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Keywords: Energy Independence; Sustainable Steel; Net-Zero

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Greater Energy Independence with Sustainable Steel Production

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Abstract: Energy market price volatility and an upward trajectory of prices per unit of electricity have sent all industrial sectors and many economies to the brink of recession. Alongside the urgent need for decarbonisation of all industries, 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 and capture technologies has the potential for short-term emissions reduction to near-zero in absolute terms. The findings of this research showed CO_2 emissions reduction of ~30% from 977t of CO_2e to 684t in one single blast furnace production cycle, by switching the energy provider generating energy exclusively from renewable sources. Replacing coal with biomass (BECCS), resulted in an additional reduction of ~30%, to CO_2e to 479t CO2e. Installing solar PV panels for energy generation on site resulted in a further ~30% reduction, to 335 tonnes CO_2e. Finally, the installation of CO_2 filters reduced the CO_2 emissions to near-zero. Simultaneously, energy-saving and process improvement measures implementation (up to 60% efficiency increase), excess heat recovery (<30% of energy savings), and retrofitting renewable energy technology resulted in an energy independence of 88%. Short-term engineering solutions, partly subsidised in the UK, are readily available.

Keywords: energy independence; sustainable steel; net-zero

1. Introduction

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 refineries1, are by far the largest emitters of CO_2 emissions, due to their high energy demand. The steel industry is accounting for between 7% and 11% [1–7] of global CO_2 emissions as a result of steelmaking, and China is responsible for 50% of these GHGs [7], due to their heavy reliance on coal. The increased use of coal in energy generation, due to imposed oil and gas shortages, was found to be the main factor [1,8] driving up global energy-related anthropogenic CO_2 emissions by over 2 billion tonnes, their largest ever rise in absolute terms.

2. Materials and Methods

Throughout this project, global data in connection with renewable energy technology implementation in different settings has been utilised [9–14]. Information on factual CO_2 emissions in steel production [15] and manufacturing [16–18] have been considered, as well as data from other industrial sectors [4,9,19–21]. In order to visualise the opportunities of a circular steel production process, implementation of sustainable elements and opportunities for achieving great energy independence, a comprehensive steel manufacturing overview has been compiled, as displayed in Figure 1. The data was accumulated, analysed and used for modelling using MS Excel and

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simultaneously analysed by applying standard mathematical principles and followed for proof of concept with steel production simulations in Simul8, Inosim and Aspen.

'The 7 Steps to Net-Zero CO_2 Emissions Steel Production' [15] strategy can be seen as a strategic guidance paper for the decarbonisation of steelmaking. Simultaneously, the BiSC [15] implementation will likely achieve a higher degree of energy independence, in the short-term. It could be achieved in seven easy-to-follow steps, even if only some sections of the following are being applied:

Step 1: Switching to a 100% 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 building projects
Step 6: Further process improvement in steel manufacturing
Step 7: Implementation of AD>biogas>green hydrogen

Conventional energy use and renewable energy component implementation points have been incorporated for highlighting the simplicity of achieving a higher degree of energy independence, whilst simultaneously decarbonising the steelmaking process.

As displayed in Figure 1, the same principle applies to the steel (Figure 2), in the BF with CCUS unit in the Aspen configuration production process, as far as off-heat is concerned. It was established that a total potential of 425PJ (1 PJ (Petajoule) = 31.6 million m^3 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 [22]. This amount is thought to represent between 4% and 9% of the total industrial final energy demand. 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 [22]. Process simulations in Simul8, INOSIM and Aspen+ (BF, Figure 2) were used to explain the individual production process implications. The BF/BOF route is the most widespread method of steelmaking, representing ~70% of current global crude steel production [23]. It needs to be emphasised, though, that the displayed 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. 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 CO_2/t cs was allocated for entering in the input stream in S8 as BF 2.95t of CO_2 per metric tonne of liquid iron produced and BOF 2t/t of CO_2 per metric tonne of steel produced.

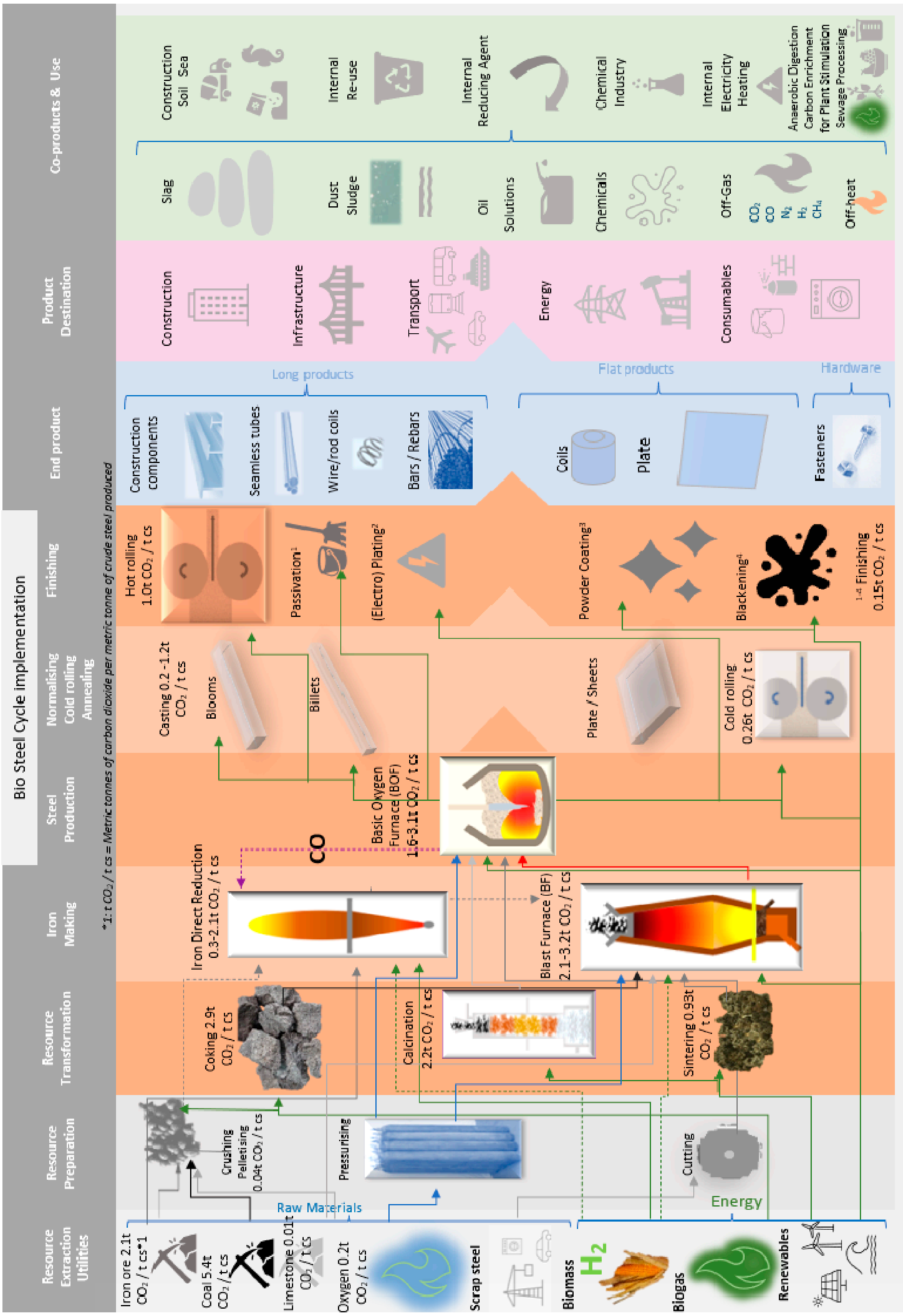

Figure 1. Steelmaking table flowchart with BiSC.

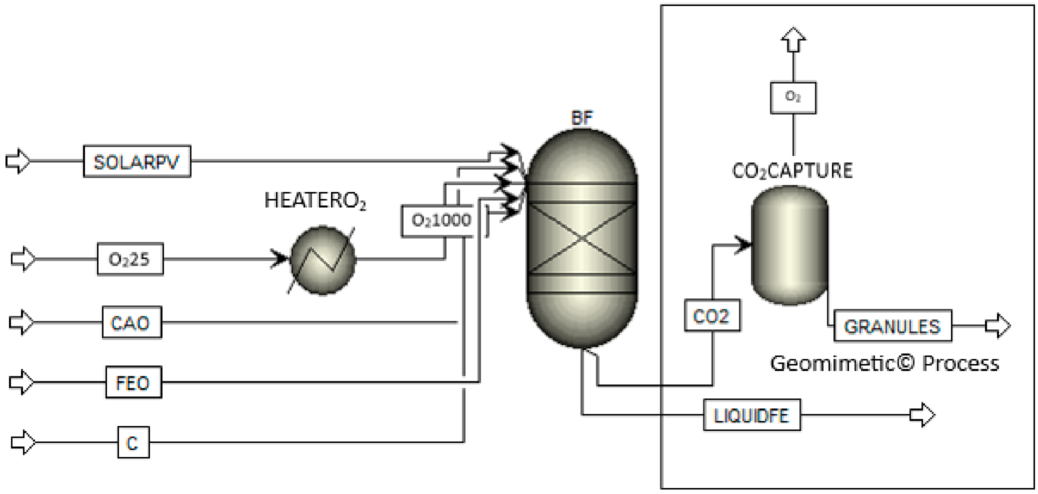

Figure 2. Aspen BF configuration with CCUS unit.

The BF-EAF-process-route simulation, representing the second most-common method of steelmaking, has a share of ca. 20% of global steel production. Initially, and as biomass [21,61] has the potential to reduce CO_2 emissions by ~30%, the usage of biomass was implemented [21,61] and filters as well as CCUS units installed (Figure 2 and 3), in direct comparison with the MS Excel modelling, and mathematical calculations. The calculations are set to work for a 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 (Figure 4). Verifying the results of the preceding evaluations, computations and calculations, initially 977t of CO_2e flow was reported by the Aspen system analysis, without any mitigating measures.

The CO_2 reductions in relation to a 330t blast furnace vessel, modelled in comparison to the British Steel Scunthorpe site, are quite remarkable. Having implemented steps of the Bio Steel Cycle model and strategy , the %-reduction per stage in CO_2 emissions have been successively implemented and the results in percentage and tonnes are displayed in Figure 4. A reduction of ~30%, to 684t of CO_2e flow was reported when solar PV panels for energy generation on site were installed and subsequently a carbon capture module was installed (Figure 2).

The process simulations and carbon reports in Simul8, demonstrated the effect of implementing biomass and carbon capture technology in the steelmaking process. These simulations were followed by configurations in Aspen and Inosim, including the implementation of CCUS processes, as the implementation of this process, which includes off-gas flue stack filters, makes it possible to produce steel at almost zero CO_2 emissions – for both, the BF/BOF and BF/EAF-process-route. To corroborate the results from the MS Excel modelling, the mathematical formulation and calculations, and Simul8 process simulation by producing configurations in AspenV12.1 and INOSIM, as displayed in Figure 3.

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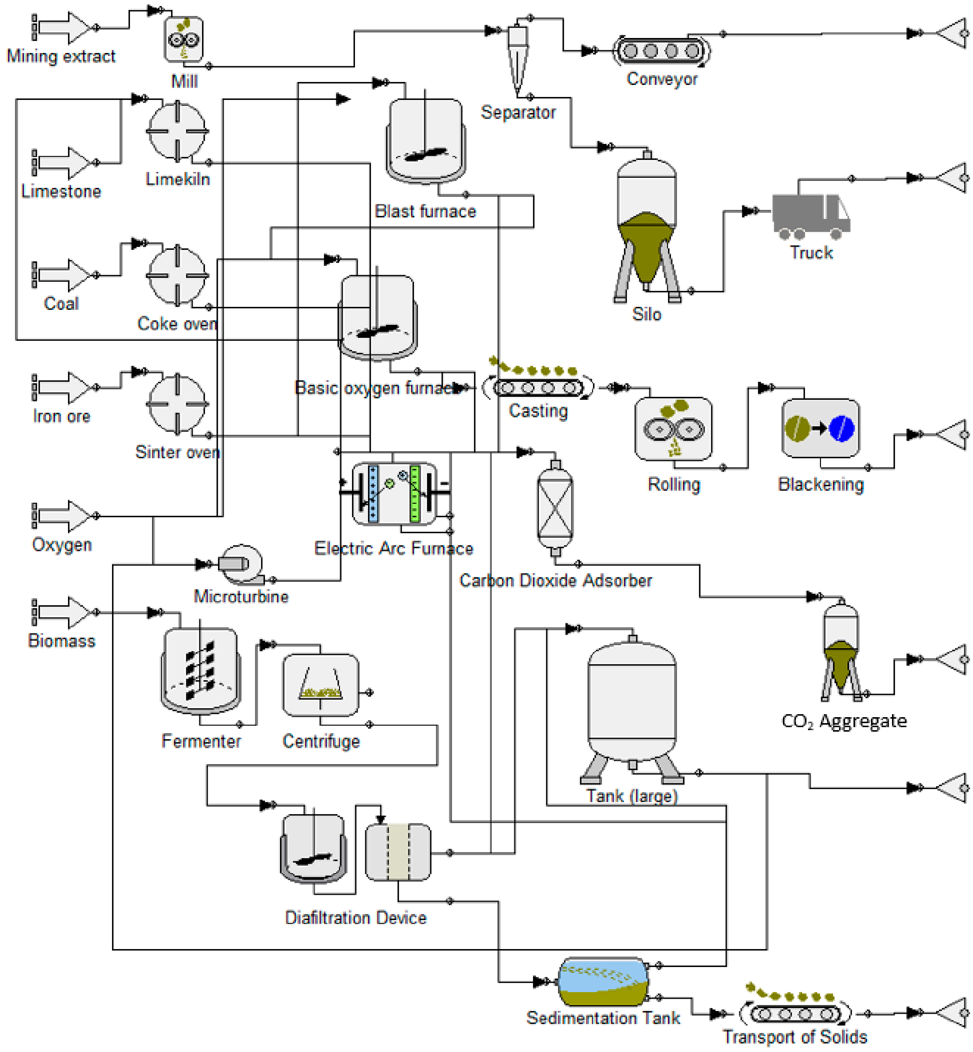

Figure 3. INOSIM configuration mining to marketing with CCUS .

The simulations 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 zero, as detailed in Figure 4. 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 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 other components of the Bio Steel Cycle, including renewable energy sources, are being installed which will be further elaborated on in the following text and the summary results are shown in Figure 4.

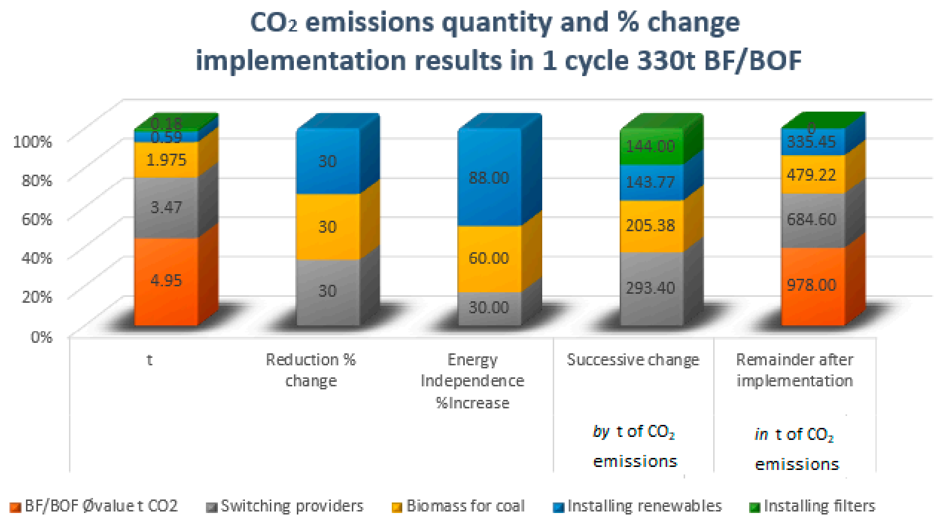

Figure 4. CO_2 emissions change with CAT and CCUS implementation.

The simulation results are detailed in metric tonnes, occurring during one production cycle, based on 330 tonne BF and BOF furnaces.

2.1. Heat loss recovery – energy and CO_2 saving protocols

Already since the 1990s, scientists were convinced [24] that 30% of the heat energy entering any production process is: a) lost and b) could be recovered. The required technology 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 was produced by Moran and Sciubba (1994) [24]. The theory of 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. Excess heat is a hidden resource of energy, and it is all around us. Utilising excess heat means enabling >95% energy efficiency. According to the International Energy Agency [1,5], 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 energy more efficiently, we will not get on track to meet global climate goals.

Global emissions [25] 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. A global push for more efficient use of energy can reduce CO_2 emissions by an additional 5 gigatons per year by 2030 [1,8,26–28], based on current energy demand. The global electricity consumption is displayed in the following Figure 5. However, energy efficiency increases constitute merely 30% of the required CO_2 reduction needed to meet the Net Zero by 2050 Scenario [1,8,26–28]. 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 20211. Although there has been a steady decline in overall electricity consumption in the iron and steel manufacturing sector (Figure 6), due to already implemented structural changes towards more sustainable production processes in the industry, along with the installation of energy efficiency measures, and improved energy efficiency measures [29], there is still a substantial amount of electricity which could be saved (Figure 5). Additionally, this would render the existing infrastructure

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utilisation more efficient. One of the most important factors, the required short-term solutions, is helped by using suitable existing infrastructure as it can be easily retrofitted with technology to prevent heat loss, and decarbonise production process technology at the same time.

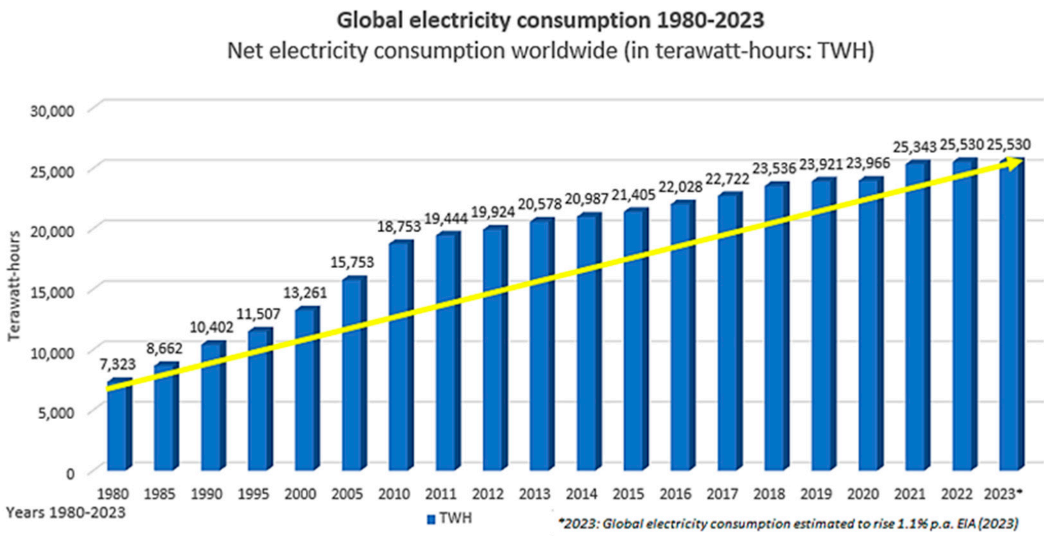

Figure 5. Global electricity consumption 1980-2023.

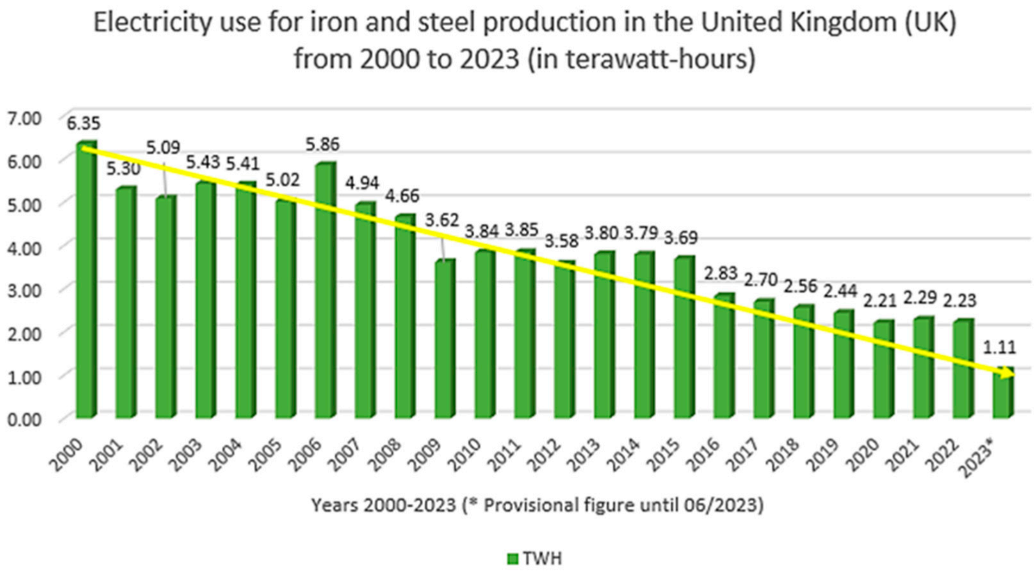

Figure 6. Electricity use iron/steel industry from 2000-2023.

Simultaneously, it could be utilised to a) capture >98% [30] 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 from somewhere else, at fluctuating prices [1,8,26]. As shown in Figure 6, 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 [1,8,26] as previously demonstrated in Figure 5. Global electricity consumption has continuously increased during the last 50 years, arriving at an estimated 25,530 terawatt-hours in 2023 [27,31] (Figure 6). Since 1980 and up to 2021, global electricity consumption has increased three-fold, and the global population increased by roughly 75%, 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 [7,27,28] 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. [7,27,28]. 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, and exergy loss prevention, is a technically simple and effective short-term solution. 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%). Meaning: 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.

2.2. Retrofitting renewable energy technologies on site

Renewable energy technologies are an economically viable alternative [12] to combustion processes based on fossil fuels such as coal and gas to produce heat and energy [4,14,27–32]. Solar, wind, geothermal and hydropower are well-established technical solutions [4,14,27–32], which have already been successfully implemented in a range of countries and settings [33–38]. In the UK, there are a range of schemes accessible to businesses, such as finance and support from the Department for Business, Energy & Industrial Strategy (2023) and others, as displayed in the following Table 1. Some countries and industries are supplying their entire energy needs via renewable energy solutions [4,29,31] - 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 [14,26,27,29,39–41]. 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 which are deriving their energy at 100% from renewable sources. 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 [42,43]. Additionally, the same applies to wind turbines, technology generating electricity using either biomass or hydro-turbines turbines (water-based), and anaerobic digestion (AD) systems.

Table 1. UK support schemes renewable energy technologies.

Scheme	*Description*
England Woodland Creation Offer	Landowners, land managers and public bodies can apply to the England Woodland Creation Offer (EWCO) for support to create new woodland. Over £10,000 per hectare.
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

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	on how to reduce emissions. A £400,000 grant fund has been established to help to capital investment projects delivering emission reductions.
Green Heat Network Fund	Commercialisation and construction of new low and zero carbon (LZC) heat networks (including the supply of cooling). Retrofitting and expansion of existing heat networks. Funding will support the uptake of low-carbon technologies like 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 (no individuals, households, sole traders).
Green Gas Support Scheme	Funding support for biomethane injection to the national grid.
Clean Heat Grant	Upfront capital funding for households and businesses for the installation of sustainable heating technologies (heat pumps, biomass).
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.
SMEES	SMEES (SME Energy Efficiency Scheme): Guidance and funding for businesses looking to improve their energy efficiency.
Energy for Business	Support and grant funding for SMEs with projects to reduce carbon emissions or save energy.
HNIP	Heat Networks Investment Project (HNIP) government-backed funding
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
Business Energy Efficiency Programme	Energy reviews and grants to help businesses in the West Midlands manage and reduce energy costs.
Low Carbon Workspaces	Offers grants to implement energy efficiency measures, to save money and cut waste
Horizon Europe funding	Funding for research or innovation that's ground breaking, improves European research standards or responds to challenges like climate change or food security.
Coventry and Warwickshire Green Business Programme	Grants, free energy audits and low carbon product development support for businesses.

Renewable energy technology is market ready – now the implementation is key.

The choice and implementation of any of these 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 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. Some examples in Table 2:

Table 2. MCDA excerpt implementation details and cost.

Step 1-7		*Project or*		
BiSC	**Technique**	**Process**	**Company**	**System / Performance**
1	Switching>Green energy	Energy Provider	See Appendix 4	100% renewable energy
2	Installing renewables: Solar	Solar PV panels	IBC (Internal back contact)	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/£1,829,271.35x 3
2	Installing renewables: Wind	Horizontal axis w. turbine	Enercon E126 EP3	3.5 MW/£2,458,302.00x 2
2	Installing renewables: Wind	Vertical axis wind turbine	Patriot Modular	70kW/£188,196.00/x 92
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-based filter
5	Utilisation captured CO_2	Geomimetic: CCUS in aggregate	Blue Planet	100% CCUS
6	Process improvement	Hisarna; ironmaking by simultaneous 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 in the data filed indicates the presence of relevant data. .

Some technical solutions for achieving a higher degree of energy independence have been intensely researched [23,44–47] and implemented in a range of industrial sectors. Projects containing components such as DAC (Direct Air Capture), re-directing heat and utilising anaerobic digesters to produce biogas (methane and hydrogen), and producing energy on-site with suitably sized turbines [48] can be directly linked to one of the incentives shown in Table 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 [43]. 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. 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 [14]. 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%14. Although there is a variety of renewable energy technologies at TRL9 available (Table 2), PV technology and on-shore wind generation for independent energy production were established as the mainly utilised renewable energy technology in a competitive market. The second largest dominant technology after solar in the UK is wind energy. 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. 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% [49]. 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% and 88% [15,49]. 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 88%, 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. The MCDA analysis of different renewable energy systems, taking into consideration the incentives in table 1, leaves much hope for the establishment of the UK as a green energy hub, as the provided initiatives can enable the stakeholders willing to invest in green energy to not only make the green industrial revolution in the UK happen, but could enable the investors to do so at minimal cost. Table 2 shows an extract of the extensive BiSC implementation MCDA analysis. Observing economic principles and baselines, it can be assumed that, overall, there is a third of cost involved, with two-thirds of savings on energy cost 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. The political and legal landscape and country governmental guidance will have to change dramatically [50,51] in order to meet the targets, set by the Paris Agreement [52] and COP15 [51] and the dire warnings issued by the recent IPCC reports (2023) [53]. By improving their carbon capture and off-heat utilisation capabilities, and investing in renewable energy technology, businesses are:

- supporting the decarbonisation of production,

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- reaching a higher degree of energy independence,
- achieving a higher level of asset efficiency,
- training workforce in required 'green' skills,
- reducing their energy costs and
- creating a viable additional income stream

Additionally, besides achieving a higher degree of energy independence, economic advantages in monetary terms are almost inevitable when renewable energy systems are being installed. Doing so will also support achieving limiting the global temperature rise to below 2°C and thus support avoiding climate disaster. The CO_2 emissions by industry sector were analysed [33,39,54–57] and besides the iron and steel industry, there are other heavy industries which are CO_2 emitters, and generating copious amounts of off-heat, co-products and therewith resources, which could be harvested and used to power energy-dependent devices: Transport, Chemical industry, Energy Supply, Residential/Commercial buildings sector, Agriculture, and Waste Management.

3. Conclusions

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 process simulations compiled within the systems S8, Aspen+ and Inosim aligned with the mathematical analysis and modelling in MS Excel and provided almost matching reports stating a reduction of 30% from 977t of CO_2e to 684t of CO_2e flow in a 330t furnace, when the energy provider was switched to a 100% green energy provider (derived at 100% from renewable energy). Additional reductions to the value of 30% were observed, where CO_2 emissions declined from 684t CO_2e to 479t CO_2e, when coal and coke were replaced by biomass (BECCS). The installation of solar PV panels for energy generation on site resulted in a further 30% reduction from 479t CO_2e to 335t. Finally, the installation of CO_2 filters reduced the CO_2 emissions to almost '0'. Furthermore, the application points of renewable energy technology within the steel production process were established where achieving a 30%, 49% and 65.7% higher energy independence is achievable, in the short term. The cost risk of installing renewable energy and decarbonisation technology was minimised to less than a third of the initial outlay in individual cases, as the UK government is providing grants, funding and loan schemes to encourage all industrial sectors to work towards Net-Zero. 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:

- Utilisation of captured CO_2 in the building industry (CCUS), agriculture (CEPS), chemical industry, food & drinks industry, and pharmaceuticals
- Utilisation of waste products from steel making in infrastructural projects
- Other GHG captured from post-combustion processes can be reused in the chemical industry, thus eliminating the need for waste management.

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

- Adding solar foil, panels, tiles and shingles to buildings and carparks deemed structurally sound
- Adding a biogas and/or hydrogen transfer network for hydrogen direct reduction in steel production from anaerobic digesters
- Installing wind turbines at brownfield sites not suitable for human habitation
- Developing filters to be retrofitted to existing production plants emitting GHGs, which are not based on using Zeolite or water based chemical processes

Further work is currently underway and will provide more detail on the more salient points of this paper, upon publication. as appropriate.

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Appendix

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
CAT – Carbon avoidance technology
CCUS - Carbon capture and utilization or storage
CGE - Computable general equilibrium
CH4 - Methane CCS – Carbon capture and storage
CO_2 - Carbon dioxide
DRI - Direct reduced iron
DRI - Direct reduced iron
EAF - Electric arc furnace
EAF - Electric arc furnace
Eimp - Total imported energy (kg/steel)
EmSp.El. - CO_2 emission savings/avoidance potency factor
Fe_2O_3 - Hematite
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)

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LST - Tonne (metric) liquid steel
MAC - Marginal abatement cost
MCO_2,proc - Onsite CO_2 emission (kg/steel)
Mind - Production rate of steel (kg) capacity
MO.Ind - Usage of oxygen on site
NG - Natural gas, fossil derived methane
O&M - Operation and maintenance
O_2 - Oxygen, chemical formula
OPC - Ordinary Portland Cement
OPEX - Operating expenses
PC - Pulverized coal
PCC - 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 - Net work 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
Ø - Sign for average

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