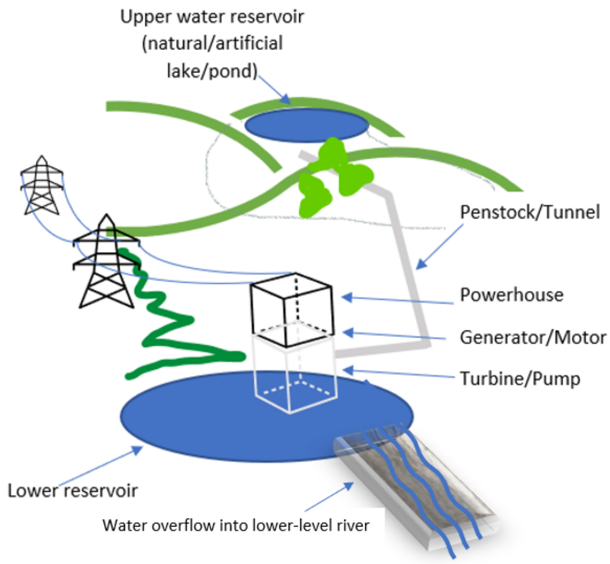

Figure 6. Pumped-storage hydropower, open loop.

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 [6–9,35,59,67,95] 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 [25,26,35,60,64–66,69,70,72,96] 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 [83–85] 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 [6–9,83–85] and both anaerobic digester and biochar plants [6–9] 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 [6–9,35,62,81], 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 [6–9]). 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.

Step in Production CO_2	SEC * CO_2		Author
	−t/t product		
Blast furnace	0.288	2.1	[31,42,43,112,125]
Basic oxygen f.	0.018	2.2	[31,32,43,55,76,125]
Total ∑	0.306	4.3	
Total ∑	4.606		Total t/CO_2/t steel produced

* SEC = Specific Energy Consumption.

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:

Table 2. 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.

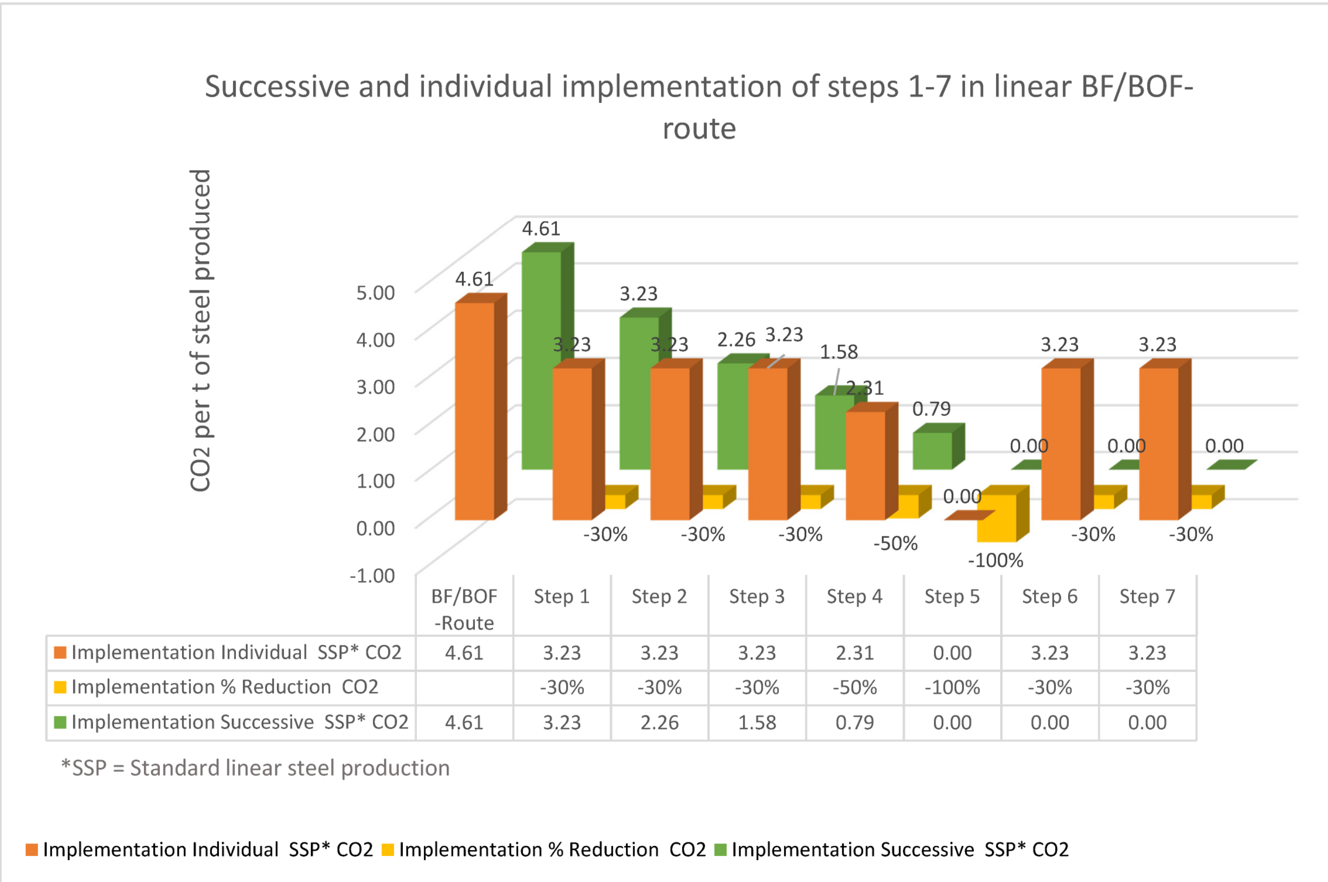

Figure 7. Individual and successive implementation of Steps 1–7.

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.

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References and Note

1. Swalec, C. Clear on Climate: The Iron and Steel Industry is Responsible for 11% of Global Carbon Dioxide (CO_2) Emissions and will need to Change Rapidly to Align with the World's Climate Goals. *Carbon Brief* **2021**. Available online: https://www.carbonbrief.org/guest-post-these-553-steel-plants-are-responsible-for-9-of-global-co2-emissions/ (accessed on 3 September 2022).
2. Ren, L.; Zhou, S.; Penga, T.; Ou, X. A review of CO_2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110846. [CrossRef]
3. IEA. Global Energy Demand Grew by 2.1% in 2017, and Carbon Emissions Rose for the First Time Since 2014. Available online: https://www.iea.org/news/global-energy-demand-grew-by-21-in-2017-and-carbon-emissions-rose-for-the-first-time-since-2014 (accessed on 12 December 2019).
4. IEA. Tracking Industry 2021. Available online: https://www.iea.org/reports/tracking-industry-2021 (accessed on 2 March 2022).
5. IEA. Global CO_2 Emissions Rebounded to Their Highest Level in History in 2021. Available online: https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021 (accessed on 3 March 2022).
6. COM (European Commission). BIONICO: A Pilot Plant for Turning Biomass Directly into Hydrogen—Horizon 2020: BIOgas Membrane Reformer for Decentralized Hydrogen Production. Available online: https://cordis.europa.eu/article/id/394984-bionico-a-pilot-plant-for-turning-biomass-directly-into-hydrogen (accessed on 19 August 2021).

7. COM (European Commission). ULCOS—Ultra-Low CO_2 Steel Making. Available online: https://cordis.europa.eu/article/id/29184-steel-industry-boost-research-into-cleaner-technologies (accessed on 7 August 2021).
8. COM (European Commission). How Horizon Europe Was Developed. Available online: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/how-horizon-europe-was-developed_en (accessed on 3 August 2022).
9. COM. EU Climate Targets: How to Decarbonise the Steel Industry. Available online: https://joint-research-centre.ec.europa.eu/jrc-news/eu-climate-targets-how-decarbonise-steel-industry-2022-06-15_en#_ftn1 (accessed on 10 October 2022).
10. Kiessling, S.; Darabkhani, H.G.; Soliman, A.H. Blueprint for zero carbon steel production by introducing the Bio Steel Cycle. *J. Prod. Manuf. Res.* 2022, *submitted*.
11. Eggelston, S.; Buendia, L.; Miwa KNgara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies (IGES) for the IPCC: Geneva, Switzerland, 2006.
12. IPCC (Intergovernmental Panel on Climate Change). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Workbook*; IPCC: Geneva, Switzerland, 1996. Available online: https://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch2wb1.pdf (accessed on 19 December 2020).
13. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2021—The Physical Science Basis Summary for Policymakers*; IPCC: Geneva, Switzerland, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf (accessed on 3 October 2021).
14. IPCC (Intergovernmental Panel on Climate Change). Climate Change 2022: Impacts, Adaptation and Vulnerability. Available online: https://www.ipcc.ch/report/ar6/wg2/ (accessed on 12 February 2022).
15. IPCC (Intergovernmental Panel on Climate Change). Climate Change 2022: Mitigation of Climate Change. Available online: https://www.un.org/en/climatechange/reports?gclid=EAIaIQobChMIxsyF3ZSl-AIVoo1oCR19Dw3IEAAYAiAAEgItyfD_BwE (accessed on 16 April 2022).
16. IPCC (Intergovernmental Panel on Climate Change). Available online: https://www.ipcc.ch/about/ (accessed on 22 August 2022).
17. WSA (World Steel Association). Steel Statistical Yearbook 2019. Available online: https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2019-concise-version.pdf (accessed on 18 August 2022).
18. WSA (World Steel Association). Worldsteel 2019. Available online: https://www.worldsteel.org/en/dam/jcr:96d7a585-e6b2-4d63-b943-4cd9ab621a91/World%2520Steel%2520in%2520Figures%25202019.pdf (accessed on 11 October 2020).
19. WSA (World Steel Association). Steel Statistical Yearbook 2020. Available online: https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2020-concise-version.pdf (accessed on 17 December 2021).
20. WSA (World Steel Association). Word Steel in Figures. Available online: https://www.worldsteel.org/en/dam/jcr:976723ed-74b3-47b4-92f6-81b6a452b86e/World%2520Steel%2520in%2520Figures%25202021.pdf (accessed on 23 October 2021).
21. WSA (World Steel Association). World Steel in Figures 2022—A Healthy Economy Needs a Healthy Steel Industry. Available online: https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022-infographic.pdf?x65430 (accessed on 7 July 2022).
22. The Rodney and Otamatea Times. Science Notes and News—Coal Consumption Affecting Climate. 1912. Available online: https://commons.wikimedia.org/wiki/File:Rodney%C2%B7and%C2%B7Otamatea%C2%B7Times%E2%80%A21912%E2%80%A2Coal%C2%B7consumption%C2%B7affecting%C2%B7climate.jpg (accessed on 18 December 2020).
23. EIA (US Energy Information Administration). Carbon Dioxide Emission Factors for Coal. Available online: https://www.eia.gov/coal/production/quarterly/co2_article/co2.html (accessed on 16 August 2020).
24. Griffin, R.; Putting Coal Mine Emissions under the Microscope. Wood McKenzie. Available online: https://www.woodmac.com/news/opinion/putting-coal-mine-emissions-under-the-microscope/#:~{}:text=As%20a%20result%2C%20we%20estimate,on%20average%20than%20thermal%20coal (accessed on 14 March 2022).
25. Bataille, C.; Åhman, M.; Neuhoff, K.; Nilsson, L.J.; Fischedick, M.; Lechtenböhmer, S.; Solano-Rodriquez, B.; Denis-Ryan, A.; Stiebert, S.; Waisman, H. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *J. Clean. Prod.* **2018**, *187*, 960–973. [CrossRef]
26. Bataille, C.; Nilsson, L.J.; Jotzo, F. Industry in a net-zero emissions world: New mitigation pathways, new supply chains, modelling needs and policy implications. *Energy Clim. Change* **2021**, *2*, 100059. [CrossRef]
27. Muslemani, H.; Liang, X.; Kaesehage, K.; Ascuia, F.; Wilson, J. Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products. *J. Clean. Prod.* **2021**, *315*, 128127. [CrossRef]
28. Arens, M.; Åhman, M.; Vogl, V. Which countries are prepared to green their coal-based steel industry with electricity?—Reviewing climate and energy policy as well as the implementation of renewable electricity? *Renew. Sustain. Energy Rev.* **2021**, *143*, 110938. [CrossRef]
29. Wang, C.; Walsh, S.D.C.; Haynes, M.W.; Weng, Z.; Feitz, A.; Summerfield, D.; Lutalo, I. From Australian iron ore to green steel: The opportunity for technology-driven decarbonisation. *Geosci. Aust.* **2022**. Available online: https://www.researchgate.net/profile/Israel-Lutalo/publication/362546377_From_Australian_iron_ore_to_green_steel_the_opportunity_for_technology-driven_decarbonisation/links/62f0e52e0b37cc34477d9141/From-Australian-iron-ore-to-green-steel-the-opportunity-for-technology-driven-decarbonisation.pdf (accessed on 27 August 2022).
30. Wang, R. Energy Saving Technologies and Optimisation of Energy Use for Decarbonised Iron and Steel Industry. PhD Thesis, Durham University, Durham, UK, 2022. Available online: http://etheses.dur.ac.uk/14289/ (accessed on 20 August 2022).

31. Liu, Z.; Ciais, P.; Deng, Z.; Lei, R.; Davis, S.J.; Feng, S.; Zheng, B.; Cui, D.; Dou, X.; Zhu, B.; et al. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **2020**, *11*, 5172. [CrossRef]
32. Liu, X.; Peng, R.; Bai, C.; Chi, Y.; Li, H.; Guo, P. Technological roadmap towards optimal decarbonization development of China's iron and steel industry. *Sci. Total Environ.* **2022**, *850*, 157701. [CrossRef]
33. Richardson-Barlow, C.; Pimm, A.J.; Taylor, P.G.; Gale, W.F. Policy and pricing barriers to steel industry decarbonisation: A UK case study. *Energy Policy* **2022**, *8*, 113100. [CrossRef]
34. Öhman, A.; Karakaya, E.; Urban, F. Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe. *Energy Res. Soc. Sci.* **2021**, *84*, 102384. [CrossRef]
35. Toktarova, A.; Karlsson, I.; Rootzén, J.; Göransson, L.; Odenberger, M.; Johnsson, F. Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies* **2020**, *13*, 3840. [CrossRef]
36. Toktarova, A. The Low-Carbon Steel Industry-Interactions between the Hydrogen Direct Reduction of Steel and the Electricity System. Bachelor Thesis, Department of Space, Earth and Environment at Chalmers University of Technology, Göteborg, Sweden, 2021. Available online: https://search.proquest.com/openview/c2a4d77d71403fdbffd33f250b13251d/1?pq-origsite=gscholar&cbl=2026366&diss=y (accessed on 16 August 2022).
37. Matino, I.; Colla, V. Special Issue on 'Overview, state of the art, recent developments and future trends regarding Hydrogen route for a green steel making process. *Matériaux Tech.* **2021**, *109*, E301.
38. García-Herrero, A.; Tagliapietra, S.; Vorsatz, V. Hydrogen development strategies: A global perspective. *Bruegel-Blogs—Gale Acad.* **2021**. Available online: https://go.gale.com/ps/i.do?id=GALE%7CA673932617&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=&p=AONE&sw=w (accessed on 1 August 2022).
39. Grasa, G.; Díaz, M.; Fernández, J.R.; Amieiro, A.; Brandt, J.; Abanades, C. Blast Furnace Gas Decarbonisation Through Calcium Assisted Steel-Mill Off-Gas Hydrogen Production. Experimental and Modelling Approach. 2022. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4171691 (accessed on 7 August 2022).
40. Devlin, A.; Yang, A. Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation. *Energy Convers. Manag.* **2022**, *254*, 115268. [CrossRef]
41. Gosens, J.; Turnbull, A.; Jotzo, F. An Installation-Level Model of China's Coal Sector Shows How its Decarbonization and Energy Security Plans will Reduce Overseas Coal Imports (CCEP Working Paper). 2021. Available online: https://ccep.crawford.anu.edu.au/sites/default/files/publication/ccep_crawford_anu_edu_au/2021-12/ccep2109_-_gosens_turnbull_jotzo_-_china_coal_model.pdf (accessed on 4 August 2022).
42. Griffin, P.W.; Hammond, G.P. The prospects for 'green steel' making in a net-zero economy: A UK perspective. *Glob. Transit.* **2021**, *3*, 72–86. [CrossRef]
43. Griffin, P.; Hammond, G. Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective. *J. Appl. Energy* **2019**, *249*, 109–125. [CrossRef]
44. Lu, X.; Tian, W.; Li, H.; Li, X.; Quan, K.; Bai, H. Decarbonisation options of the iron and steel making industry based on a 3-dimensional analysis. *Int. J. Miner. Metall. Mater.* **2022**. Available online: http://ijmmm.ustb.edu.cn/article/doi/10.1007/s12613-022-2475-7 (accessed on 25 August 2022).
45. Steenbrink, F. An economic and Geopolitical Assessment of the German-Chinese Aluminium Trade Flows. Master's Thesis, Technical University Delft (NL), Delft, The Netherlands, 2022. Available online: https://repository.tudelft.nl/islandora/object/uuid:1a176161-908d-41b0-a9b0-d7b961744a9d (accessed on 28 August 2022).
46. Kempken, T.; Hauck, T.; De Santis, M.; Rodriguez, P.Q.; Miranda, M.; Gonzalez, D.; Simonelli, F.; Vu, H.; Szulc, W.; Croon, D.; et al. *Collection of Possible Decarbonisation Barriers (Deliverable D1.5)*; Centre for European Policy Studies (CEPS): Brussels, Belgium; Green Steel for Europe Consortium: Brussels, Belgium, 2021.
47. Williams, R.; Jack, C.; Gamboa, D.; Shackley, S. Decarbonising steel production using CO_2 Capture and Storage (CCS): Results of focus group discussions in a Welsh steel-making community. *Int. J. Greenh. Gas Control.* **2021**, *104*, 103218. [CrossRef]
48. Tanzer, S.E.; Blok, K.; Ramírez, A. Decarbonising Industry via BECCS: Promising Sectors, Challenges, and Techno-economic Limits of Negative Emissions. *Curr. Sustain./Renew. Energy Rep.* **2021**, *8*, 253–262. [CrossRef]
49. Sarić, M.; Dijkstra, J.W.; Van Delft, Y.C. CO_2 Abatement in the Steel Industry through Carbon Recycle and Electrification by Means of Advanced Polymer Membranes. *Membranes* **2021**, *11*, 856. [CrossRef] [PubMed]
50. Singh, V.; Buelens, L.C.; Poelman, H.; Saeys, M.; Marin, G.B.; Galvita, V.V. Decarbonisation of steel mill gases in an energy-neutral chemical looping process. *Energy Convers. Manag.* **2022**, *254*, 115248. [CrossRef]
51. Jacob, R.; Sergeev, D.; Müller, M. Valorisation of waste materials for high temperature thermal storage: A review. *J. Energy Storage* **2021**, *47*, 103645. [CrossRef]
52. Sun, Y.; Tian, S.; Ciais, P.; Zeng, Z.; Meng, J.; Zhang, Z. Decarbonising the iron and steel sector for a 2 °C target using inherent waste streams. *Nat. Commun.* **2022**, *13*, 297. [CrossRef] [PubMed]
53. Antonazzo, L.; Stroud, D.; Weinel, M.; Dearden Mowbray, A. Preparing for a Just Transition—Meeting Green Skill Needs for a Sustainable Steel Industry. 2021. Available online: https://orca.cardiff.ac.uk/id/eprint/145353/1/RGB_Meeting_Green_Skills_Needs_A4_booklet_singlepages.pdf (accessed on 9 August 2022).
54. Zhiming, Y.; Li, Z.; Manocha, S.; Ponchon, F.; Sorinel, N. Value in use of lime in BOF steelmaking process', Ironmaking & Steelmaking Processes. *Prod. Appl.* **2021**, *49*, 42–48.

55. Garvey, A.; Norman, J.B.; Barrett, J. Technology and material efficiency scenarios for net zero emissions in the UK steel sector. *J. Clean. Prod.* **2022**, *333*, 130216. [CrossRef]
56. IEA. Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy%20transition%20indicators&indicator=ETISharesInPowerGen (accessed on 3 September 2021).
57. Arnold, V.I. *Mathematical Methods of Classical Mechanics*, 2nd ed.; Springer: New York, NY, USA, 1980.
58. Aylen, J. *Innovation in the British Steel Industry*; Pavitt, K., Ed.; Technical Innovation and British Economic Performance; Palgrave Macmillan: London, UK, 1980.
59. Mandova, H.; Patrizio, P.; Leduc, S.; Kjärstad, J.; Wang, C.; Wetterlund, E.; Kraxner, F.; Gale, W. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. *J. Clean. Prod.* **2019**, *218*, 118–129. [CrossRef]
60. Santos, M.P.S.; Hanak, D. Carbon capture for decarbonisation of energy-intensive industries: A comparative review of techno-economic feasibility of solid looping cycles. *Front. Chem. Sci. Eng.* **2022**, *114*, 6–12. [CrossRef]
61. Franciosi, C.; Voisin, A.; Miranda, S.; Iung, B. Integration of I4.0 technologies with maintenance processes: What are the effects on sustainable manufacturing? *IFAC-PapersOnLine* **2020**, *53*, 1–6. [CrossRef]
62. 62. Jahani, N.; Sepehri, A.; Vandchali, H.R.; Tirkolaee, E.B. Application of Industry 4.0 in the Procurement Processes of Supply Chains: A Systematic Literature Review. *Sustainability* **2021**, *13*, 7520. [CrossRef]
63. Office for National Statistics (ONS) 2019 UK Greenhouse Gas Emissions. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957687/2019_Final_emissions_statistics_one_page_summary.pdf (accessed on 22 October 2021).
64. Chen, Q.; Gua, Y.; Tang, Z.; Wei, W.; Sun, Y. Assessment of low-carbon iron and steel production with CO_2 recycling and utilization technologies: A case study in China. *Appl. Energy* **2018**, *220*, 192–207. [CrossRef]
65. Kuramochi, T.; Ramírez, A.; Turkenburg, W.; Faaij, A. Techno-economic assessment and comparison of CO_2 capture technologies for industrial processes: Preliminary results for the iron and steel sector'. *Energy Procedia* **2011**, *4*, 1981–1988. [CrossRef]
66. Kuramochi, T.; Höhne, N.; Schaeffer, M.; Cantzler, J.; Hare, B.; Deng, Y.; Sterl, S.; Hagemann, M.; Rocha, M.; Yanguas-Parra, P.A.; et al. *Climate Policy—Ten Key Short-Term Sectoral Benchmarks to Limit*; Taylor Francis: London, UK, 2018. Available online: https://www.tandfonline.com/doi/abs/10.1080/14693062.2017.1397495 (accessed on 7 September 2021).
67. Vogl, V.; Åhman, M.; Nilsson, L.J. Assessment of hydrogen direct reduction for fossil-free steelmaking'. *J. Clean. Prod.* **2018**, *203*, 736–745. [CrossRef]
68. Babich, A.; Senk, D. Recent developments in blast furnace iron-making technology. *Mineral. Process. Environ. Sustain.* **2015**, 505–547. [CrossRef]
69. Tata Steel UK (TS). 2019. Available online: https://www.tatasteeleurope.com/en/sustainability/sustainability%E2%80%93overview (accessed on 7 January 2021).
70. Tata Steel UK (TS). Fact Sheet. Available online: https://www.tatasteeleurope.com/ts/sites/default/files/Tata%20Steel%20UK%20Factsheet%202020%20%281%29.pdf (accessed on 5 July 2021).
71. United Nations (UN). Paris agreement—United Nations Framework Convention on Climate Change (UNFCCC) 2016. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 2 April 2020).
72. Tata Steel Europe. Introducing Zeremis. Available online: https://www.tatasteeleurope.com/sustainability/green-steel-solutions/zeremis (accessed on 15 October 2022).
73. IETD (The Institute for Industrial Productivity). Basic Oxygen Furnace. Available online: http://www.iipinetwork.org/wp-content/Ietd/content/basic-oxygen-furnace.html (accessed on 11 May 2021).
74. IETD (The Institute for Industrial Productivity). Electric Arc Furnace. Available online: http://www.iipinetwork.org/wp-content/Ietd/content/electric-arc-furnace.html (accessed on 22 September 2021).
75. Mannesmann Salzgitter AG (MAN) GRINHY2.0—Green Industrial Hydrogen. Available online: https://www.wasserstoff-niedersachsen.de/en/grinhy2-0/ (accessed on 11 January 2022).
76. Worrell, E.; Blinde, P.; Neelis, M.; Blomen, E.; Masanet, E. *Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry. An ENERGY STAR® Guide for Energy and Plant Managers*; Berkeley National Laboratory, University of California Berkeley: Berkeley, CA, USA, 2021. Available online: https://www.osti.gov/servlets/purl/1026806 (accessed on 23 October 2021).
77. Suopajärvi, H.; Umeki, K.; Mousa, E.; Hedayati, A.; Romar, H.; Kemppainen, A.; Wang, C.; Phounglamcheik, A.; Tuomikoski, S.; Norberg, N.; et al. Use of biomass in integrated steelmaking—Status quo, future needs and comparison to other low-CO_2 steel production technologies. *Appl. Energy* **2018**, *213*, 213–384. [CrossRef]
78. Kittipongvises, S. Assessment of Environmental Impacts of Limestone Quarrying Operations in Thailand. *Environ. Clim. Technol.* **2017**, *20*, 67–83. [CrossRef]
79. Siemens. The Power of Hydrogen. Available online: https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions.html?gclid=EAIaIQobChMI_aze8-HN-QIVx7HtCh3zpgQFEAAYASAAEgIeA_D_BwE (accessed on 15 January 2022).
80. Bao, J.; Lu, W.-H.; Zhao, J.; Bi, X.T. Greenhouses for CO_2 sequestration from atmosphere. *Carbon Resour. Convers.* **2018**, *1*, 183–190. [CrossRef]

81. IRENA (International Renewable Energy Agency). World Energy Transitions Outlook: 1.5 °C Pathway. Available online: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (accessed on 30 October 2021).
82. Waismann, H. A pathway design framework for national low greenhouse gas emission development strategies. *Nat. Clim. Change* **2019**, *9*, 261. [CrossRef]
83. FC (Forestry Commission). *Forests, Carbon and Climate Change: The UK Contribution*; Forestry Commission: Edinburgh, UK, 2021.
84. FC (Forestry Commission). *Forests, Carbon and Climate Change: The UK Contribution*; Forestry Commission: Edinburgh, UK, 2003.
85. Nix, J. *John Nix Pocketbook—For Farm Management*, 50th ed.; The Andersons Centre: Leicestershire, UK, 2020.
86. Seethalakshmi, K.K.; Jijeesh, C.M.; Balagopalan, M. *Bamboo Plantations: An Approach to Carbon Sequestration*; Kerala Forest Research Institute: Trichur, India, 2016. Available online: https://www.researchgate.net/publication/215475397_Bamboo_plantations_An_approach_to_Carbon_sequestration (accessed on 9 October 2021).
87. MacDonald, M. *Sectoral Assessment: Cement*; United Nations Industrial Development Organization: Vienna, Austria, 2010.
88. Universität Leipzig. Energy Fundamentals. Available online: https://home.uni-leipzig.de/energy/energy-fundamentals/03.htm (accessed on 3 September 2021).
89. EIA (US Energy Information Administration). Energy Outlook 2022—Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source. Available online: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-AEO2022&cases=ref2022&sourcekey=0 (accessed on 30 May 2022).
90. EIA (US Energy Information Administration). CO2 per kWh. Available online: https://www.eia.gov/tools/faqs/faq.php?id=74&t=11 (accessed on 30 October 2021).
91. Blue Planet. Technology—The Science Geomimetic®Process. Available online: https://www.blueplanetsystems.com/technology (accessed on 29 October 2021).
92. Dastoor, P. *Solar Foil*; Email 18/10/2021; Centre for Organic Electronics Department of Physics, University of Newcastle Callaghan: Callaghan, NSW, Australia, 2021.
93. Malewar, S. Japan's Researchers Fabricate Near-Invisible Solar Cells. 2022. Available online: https://www.inceptivemind.com/japans-researchers-fabricate-near-invisible-solar-cells/25508/ (accessed on 30 July 2022).
94. Blakers, A.; Stocks, M.; Lu, B.; Cheng, C. A review of pumped hydro energy storage. *Prog. Energy* **2021**, *3*, 022003. [CrossRef]
95. EERE (US Department of Energy Efficiency and Renewable Energy). Hydrogen Production: Natural Gas Reforming. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming (accessed on 26 October 2021).
96. British Steel. How We Make Steel. Available online: https://britishsteel.co.uk/what-we-do/how-we-make-steel/ (accessed on 3 March 2022).
97. EULA (European Lime Association. *How much Lime per Tonne of Steel? Summary of the Technical Report A Competitive and Efficient Lime Industry—Cornerstone for a Sustainable Europe*; European Lime Association: Brussels, Belgium, 2012. Available online: https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Summary_0.pdf (accessed on 24 October 2021).
98. Takachar Email from Kevin Keung, Research and Development Lead, to Sandra Kiessling. 18 October 2021.
99. Shell. Shell Invests in the Jackdaw Gas field in the UK North Sea. Available online: https://www.shell.com/media/news-and-media-releases/2022/shell-invests-in-the-jackdaw-gas-field-in-the-uk-north-sea.html#:~{}:text=The%20Jackdaw%20field%20is%20located,group%20of%20companies%20in%202016 (accessed on 30 July 2022).
100. BBC. Cumbria Coal Mine: Decision Delayed until November. Available online: https://www.bbc.co.uk/news/uk-england-cumbria-62499981 (accessed on 30 August 2022).
101. HM Government. The Ten-Point Plan for a Green Industrial Revolution. Available online: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution (accessed on 12 December 2020).
102. Shan, Y.; Liu, Z.; Guan, D. CO_2 emissions from China's lime industry. *Appl. Energy* **2016**, *166*, 245–252. [CrossRef]
103. Sausen, R.; Schumann, U. Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios. *Clim. Change* **2000**, *44*, 27–58. [CrossRef]
104. Aguilera, J.; Whigham, L.D. Using the 13C/12C carbon isotope ratio to characterise the emission sources of airborne particulate matter: A review of literature. *Isot. Environ. Health Stud.* **2018**, *54*, 573–587. [CrossRef] [PubMed]
105. Bhaskar, A.; Abhishek, R.; Assadi, M.; Somehesaraei, H.N. Decarbonizing primary steel production : Techno-economic assessment of a hydrogen based green steel production plant in Norway. *J. Clean. Prod.* **2022**, *350*, 131339. [CrossRef]
106. Bogunovic, D.; Kecojevic, V.; Lund, V.; Heger, M.; Mongeon, P. Society for Mining, Metallurgy, and Exploration, Inc.—Analysis of energy consumption in surface coal mining. *J. Clean. Prod.* **2009**, *326*, 79–87.
107. De Coninck, H.; Mikunda, T. *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report*; Working Paper; United Nations Industrial Development Organization: Vienna, Austria, 2010.
108. Department of Industry (DOI). *The Iron and Steel Industry*; Energy Audit Series, No. 16. Department of Industry: London, UK, 1982.
109. ECRA. *ECRA CCS Project and Report about Phase II*; European Cement Research Academy: Duesseldorf, Germany, 2009.
110. ECRA. *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead*; European Cement Research Academy: Duesseldorf, Germany; Geneva, Switzerland, 2009.
111. Farla, J.C.M.; Hendriks, C.A.; Blok, K. Carbon dioxide recovery from industrial Processes. *Clim. Change* **1995**, *29*, 439–461. [CrossRef]

112. Ferreira, H.; Garcia, M.; Leit, P. A Life Cycle Assessment study of iron ore mining. *J. Clean. Prod.* **2015**, *108*, 1081–1091. [CrossRef]
113. Galitskaya, E.; Zhdaneev, O. Development of electrolysis technologies for hydrogen production: A case study of green steel manufacturing in the Russian Federation. *Environ. Technol. Innov.* **2022**, *27*, 102517. [CrossRef]
114. Global Carbon Project. Science Framework and Implementation. Canadell, J.G., Dickson, R., Hibbard, K., Raupach, M., Young, O., Eds.; Earth System Science Partnership (IGBP, IHDP, WCRP, DIVERSITAS) Report No. 1; Global Carbon Project Report No. 1; 2003; pp. 1–69. Available online: https://www.globalcarbonproject.org/science/sfi.htm (accessed on 11 October 2020).
115. Gupta, R.C. Treatise on Process Metallurgy Chapter 4.2—Energy Resources, Its Role and Use in Metallurgical Industries. 2014. Available online: https://www.sciencedirect.com/topics/engineering/coke-rate#:~{}:text=The%20coke%20is%20the%20major,metal%20under%20global%20best%20practice (accessed on 10 October 2021).
116. HM Government. The Climate Change Act 2008. Available online: https://www.legislation.gov.uk/ukpga/2008/27/contents (accessed on 3 June 2020).
117. House, K.Z.; Baclig, A.C.; Ranjan, M.; Van Nierop, E.A.; Wilcox, J.; Herzog, H.J. Economic and energetic analysis of capturing CO_2 from ambient air. *NIH Natl. Libr. Med.* **2011**, *108*, 20428–20433.
118. Hundermark, K.; Zackrisson, M. Ovako—Cradle-to-Gate—Understanding CO_2 Footprint of Hot-Rolled Bar Steel Products. OVAKO Report 2019. Available online: https://www.ovako.com/globalassets/downloads/products/cradle-to-gate-understanding-co2-footprint.pdf (accessed on 6 June 2021).
119. Julia, G. Sur les équations fonctionelles. *J. Mathématiques Pure Appl.* **1918**, *4*, 47–245.
120. Fraunhofer Institute. Methodology for the Free Allocation of Emission Allowances in the EU ETS Post 2012. Sector Report for the Iron Ore Industry by Order of the European Commission 2009. Available online: https://ec.europa.eu/clima/system/files/2016-11/bm_study-iron_ore_en.pdf (accessed on 24 February 2021).
121. GEI (Global Efficiency Intelligence). Global Steel Industry's GHG Emissions. Available online: https://www.globalefficiencyintel.com/new-blog/2021/global-steel-industrys-ghg-emissions (accessed on 5 May 2022).
122. Hall, W.; Millner, R.; Rothberger, J.; Singh, A.; Shah, C.K. *Green Steel through Hydrogen Direct Reduction: A Study on the Role of Hydrogen in the Indian Iron and Steel Sector*; The Energy and Resources Institute (TERI): New Delhi, India, 2021.
123. Hasanbeigi, A.; Arens, M.; Carlos, J.; Cardenas, R.; Price, L.; Triolo, R. Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States' resources. *Conserv. Recycl.* **2016**, *113*, 127–139. [CrossRef]
124. Khakimov, H.T.; Shayumova, Z.M.; Kurbanbaeva, Z.K.H.; Khusanov, B.M. Development of Optimal Modes and Mathematical Models of Energy Performance of Electric Steelmaking Production. Available online: https://www.e3s-conferences.org/articles/e3sconf/pdf/2019/65/e3sconf_rses2019_01076.pdf (accessed on 25 October 2021).
125. Li, Y.; Zhu, L. Cost of energy saving and CO_2 emissions reduction in China's iron and steel sector. *Appl. Energy* **2014**, *130*, 603–616. [CrossRef]
126. McKinsey & Company. Metals & Mining Practice: The Future of the European Steel Industry. A Road Map toward Economic and Environmental Sustainability 2021. Available online: https://www.mckinsey.com/~{}/media/mckinsey/industries/metals%20and%20mining/our%20insights/the%20future%20of%20the%20european%20steel%20industry/the-future-of-the-european-steel-industry_vf.pdf (accessed on 23 February 2022).
127. Mehmood, I.; Bari, A.; Irshad, S.; Khalid, F.; Liaqat, S.; Anjum, H.; Fahad, S. Carbon Cycle in Response to Global Warming. In *Environment, Climate, Plant and Vegetation Growth*; Springer: Cham, Switzerland, 2020; pp. 1–15. Available online: https://link.springer.com/chapter/10.1007/978-3-030-49732-3_1 (accessed on 3 August 2022).
128. Mikhaylov, A.; Moiseev, N.; Aleshin, K.; Burkhardt, T. Direct from MIDREX TM Report 4TH QUARTER 2021. Available online: https://www.midrex.com/wp-content/uploads/Midrex-DFM-4Qtr2021-Final1.pdf (accessed on 23 August 2022).
129. Omoregbe, O.; Mustapha, A.N.; Steinberger-Wilckens, R.; El-Kharouf, A.; Onyeaka, H. Carbon capture technologies for climate change mitigation: A bibliometric analysis of the scientific discourse during 1998–2018. *Energy Rep.* **2020**, *6*, 1200–1212. [CrossRef]
130. Prakash, R.; Muller, M. Industrial Oxygen: Its Generation and Use. 2007. Available online: https://www.aceee.org/files/proceedings/2007/data/papers/78_6_080.pdf (accessed on 29 October 2021).
131. Rudd, L.; Kulshreshtha, S.; Belcher, K.; Amichev, B. Carbon life cycle assessment of shelterbelts in Saskatchewan, Canada. *J. Environ. Manag.* **2021**, *297*, 113400. [CrossRef]
132. SSAB (Svenskt Stål AB). Use Better Steel: SSAB's Customers Benefit from Leading CO_2 Efficient Production. Available online: https://www.ssab.com/en/company/sustainability/sustainable-operations/co2-efficiency (accessed on 13 July 2022).
133. Sunny, N.; MacDowell, N.; Shah, N. What is needed to deliver carbon-neutral heat using hydrogen and CCS? *Energy Environ. Sci.* **2020**, *11*, 4204–4224. [CrossRef]
134. UNIDO. *Global Technology Roadmap for Carbon Capture and Storage for Industry—Emission Reduction and Industrial Development: The Role of CO2 Capture and Storage in Industry*; United Nations Industrial Development Organization: Vienna, Austria, 2010.
135. United Nations (UN). Kyoto Protocol. Available online: https://unfccc.int/kyoto_protocol (accessed on 16 June 2020).
136. USA Congress. Energy Independence and Security Act of 2007. Available online: https://www.congress.gov/bill/110th-congress/house-bill/6 (accessed on 22 July 2020).
137. US Department of Energy (USDE). ITP Mining: Energy and Environmental Profile of the U.S. Mining Industry: Chapter 4: Iron. Available online: https://www.energy.gov/sites/prod/files/2013/11/f4/iron.pdf (accessed on 13 November 2020).

138. Variny, M.; Jediná, D.; Rimár, M.; Kizek, J.; Kšiňanová, M. Cutting Oxygen Production-Related Greenhouse Gas Emissions by Improved Compression Heat Management in a Cryogenic Air Separation Unit. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10370. [CrossRef]
139. Wänerholm, M. Rapport nr. 2016-008—Climate Impact of Metal-Casting', Swerea/SWECAST 2016. Available online: https://www.diva-portal.org/smash/get/diva2:1140576/FULLTEXT01.pdf (accessed on 12 December 2020).
140. West, K. IEA (International Energy Agency) at OECD 12 May 2015 Steel Committee Meeting: ETP (Energy Technology Perspective) 2015: Iron & Steel Findings. Available online: https://www.oecd.org/sti/ind/Item%208b%20-%20IEA_ETP2015_OECD%20Steel%20Committee_final.pdf (accessed on 9 September 2020).
141. Yang, Y.; Raipala, K.; Holappa, L. Chapter 1.1—Ironmaking. 2014. Available online: https://www.sciencedirect.com/science/article/pii/B9780080969886000171 (accessed on 30 October 2021).
142. Yi, S.H.; Choi, M.E.; Kim, D.H.; Ko, C.K.; Park, W.I.; Kim, S.Y. FINEX® as an environmentally sustainable ironmaking process. *Ironmak. Steelmak.* **2019**, *46*, 625–631. [CrossRef]
143. Zakkour, P.; Cook, G. *CCS Roadmap for Industry: High-Purity CO_2 Sources. Sectoral Assessment and Final Draft Report*; United Nations Industrial Development Organization: Vienna, Austria, 2010.
144. Zhang, H.; Sun, W.; Li, W.; Wang, Y. Physical and chemical characterization of fugitive particulate matter emissions of the iron and steel industry. *Atmos. Pollut. Res.* **2022**, *13*, 101272. [CrossRef]
145. Hasanbeigi, A. Steel Climate Impact—An International Benchmarking of Energy and CO_2 Intensities. Available online: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/624ebc5e1f5e2f3078c53a07/1649327229553/Steel+climate+impact-benchmarking+report+7April2022.pdf (accessed on 31 October 2022).
146. Yurcent. Comprehensive Treatment of Industrial Waste Gas—Xeolite Rotor. Available online: https://en.yurcent.com/Products_3/20.html (accessed on 3 September 2021).