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Greater Energy Independence with Sustainable Steel Production

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Abstract: Global 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 globally 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 the steel industry—although some of the mechanisms can be implemented across most heavy industries. The findings of this research show a CO_2 emissions reduction of ~30% from 977 t of CO_2 to 684 t in one single blast furnace production cycle (based on 330 tonnes of liquid iron production capacity, with the mean of 2.1–3.2 tonnes CO_2/t of steel and chemical reactions emissions applied), by switching the electricity provider for operating the electric heaters to providers generating energy exclusively from renewable sources. Replacing coal with biomass and adding post-combustion capture units to the blast furnace operation, will add carbon neutrality into the process—resulting in CO_2 emissions reduction to near-zero. Carbon capture from biomass utilisation (BECCS) will add the benefit of carbon-negative emissions to the cycle. 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%. Engineering solutions, partly subsidised in the UK, are readily available for implementation in the iron and steel manufacturing industry.

Keywords: energy independence; sustainable steel; net zero

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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 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—the demonstration of the feasibility being the purpose of this paper. This could be considered one of the foremost important contemporary endeavours. The energy sector, the iron and steel industry, along with heavy industry and petroleum refineries [1], are by far the largest emitters of CO_2 emissions, due to their high fuel and energy demand. The steel industry accounts 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.

This research focused on the technical solutions currently available for the decarbonisation of the steel industry and how decarbonisation could lead to a higher degree of energy independence, based on the currently known energy consumption trends. The consumption trend evaluation or influence of renewables implementation on consumption trends on a global scale were not the key focus of this project, as these are two completely independent, separate issues altogether, but pose an interesting challenge for future research. This research focused on the steel industry and connected subsidiary industries only.

2. Materials and Methods

Throughout this project, global data sets in connection with renewable energy technology implementation in different settings were 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 simultaneously analysed by applying standard mathematical principles and followed for proof of concept with steel production simulations in Simul8, Inosim and Aspen. Although there are currently several projects in progress concerned with filtering CO_2 emissions from post-combustion off-gas, a solution has yet to be found that could achieve a 100% filtering of CO_2 emissions.

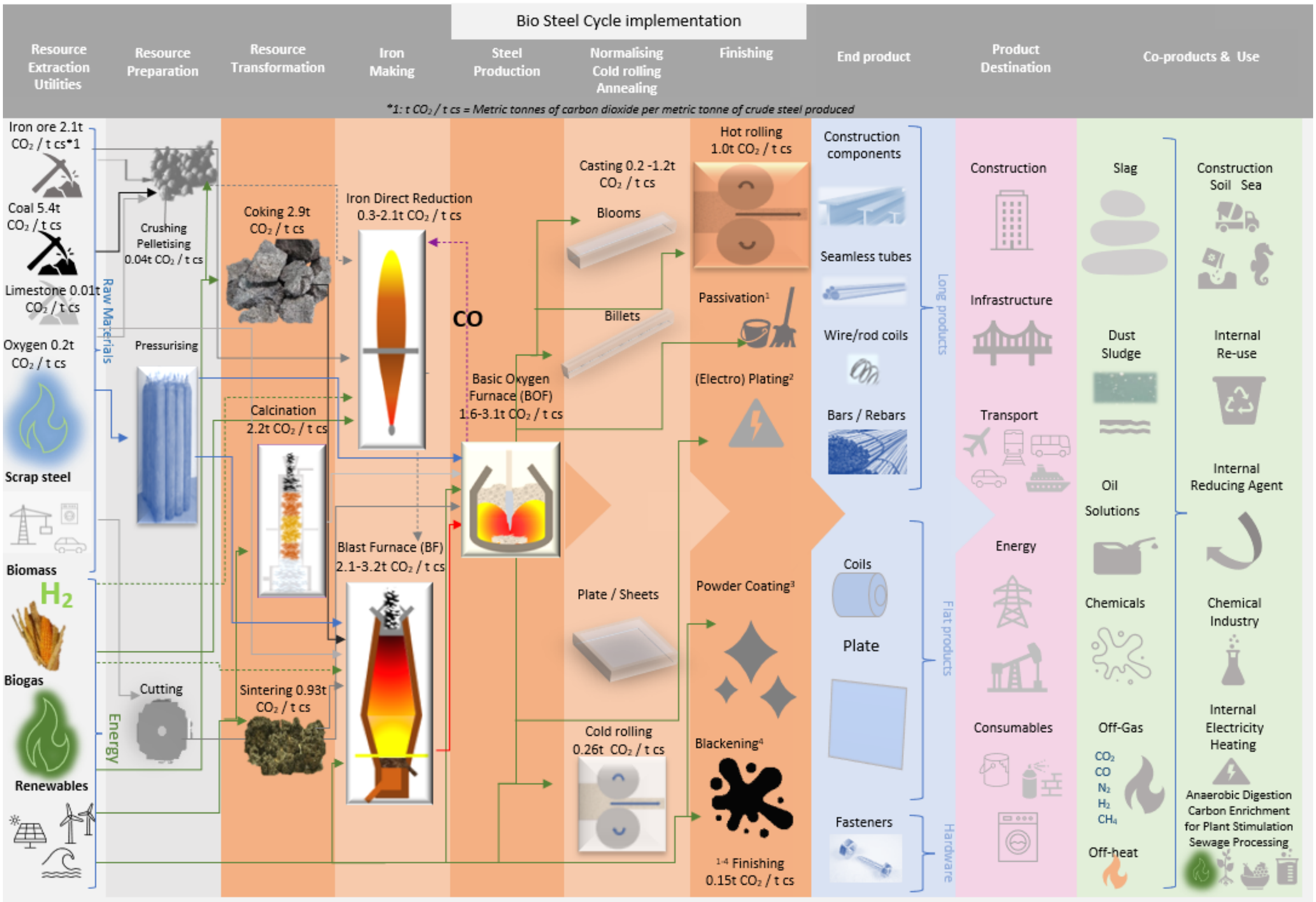

Figure 1. Steelmaking table flowchart with BiSC.

There are two major hurdles to the implementation of sustainable steel and other production techniques: (1) lack of willingness across all industries to incorporate the required changes in their financial and production planning and managing the installation of suitable technology and (2) ensuring a viable financing of all efforts using appropriate MCDA and costings and incentives provided by the respective governments. The first hurdle relies on industry leaders to act and drive the decarbonisation of the steel industry to avert climate disaster, as politicians worldwide seem to lack the willingness to implement and enforce adequate policies—the signs are all around us. There are continued research and campaigning efforts taking place in this direction. The second hurdle has been partly addressed by governments across the globe and the UK government with grants, loans, and subsidies.

The preceding publication '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, in tandem with this publication as a guideline for achieving higher energy independence. The systems implementation, as described in [15] 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 post-combustion carbon capture technology;
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 to highlight 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 AspenV.12.1 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 4.95 t CO_2/t cs was allocated for entering the input stream in S8 as BF 2.95 t of CO_2 per metric tonne of liquid iron produced and BOF 2 t/t of CO_2 per metric tonne of steel produced.

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 [21,24] has the potential to reduce CO_2 emissions by ~30%, the usage of biomass was implemented [21,24] and filters as well as CCUS units were installed (Figures 2 and 3), in direct comparison with the MS Excel modelling, and mathematical calculations. The calculations are set to work for a 330-t blast furnace, similar to the British Steel site in Scunthorpe, and for the operational year of 1 h, to reflect the 40-min average charge processing and discharge time (Figure 4). Verifying the results of the preceding evaluations, computations, and calculations, initially, 977 t of CO_2 flow was reported by the Aspen system analysis, without any mitigating measures.

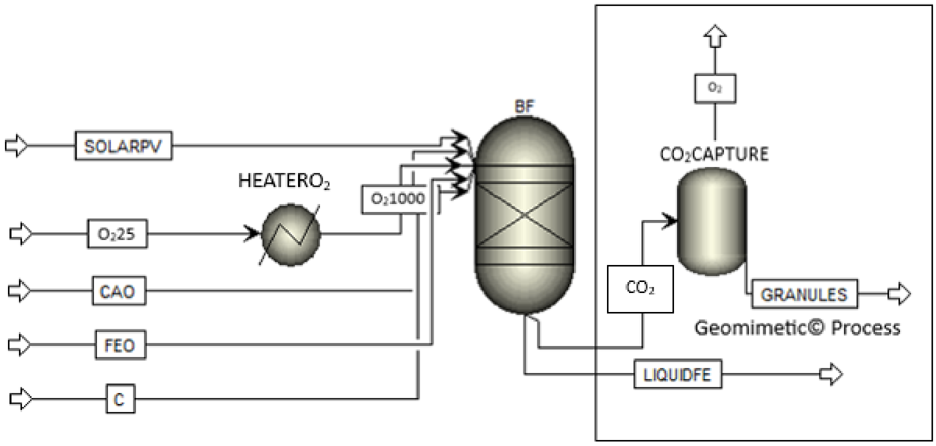

Figure 2. Aspen BF configuration with CCUS unit.

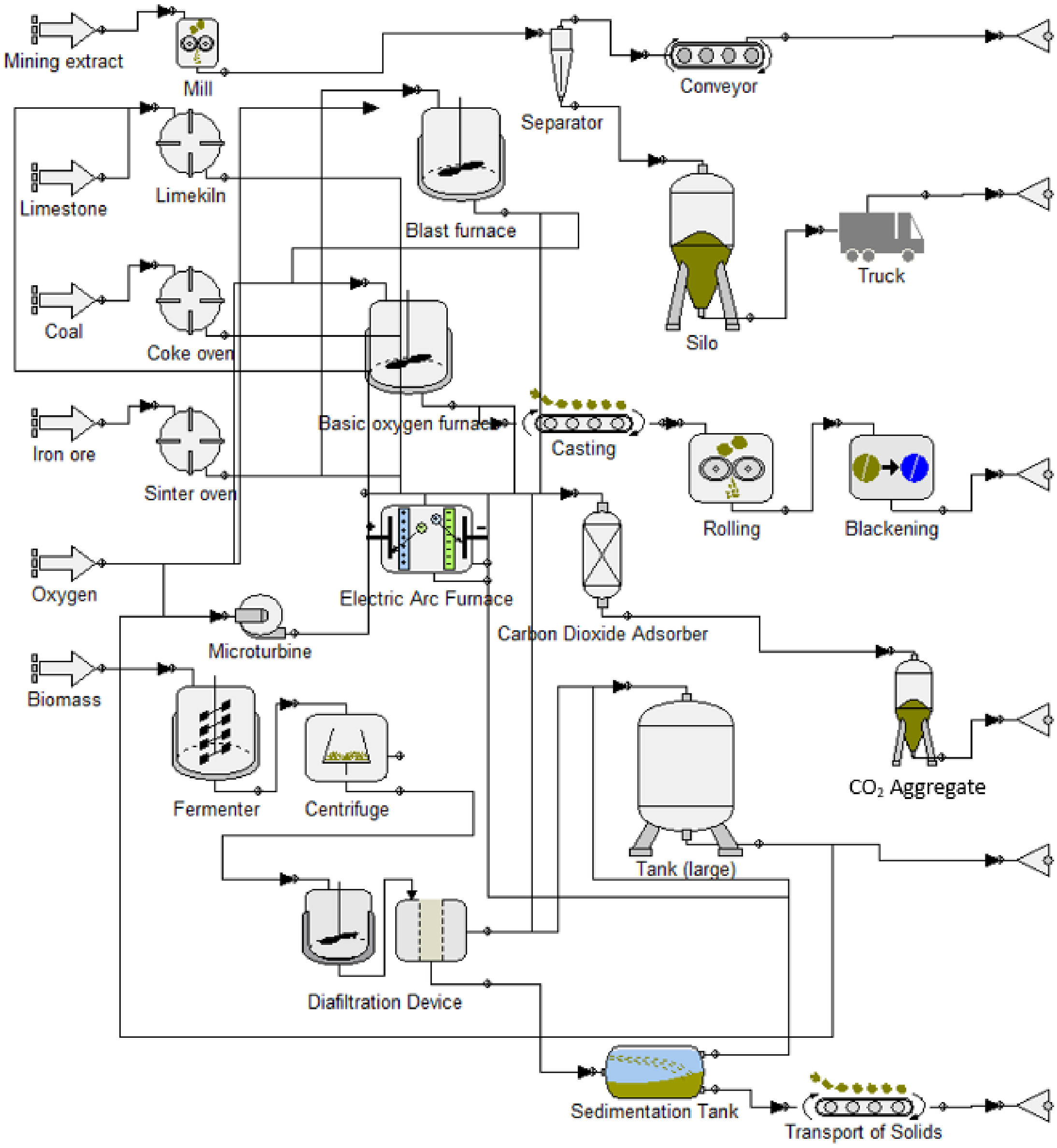

Figure 3. INOSIM configuration mining to marketing with CCUS.

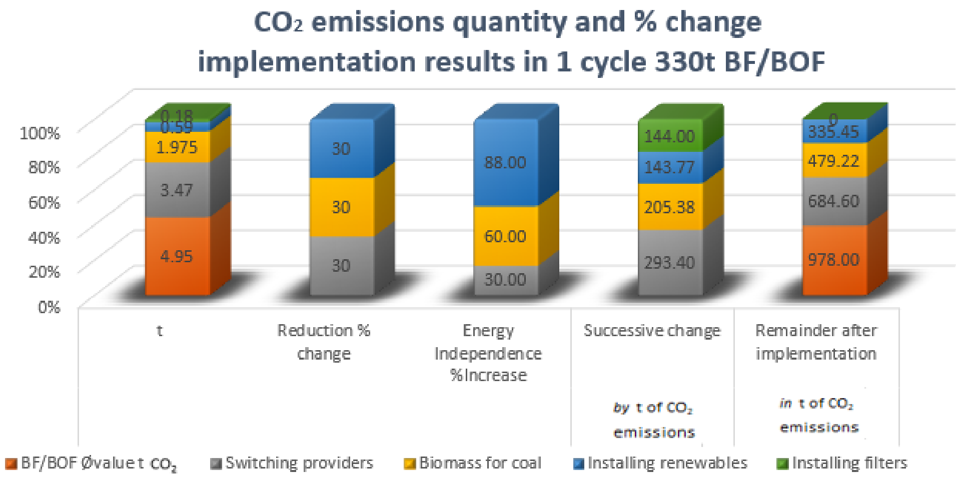

Figure 4. CO_2 emissions change in tonnes (t) with CAT and CCUS implementation.

The CO_2 reductions concerning a 330-t blast furnace vessel have been modelled in three separate process simulation software packages and have been carried out considering the production parameters of the British Steel Scunthorpe site. Having implemented steps of the Bio Steel Cycle model and strategy, the findings of this research show a CO_2 emissions reduction of ~30% from 977 t of CO_2 to 684 t in one single blast furnace production cycle (based on 330 tonnes of liquid iron production capacity that mean 2.1–3.2 tonnes CO_2/t of steel), by switching the electricity provider for operating the electric heaters to providers generating energy exclusively from renewable sources and replacing coal with biomass added carbon neutrality into the process. Adding post-combustion capture units to the blast furnace resulted in CO_2 emissions reduction to near-zero. Carbon capture from biomass utilisation (BECCS) also added the benefit of carbon-negative emissions to the cycle (Figure 2).

The process simulations and carbon reports in Simul8 demonstrate 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 (Microsoft 365, 2020 version, on Windows 10) modelling, the mathematical formulation and calculations, and Simul8 (version 2020) process simulation were utilised by producing configurations in Aspen (V12.1) and INOSIM (Expert Edition 13.0), as displayed in Figure 3.

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 were 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 is further elaborated on in the following text; the summary results are shown in Figure 4.

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

The first column demonstrates the emission levels in metric tonnes (t) as per legend underneath from BF/BOF average value in CO_2 emissions, the reduced level of CO_2 emissions after switching to an energy provider deriving their energy at 100% from renewable sources, the reduced level of CO_2 emissions after replacing coal with biomass in the BF, the reduced level of CO_2 emissions after installation of renewable energy technologies (solar, wind, hydro as appropriate), and the reduced level of CO_2 emissions after the installation of post-combustion CO_2 emissions filters. The second column shows the individual percentage proportion in reduction as a result of implementation. The third column shows the successive percentage increase in energy independence. The fourth column shows the successive change in CO_2 emissions in t, based on one cycle of a 330 t BF/BOF process. The fifth column shows the remainder of the CO_2 emissions after successive implementation of the suggested technologies—resulting in 0.18 t of CO_2 emissions but displaying as 0 due to set software parameters, after successful installation of post-combustion CO_2 filters at the individual sites of off-gas outlets.

2.1. Heat Loss Recovery—Energy and CO_2 Saving Protocols

Already since the 1990s, scientists were convinced [25] 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) [25]. 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% is lost due to inefficiencies and deficits within the production and processing infrastructure. The strategy for making existing infrastructure more efficient is to (a) upgrade the existing energy infrastructure, (b) reduce energy/heat loss by improving energy efficiency with focused energy utilisation, and (c) capture and re-utilise lost energy/heat.

The technologies utilised for the strategy points a–c, are as follows:

(a) Repair energy/heat escape points and insulate as a preventive measure;
(b) Using the most focused technology: instead of the BF/BOF-route, using the BF/EAF route for steel production;
(c) Installation of baffles, plate heat exchangers, and other energy/heat-capturing technology where technically feasible.

On a practical level, this means insulation of the heat-bearing infrastructure (furnaces and pipework). Via a connected network of pipes and lines, the energy or heat captured 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 [26] of CO_2—including land use and fossil CO_2—will remain relatively high at 40.5 Gt CO_2 in 2022, but still below their 2019 peak of 40.9 Gt 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 [1,8,27–29], 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 [1,8,27–29].

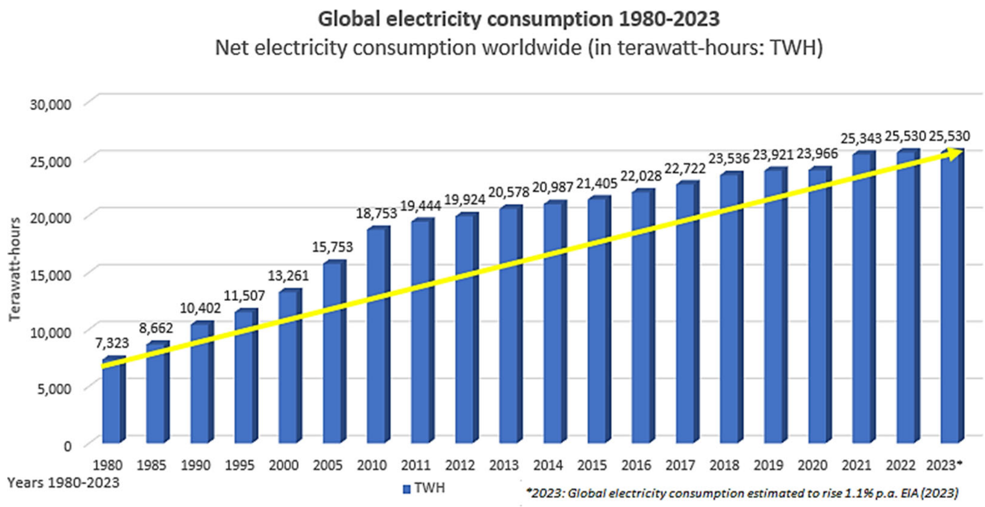

Figure 5. Global electricity consumption 1980–2023 [1,5,8,27–29].

As far as energy security and greater energy independence are concerned, these energy savings are set to avoid having to produce almost 30 million barrels of oil—per day (three times Russia's average annual production, based on 2021 data), and 650 billion m^3 of natural gas per year—around four times of EU imports from Russia in 2021. 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 [30], there is still a substantial amount of electricity that could be saved (Figure 5). Additionally, this would render the existing infrastructure 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.

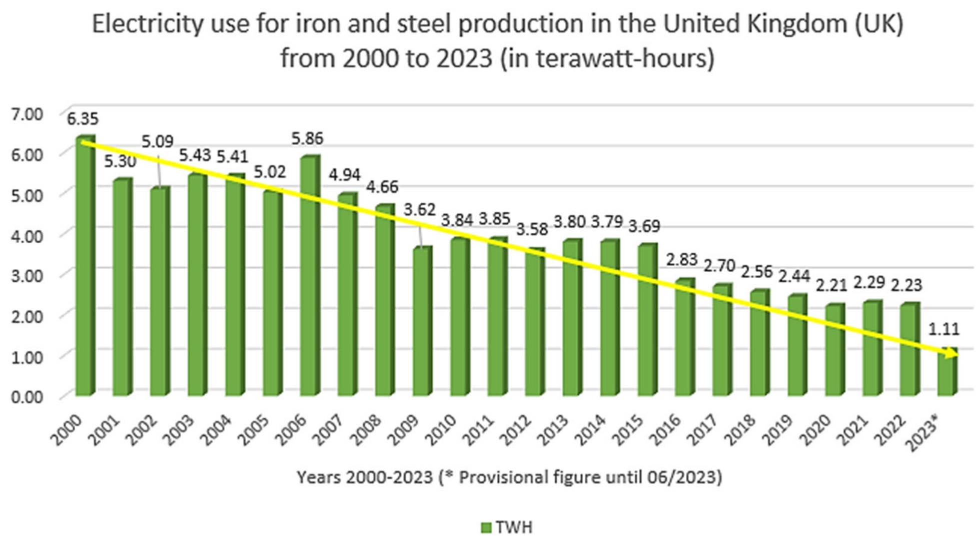

Figure 6. Electricity use iron/steel industry from 2000–2023 [29,30].

Simultaneously, it could be utilised to (a) capture >98% [31] of CO_2 emissions, use the captured CO_2 in ancillary industries, and (b) install 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 [1,8,27]. 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. The 2023 figures are provisional, as the reported figures are yet to be confirmed—hence the *. In stark contrast, quite the opposite observation was made for global electricity consumption [1,8,27] 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 [28,32] (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 [7,28,29]—therefore, establishing China as the second-largest 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. [7,28,29]. 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, that this is 30% of the energy that the 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 [4,14,28–33]. Solar, wind, geothermal, and hydropower are well-established technical solutions [4,14,28–33], which have already been successfully implemented in a range of countries and settings [34–39]. In the UK, there are a range of schemes accessible to businesses, such as finance and support from the Department for Business, Energy and 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 [4,30,32]—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 [14,27,28,30,40–42]. 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 that is deriving their energy 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 [43,44]. Additionally, the same applies to wind turbines, technology generating electricity using either biomass or hydro-turbines (water-based), and anaerobic digestion (AD) systems. The following Table 1 shows the relevant schemes and their descriptions, mostly detailing how the different technologies could potentially qualify for the individual schemes. 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, and viability with an outlook over the next 30 years. The accurate potential return on investment (ROI) can only be determined for every individual site, as the current contracts with energy providers are one of the determining factors and the authors have not been privy to this kind of information.

Table 1. UK support schemes for 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 GBP 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 on how to reduce emissions. A GBP 400,000 grant fund has been established to help capital investment projects deliver 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, or sole traders).
Green Gas Support Scheme	Funding support for biomethane injection to the national grid.
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	SME Energy Efficiency Scheme (SMEES): 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, save money and cut waste.
Horizon Europe funding	Funding for research or innovation that is groundbreaking, 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.

Some technical solutions for achieving a higher degree of energy independence have been intensely researched [23,45–48] and implemented in a range of industrial sectors. Projects containing components such as direct air capture (DAC), re-directing heat and utilising anaerobic digesters to produce biogas (methane and hydrogen), and producing energy on-site with suitably sized turbines [49] 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 [44]. 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 MCDA in Table 2 includes 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. Projections for policy making, return over investment (ROI), or how this could lead to the development of new incentives in the realm of renewable energy and sustainable industrial practices was not the substance of this research. 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 A	100% renewable energy
2	Installing renewables: solar	Solar PV panels	Internal contracts	1 kWh/4 panels = 25,667 panels
2	Installing renewables: wind	Horizontal axis w. turbine	Norvento nED100	100 kW/£317,655.27 × 65
2	Installing renewables: wind	Horizontal axis w. turbine	Enercon E53	800 kW/£807,581.80 × 8
2	Installing renewables: wind	Horizontal axis w. turbine	EWT DW61	1 MW/£981,368.75 × 6
2	Installing renewables: wind	Horizontal axis w. turbine	Enercon E82	3 MW/£1,829,271.35 × 3
2	Installing renewables: wind	Horizontal axis w. turbine	Enercon E126 EP3	3.5 MW/£2,458,302.00 × 2
2	Installing renewables: wind	Vertical axis wind turbine	Patriot Modular	70 kW/£188,196.00/ × 92
2	Installing renewables: hydro	Small closed-loop system	Helios Atlas	6.5 MW
3	Using biomass/green H_2	H_2ermes: H_2 from seawater	HyCC/Tata Steel	15,000 t 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 of 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	3300 t hot metal per day
7	Anaerobic digestion > biogas utilisation in steelmaking	Biogas and H_2 from anaerobic digestion	Biogen	Biogas production

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% [50]. 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%, 65.7%, and 88% [15,50]. 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 achieving a higher level of independence, at least by 30% and ideally, at 88%, and 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 steps 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 countries' governmental guidance will have to change dramatically [51,52] in order to meet the targets set by the Paris Agreement [53] and COP15 [52] and the dire warnings issued by the recent IPCC reports (2023) [54]. By improving their carbon capture and off-heat utilisation capabilities, and investing in renewable energy technology, businesses are:

- Supporting the decarbonisation of production;
- Reaching a higher degree of energy independence;
- Achieving a higher level of asset efficiency;
- Training workforce in required 'green' skills;
- Reducing their energy costs;
- 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 [34,40,55–63] and besides the iron and steel industry, there are other heavy industries that 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. There are currently globally 89 projects in process with the aim to achieve climate neutrality at the latest by 2050 [64].

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, including the UK. The opportunities are manifold, they merely require political willingness and implementation across all industries. The process simulations compiled within the systems S8, AspenV.12.1 and Inosim aligned with the mathematical analysis and modelling in MS Excel and provided almost matching reports, stating a reduction of 30% from 977 t of CO_2 emissions to 684 t of CO_2 flow in one single blast furnace production cycle (based on 330 tonnes liquid iron production capacity and a mean of 2.1–3.2 tonnes CO_2/t of steel and emissions from chemical reactions considered), by switching the electricity provider for operating the electric heaters to providers generating energy exclusively from renewable sources. Replacing coal with biomass added carbon neutrality into the process. Adding the post-combustion capture unit to the blast furnace resulted in a CO_2 emissions reduction to near zero. Carbon capture from biomass utilisation (BECCS) added the benefit of carbon-negative emissions to the cycle. 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%. Engineering solutions that are partly subsidised in the UK—as described in Table 1—are readily available for implementation in the iron and steel manufacturing industry. Furthermore, the application points of renewable energy technology within the steel production process were established where achieving a 30%, 49%, and up to 88% 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 that 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 CO_2 in the building industry (CCUS), agriculture (CEPS), chemical industry, food and drinks industry, and pharmaceuticals;
- Utilisation of waste products from steelmaking in infrastructural projects;
- Other GHG (CO, H_2) captured in TGRB, can also 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 available in the UK, not limited to:

- Adding solar foil, panels, tiles, and shingles to buildings and carparks;
- Adding a biogas, replacing fossil fuel, and a hydrogen network from anaerobic digestion for hydrogen direct reduction of iron ore (DRI) in steel production, in addition to reformers and electrolysers;
- Installing wind turbines at brownfield sites not suitable for human habitation;
- Developing filters and capture units to be retrofitted to existing production plants emitting GHGs.

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

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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
CH_4	Methane CCS—carbon capture and storage
CO_2	Carbon dioxide
DRI	Direct reduced iron
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)
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 performed by the system; W is the sum of all work performed on/by the system
WTO	World Trade Organization
ΔU	Change in internal energy U of the system
Ø	Sign for average

Appendix A

Table A1. UK green energy providers.

Energy Provider	UK Headquarters Address	Renewable Sources	Green Electricity	Green Gas	Carbon Offsetting
Octopus Energy, 2023	UK House, 5th floor, 164-182 Oxford Street, London, W1D 1NN https://octopus.energy/ (accessed on 23 January 2024)	Anaerobic digestion, solar, wind, hydro	100%	0%	Yes
Green Energy UK, 2023	Green Energy (UK) plc Black Swan House, 23 Baldock Street Ware, Herts, SG12 9DH https://www.greenenergyuk.com (accessed on 23 January 2024)	Hydro, solar, wind	100%	100%	No
OUTFOX The Market, 2023	16 North Mills, Frog Island, Leicester, Leicestershire, LE3 5DL https://www.outfoxthemarket.co.uk/ (accessed on 23 January 2024)	Wind	100%	0%	No
Ecotricity, 2023	Lion House, Rowcroft, Stroud, Gloucestershire, GL5 3BY https://www.ecotricity.co.uk/our-green-energy/green-electricity (accessed on 23 January 2024)	Wind (98%), solar (0.12%) and hydro (0.7%)	100%	Yes	Yes
OVO Energy, 2023	1 Rivergate Temple Quay Bristol BS1 6ED https://www.ovoenergy.com/ (accessed on 23 January 2024)	Anaerobic digestion 49%, solar 32%, wind 18%, hydro 1%	100%	15%	Yes
Good Energy UK, 2023	Monkton Park Offices, Monkton Park Chippenham SN15 1GH https://www.goodenergy.co.uk/our-energy/electricity/ (accessed on 23 January 2024)	49.41% = Wind. 32.71% = Bio generation. 13.60% = Solar. 4.28% = Hydro	100%	No	Yes
SSE Energy Solutions, 2023	Inveralmond House, 200 Dunkeld Road, Perth PH1 3AQ https://www.sseenergysolutions.co.uk/business-energy/our-renewable-electricity (accessed on 23 January 2024)	Hydro plants and wind farms	100%	No	Yes

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