Environmental Impacts of Alternative Reductants in Blast Furnace Ironmaking in the UK

by

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DEDICATION

To my husband, whose quiet sacrifices, kindness, and constant belief carried me more than you will ever know.

To my daughter, Sofia, whose resilience and bright spirit remind me every day of the joy of being a mother.

To my son, Daniel, whom I welcomed during my second year of this EngD - you arrived at the busiest moment of my life, yet you became the reason I found the strength to finish.

This thesis is for all of you, with all my love.

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I am also sincerely grateful to Dr Pete Hodgson (Tata Steel UK), Dr Stuart Walker, Professor Pete Holliman, and the Sheffield LCA Focus Group for the invaluable insight, expertise, direction and constructive feedback that strengthened this thesis.

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ABSTRACT

The steel industry contributes approximately 8% of global CO_2 emissions, with blast furnace operations accounting for the majority within integrated steelmaking. Although the United Kingdom plans to transition toward electric arc furnace technology, this pathway faces constraints including high electricity prices, limited high-quality scrap availability, and long infrastructure timelines. Therefore, blast furnace ironmaking will remain important in the medium term. No previous study has provided a UK-specific environmental and economic comparison of solid and gaseous reductants within a single framework, which defines the research gap addressed in this thesis.

This research evaluates the environmental, economic, and practical feasibility of charcoal, switchgrass, grey hydrogen, and green hydrogen relative to a conventional coke and pulverised coal baseline. A cradle-to-gate life cycle assessment was conducted for one tonne of hot metal across five midpoint impact categories: global warming potential (GWP), land use, fossil resource scarcity (FRS), water consumption, and mineral resource scarcity. This was supported by data quality evaluation and sensitivity analysis. A simplified economic assessment was performed for charcoal and green hydrogen.

Results show that charcoal reduces GWP by 11% and FRS by 25% but increases land occupation threefold. Green hydrogen reduces GWP by 10% without land pressure but increases water consumption by 17%. Grey hydrogen performs worse than the baseline, while switchgrass provides only marginal improvements. All scenarios achieved a pedigree matrix score of 15 or below, indicating robust data quality. Economically, the baseline remains the lowest-cost option. Charcoal is more expensive due to imported feedstock but offers a lower cost per tonne of CO_2 avoided than green hydrogen, which remains the most costly despite future cost reduction potential.

The findings suggest a phased decarbonisation strategy for UK blast furnace ironmaking, combining immediate operational improvements, short term adoption of certified charcoal, and medium to long-term deployment of hydrogen-based and carbon capture solutions.

CONFERENCES AND RESEARCH OUTPUTS

Conferences and Events-Participation

Year	Event	Location
2024	Conference of Parties, COP29	Baku, Azerbaijan
2024	UKRI SUSTAIN Steel Conference	Swansea, United Kingdom
2024	STEM Outreach Event Presenting Steel Decarbonisation	Sheffield, United Kingdom

Conferences and Events-Presentation

Year	Event	Location	Notes
2025	UKRI SUSTAIN Task Update	Warwick, United Kingdom	Oral Presentation
2024	SETAC Europe 26th LCA Symposium	Gothenburg, Sweden	Poster Presentation
2024	SETAC Europe 34th Annual Meeting	Seville, Spain	Poster Presentation
2023	UKRI SUSTAIN Task Update	Sheffield, United Kingdom	Oral and Poster Presentation
2023	Slow Burn FRINGE COP28	Sheffield, UK	Poster Competition (Won 1st Place)
2023	14th Advanced Metallic CDT Conference	Sheffield, UK	Oral Presentation
2022	13th Advanced Metallic CDT Conference	Dublin, Ireland.	Poster Presentation

Interview and Publications

Year	Title	Outlet
2025	Article in UKRI SUSTAIN Steel Annual Report	SUSTAIN Annual Report 2024/2025
2024	2nd Interview with Rei Takver – COP29 Reflection	*Now Then Sheffield*
2024	1st Interview with Rei Takver- Steel Decarbonisation	*Grantham Centre Sheffield COP Representative Report*

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ACRONYMS

ACRONYM	DESCRIPTION
AF	Alternative Fuel
APOS	Attributional, Product, System model (Ecoinvent)
BECCS	Bioenergy with Carbon Capture and Storage
BF	Blast Furnace
BF-BOF	Blast Furnace–Basic Oxygen Furnace
BOF	Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DR-EAF	Direct Reduction–Electric Arc Furnace
DRI	Direct Reduced Iron
DRI-EAF	Direct Reduced Iron–Electric Arc Furnace
EAF	Electric Arc Furnace
ESP	Economic Scarcity Potential
ETS	Emission Trading Scheme
EUR	Euro
Fe	Iron
FRS	Fossil Resource Scarcity
GBP	Great British Pound
GHG	Greenhouse Gas
GJ	Gigajoule
GLO	Global (Ecoinvent location tag)
GOV	Government
GWP	Global Warming Potential
H_2	Hydrogen
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
IEA	International Energy Agency
IETF	Industrial Energy Transformation Fund
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LKAB	Luossavaara-Kiirunavaara AB
LU	Land Use
MJ	Megajoule
MRS	Mineral Resource Scarcity
O2	Oxygen
PC	Pulverised Coal
PCI	Pulverised Coal Injection
RAFT	Race Adiabatic Flame Temperature
RDF	Refuse-Derived Fuel
RoW	Rest of World (Ecoinvent location tag)

SR-BOF	Smelting Reduction–Basic Oxygen Furnace
SRF	Solid Recovered Fuel
SSAB	Swedish Steel AB
UK	United Kingdom
US	United States
USD	US Dollar
eq	Equivalent
kg	kilogram
kg Cu eq	kilograms of copper equivalent
kg oil eq	kilograms of oil equivalent
m^3	cubic metre
tHM	tonne of Hot Metal

CHAPTER 1

1.0 INTRODUCTION

This chapter introduces the background and context of blast furnace ironmaking in the United Kingdom and explains why the sector remains strategically crucial during the transition to low carbon steelmaking. It outlines recent developments at Port Talbot and Scunthorpe and discusses the drivers that shape national decarbonisation efforts. The chapter then presents the research questions and motivation before explaining the practical relevance of the research.

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1.1 Background and Context

In 2022, the global iron and steel industry emitted approximately 3.6 billion tonnes of CO_2, associated with the production of 1,885 million tonnes of crude steel globally (World Steel Association, 2023). Among the various steelmaking routes, the blast furnace/basic oxygen furnace (BF-BOF) method remains dominant, and contributes about 70% of CO_2 emissions to the integrated steel plant (Mousa et al., 2016; Fan et al., 2021). As of 2024, an estimated 1535 blast furnaces were operational across 54 countries (Global Energy Monitor, 2024). Despite its high carbon intensity, numerous studies have highlighted that the blast furnace process holds significant potential for decarbonisation through alternative reductants and process innovations to achieve environmental sustainability (Suopajärvi et al., 2013, 2018; Suer et al., 2022a; Leão et al., 2023).

In the UK, approximately 95% of steelmaking emissions come from Scunthorpe and Port Talbot steelmaking plants (UK Parliament, 2023). Together, these plants operated four blast furnaces; two located at Port Talbot, owned by Tata Steel, and another two at Scunthorpe, owned by British Steel (GMB Union, 2024). Tata Steel UK shut down Blast Furnace 5 at Port Talbot in July 2024, and subsequently ceased operations of Blast Furnace 4 in September 2024 (Hill, 2024). The closures are linked to the plan to transition to a fully electric arc furnace (EAF) steelmaking route, and for installing new an electric arc furnace (EAF) at Port Talbot by 2027 (S&P Global, 2024).

Although scrap-based EAF steelmaking offers significantly lower CO_2 emissions, typically 0.69 tonne CO_2/tonne of crude steel, compared with 2.34 tonne CO_2/tonne of crude steel via the BF-BOF route, a complete and immediate transfer to EAF in the UK faces several barriers (World Steel Association, 2025). First, EAF production depends heavily on high-quality scrap steel as its primary metallic input. While the UK produces significant quantities of scrap annually, global scrap availability is insufficient to displace primary steelmaking on a large scale. The World Steel Association estimates that the scrap steel supply can meet only a fraction of projected steel demand (World Steel Association, 2021). Second, EAF operations are highly dependent on electricity prices. UK industrial electricity prices are already among the highest in Europe, and therefore affect the economic viability of large-scale EAF operation (UK Steel, 2023; Fortune Business Insights, 2024). Third, EAF-produced steel tends to contain higher residual element concentrations, such as copper and other impurities trapped in the scrap pool, which limits its suitability for applications requiring ultra-low residual content (UK Steel, 2026). In addition, the closure of the blast furnaces has impacted the availability of blast furnace top gas for energy recovery, requiring four natural gas boilers to compensate for the lost energy supply, as informed by a University of Swansea expert familiar with Port Talbot’s operational changes.(Holliman, 2025). Besides, decarbonising the BF process represents a necessary pathway, as confirmed by the continued operation of BF at Scunthorpe following government intervention in 2025 (GOV.UK, 2025a). Collectively, these barriers indicate reasons why blast furnace ironmaking remains strategically crucial for the UK steel sector in medium term, even as the transition towards EAF technology is in progress.

Globally, the steel industry is exploring multiple decarbonisation pathways to meet the Paris Agreement target of achieving net-zero emissions by 2050. Options include increasing scrap usage (BOF), improving efficiency, co-firing hydrogen, substituting coking coal with biomass, retrofitting facilities for carbon capture and storage (CCS), and hybrid approaches that combine these measures (Rumsa et al., 2025). Much of the existing literature has focused on regions such as Australia, Brazil, Poland, Sweden, and Italy (Norgate et al., 2007; Burchart-Korol, 2013; Renzulli et al., 2016; Leão et al., 2023). However, the UK context is notably absent from the literature, despite undergoing a major industrial transformation and facing increasing policy and societal pressure to decarbonise. This research is based on an integrated steel plant in the UK, a significant point source of industrial CO_2 emissions and regarded as broadly representative of domestic integrated steel production.

1.2 Research Questions and Motivation

The primary aim of this research is to evaluate the potential of alternative reductants to support decarbonisation of blast furnace ironmaking in the UK. This research aims to provide a UK case study-based assessment that integrates environmental performance, economic feasibility, and practical deployment strategies. The study focuses on four core questions listed as follows.

- **RQ1: Research Question 1 (Scoping)**:
  - Which alternative reductants are sufficiently relevant, technically plausible, and supported by available literature to justify comparative assessment for UK BF ironmaking?
- **RQ2: Research Question 2 (Environmental)**:
  - How do charcoal, switchgrass, grey hydrogen, green hydrogen perform environmentally when they partially substitute coke and pulverised coal in UK blast furnace ironmaking, compared with a conventional coke and pulverised coal baseline?
- **RQ3 :Research Question 3 (Economic):**
  - For the alternative reductants that demonstrate environmental advantages over the conventional blast furnace baseline, what are the associated reductant costs and costs per tonne of CO_2 avoided? To what extent do these factors indicate early-stage economic feasibility within the current UK market?
- **RQ4: Research Question 4 (Implementation):**
  - Based on the comparative environmental and economic results, what practical options exist to deploy the use of most promising alternative reductants in UK blast furnace operations?

This research is fundamental to the steel industry as it bridges several critical gaps. First, it provides an integrated assessment of both solid and gaseous alternative reductants within a single comparative framework. Many prior studies have considered these alternative reductants in isolation or focused exclusively on either technical, environmental, or economic factors. Second, it utilises LCA as a holistic tool, supported by systematic data quality evaluation and sensitivity testing to ensure results are both comprehensive and robust. Finally, this research addresses a significant regional gap by focusing specifically on the UK context at a time of rapid transformation and change that happens in the steel industry.

1.2.1 Key Terminology

Throughout this thesis, the following terms are defined and used uniformly to ensure clarity and consistency. In particular, the term "alternative reductant" is defined explicitly as a partial substitute rather than a full replacement of coke, because all scenarios still retain coke as dominant reductant.

The terms used in this thesis are summarised in Table 1.

Table 1: Key Terminology

Preferred Term	Alternative Term	Definition
Hot metal	Pig iron, molten iron	The iron-carbon product tapped from the bottom of blast furnace at approximately 1450-1550°C, containing 94-95% iron and 4-5% carbon. This is the functional unit for all LCA scenarios.
Reductant	Reducing agent, fuel	Any carbon or hydrogen-bearing material used to chemically reduce iron ore to metallic iron in the blast furnace. This includes both primary reductants (coke) and auxiliary reductants (PCI, charcoal, hydrogen).
Alternative reductant	Alternative fuel (AF), bio-reductant, substitute reductant	Any non-conventional reductant used as a partial substitute for pulverised coal injection (PCI) or coke within blast furnace operation. In this thesis, 'alternative reductant' refers specifically to partial substitution scenarios in which coke remains the primary reductant. This includes charcoal, switchgrass, and hydrogen
Blast furnace top gas (BFG)	Top gas, BF gas	The gaseous co-product recovered from the top of the blast furnace, composed primarily of CO, CO_2, N_2, and H_2, used for energy recovery.
Blast furnace slag	Slag, Ground granulated blast furnace slag (GGBS)	The non-metallic co-product from the blast furnace, primarily used as a clinker substitute in cement production

1.3 Research Novelty

This research delivers a novel, first UK-contextualised integrated assessment of both the environmental and economic feasibility for alternative reductants in blast furnace ironmaking. Although several studies conducted worldwide have examined either biomass or hydrogen-based reductants in regions such as Canada, Brazil, and Germany (Ng et al., 2010; Yilmaz et al., 2017; Leão et al., 2023), no equivalent assessment has been done in the United Kingdom despite the significant industrial transitions underway at Port Talbot and Scunthorpe.

This research directly aligns with the objectives of the UK Net Zero Steel Strategy 2023-2025 which urges for development of a low-carbon ironmaking pathway that retain national capacity and expedites emissions reduction in steel industry (UK Government, 2025a). Therefore, this research directly responds to the need for a UK-focused evaluation that reflects domestic supply-chain and policy conditions.

Moreover, this research enables simultaneous and harmonised comparison of both solid and gaseous alternative reductants within a single framework. Existing literature has generally assessed these reductants in isolation or has utilised different assumptions that limit comparability across studies. The assessment of charcoal, switchgrass, grey H_2, and green H_2, alongside conventional coke and pulverised coal, provides a transparent and consistent evaluation of their respective advantages and constraints.

Additionally, this research presents an integrated approach that combines environmental and economic assessments within a single, cohesive evaluation. Life cycle assessment (LCA) was utilised as the primary analytical tool to assess the environmental performance of all scenarios in accordance with ISO 14040 and ISO 14044 standards (International Standard Organisation, 2022a, 2022b). The LCA findings were subsequently linked to an economic evaluation for the most promising reductants. This dual assessment addresses a gap in the literature where simultaneous environmental and economic assessments are often evaluated separately or not at all.

The robustness of this research is further enhanced by a systematic evaluation of data quality using the pedigree-matrix method (Ciroth et al., 2016), complemented by a structured, sensitive analysis of key assumptions. Critical factors, including coke sourcing, transport distances, iron-bearing material mixes, and biomass datasets, were examined to ensure the robustness and transparency of the results. This level of scrutiny represents a notable advancement in steel and iron-related LCA, where considerations of data quality and sensitivity are seldom addressed in such a consistent and explicit manner.

This research is also shaped by rapid policy developments that are altering the cost structure of the UK steel sector. The UK Government has confirmed the introduction of a domestic Carbon Border Adjustment Mechanism (CBAM) by 2027 that target emission-intensive imports including iron and steel (UK Government, 2025b). At the same time, the UK Emissions Trading Scheme will start to be stricter from 2027 and is expected to reduce further by 2030, therefore exposing more emissions to the carbon price. These changes aim to protect against carbon leakage and form a fair environment for domestic producers. As a result, these measures are expected to strengthen the commercial rationale to adopt low carbon technologies such as hydrogen and biomass reductants in blast furnace ironmaking. Hence, it is crucial to assess the technical feasibility, cost competitiveness, and readiness within UK context.

In parallel, this research also connects the environmental and economic findings within the evolving UK policy landscape for industrial decarbonisation. The interpretation highlights the implications of national policies such as the UK Biomass Strategy (Department for Energy Security & Net Zero, 2023a), the Low Carbon Hydrogen Standard (Department for Energy Security & Net Zero, 2023b), and the planned CBAM (UK Government, 2025b). This integration enhances the practical relevance of this research by demonstrating how current and emerging policy drivers influence blast furnace decarbonisation.

Furthermore, this research proposes a phased and hybrid decarbonisation pathway that aligns the deployment of alternative reductants with regional source availability, infrastructure readiness, and evolving market conditions in the UK. This approach moves beyond the conventional single reductant substitution and promotes more adaptive steps that are more feasible for the UK steel sector.

In summary, the originality of this research lies in its UK-specific, practically relevant assessment of alternative reductants for blast furnace ironmaking at a time of significant industrial transformation. Therefore, this research constitutes a novel and practically relevant contribution to the field of ironmaking decarbonisation.

CHAPTER 2

2.0 LITERATURE REVIEW

This chapter reviews the existing literature on steelmaking routes, blast furnace operation, and the technical roles of reductants. It examines UK policy development that influence decarbonisation pathways and evaluates the current knowledge on alternative reductants. The chapter also summarises the main findings from life cycle assessment studies in steelmaking and ironmaking before identifying the gaps that this research addresses.

2.1 Steelmaking and Blast Furnace Process

2.1.1 Global Steel Production Trends

Steel is a vital material that plays a crucial role in modern societies. Steel is primarily composed of iron and contains up to 2% carbon. Steel has been widely used in various applications, including construction and infrastructure, automotive, household products, the medical sector, and the renewable energy sector. Steel demand has steadily increased, consistent with industrial growth over the past few centuries. Figure 1 illustrates that global crude steel production has risen significantly between 1950 and 2023. According to World Steel Association data, global crude steel production reached 1892 million tons in 2023, nearly 10 times the output of 1950 (World Steel Association, 2024).

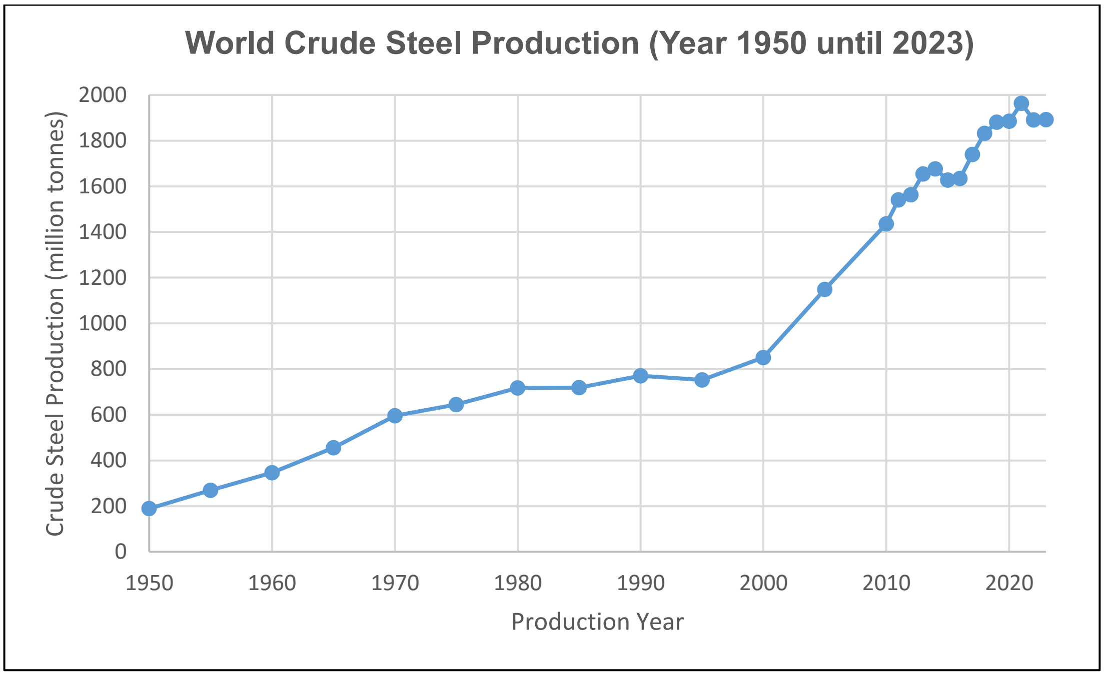

Figure 1: Global Crude Steel Production Trends from 1950 to 2023 (World Steel Association, 2024)

2.1.2 Steelmaking Routes and Emissions Intensity

As shown in Figure 2, there are four established routes for steel production: blast furnace/basic oxygen furnace (BF-BOF), direct reduction/ electric arc furnace (DR-EAF), smelting reduction/ basic oxygen furnace (SR-BOF), and scrap melting in the electric arc furnace (EAF) (Mousa et al., 2016).

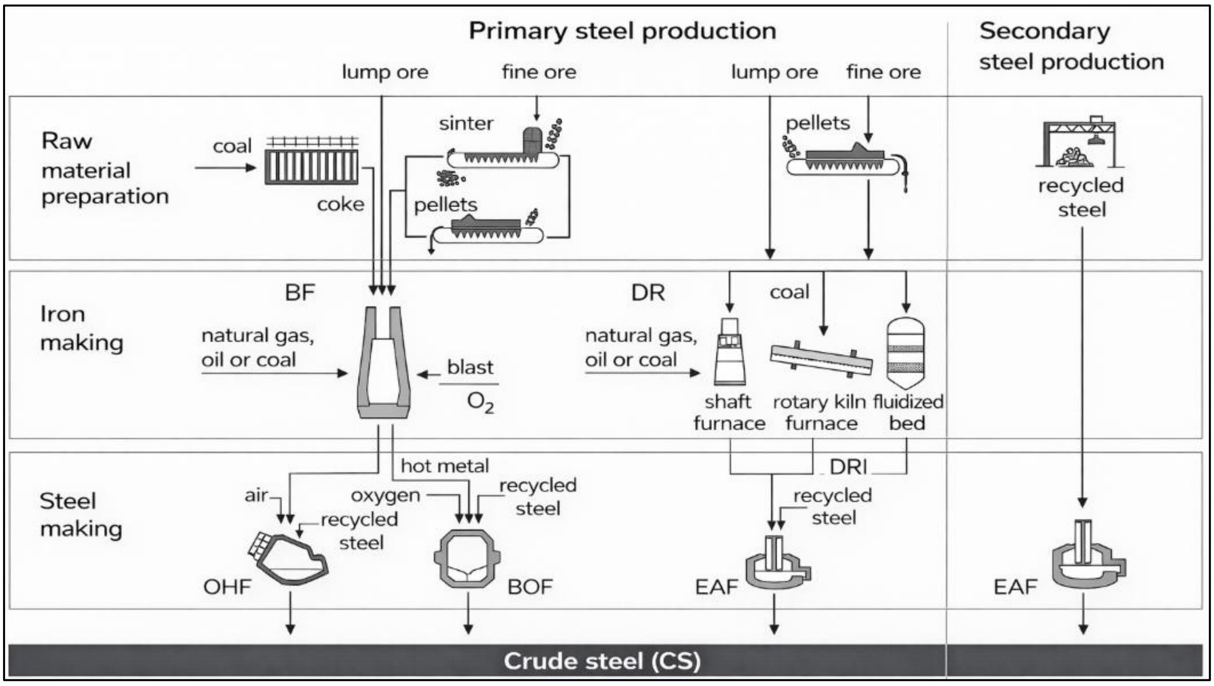

Figure 2: Process Flow and Energy Intensity of Primary and Secondary Steel Production (adapted from (Mousa et al., 2016).

In steelmaking, metallic inputs are primarily sourced from iron ore and recycled steel scrap. Figure 2 illustrates that steel production primarily uses iron ore as a metallic input, with approximately 20% steel scrap. Due to the reduction of iron ore using carbon-based reductant, the process is considered carbon-intensive. In contrast, EAF steel production relies heavily on scrap steel as metallic inputs and is regarded as more environmentally friendly (Suer et al., 2022a).

Among the established routes, BF-BOF is the most common route used in steelmaking, accounting for around 70% of world steel production. The EAF route constitutes around 25% of global steelmaking, while DR-EAF and SR-BOF routes comprise around 5% and 0.4% of global steel production, as summarised in Table 2 (Mousa et al., 2016). BF-BOF also contributes to the highest carbon emissions in steel production. Through this route, the CO_2 emissions are reported to range from 2.33 tonne CO_2/tonne of steel and specific energy consumption is around 20.99GJ/tonne of crude steel (World Steel Association, 2024). Hence, it is essential to decarbonise the BF-BOF route to reduce total GHG emissions in steel production.

Table 2: Global Steelmaking Routes and Their Share in Worldwide Production (Mousa et al., 2016)

Steelmaking Routes	Utilisation in Worldwide Steel Making (%)
Blast furnace/basic oxygen furnace (BF-BOF).	70
Electric arc furnace (EAF).	25
Direct reduction/ electric arc furnace (DR-EAF),	5
Smelting reduction/ basic oxygen furnace (SR-BOF),	0.4

2.1.3 CO_2 Emissions from Steelmaking Routes

Figure 3 illustrates the CO_2 emissions associated with steel production routes, including both conventional and non-conventional methods. The BF-BOF route emerged as the highest CO_2 producer. Moreover, the figure highlights that incorporating renewables into steel routes, such as DRI-EAF and Scrap-EAF, reduces CO_2 emissions compared to conventional processes. Furthermore, the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) route yields the least CO_2 at almost zero emissions. HYBRIT is a fossil-free steelmaking process developed by SSAB, LKAB, and Vattenfall in Sweden. The HYBRIT process utilises renewable hydrogen to make iron through the DRI process. The produced iron is then melted in the EAF, powered by electricity generated from renewable sources, making it almost emissions-free (HYBRIT, 2025).

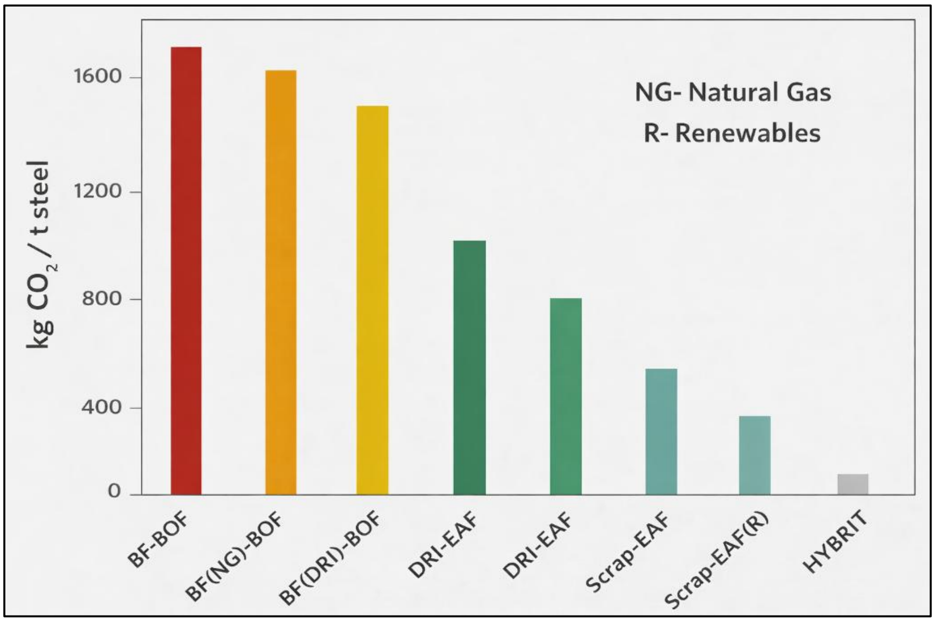

Figure 3: CO_2 Emissions per Tonne of Steel Across Different Production Routes (adapted from (Hornby et al., 2021)*.*

Since BF-BOF emerged as the most polluting route, as indicated in Figure 3, it is essential to find the primary emission source from this route. Data from Fick et al. revealed that the blast furnace contributed to the highest CO_2 emissions in the integrated BF-BOF route, at nearly 70%, as summarised in Figure 4 (Fick et al., 2014). This data highlights the importance of decarbonising the blast furnace process to reduce the total carbon footprint of the steel industry effectively.

Carbon emissions from BF-BOF steelmaking process

Process	Emission (kg-CO_2 per ton-HM)	Emission (kg-CO_2 per ton-HM)
BF	1,514	1,476
coke production	101	97
sintering	276	260
pelletizing	46	35
BOF steelmaking	229	193
total	2,225	2,061

Figure 4: CO_2 Emissions from the BF–BOF Steelmaking Route by Process Stage (figure adapted from Fick et al., 2014)

2.1.4 UK Policies on Industry Decarbonisation

Under the Climate Change Act 2008, the United Kingdom originally committed to reduce greenhouse gas emissions by at least 80 percent below 1990 levels by 2050. This Act was strengthened through The Climate Change 2008 (Order 2019), which amended the long – term target to a 100 percent reduction by 2050, thereby creating a legally net-zero commitment (UK Parliament, 2021). In response, the government has introduced several measures to decarbonise energy-intensive industries, including steelmaking. Among the various decarbonisation measures, biomass and hydrogen (H_2) have received particular attention as alternative energy carriers. However, policy instruments remain more mature and better developed for hydrogen than for biomass, particularly for blast furnace operations (UK Government, 2021a; Department for Energy Security & Net Zero, 2023a).

The steel industry is central to the UK's decarbonisation drive because steel is required for offshore wind turbine foundations, electric vehicle manufacturing, and construction to support the digital economy (UK Government, 2025a). In the UK, offshore wind alone is expected to require about 25 million tonnes of primary plate steel by 2050, representing a potential £21 billion market for UK steel (UK Steel, 2024).

The Biomass Strategy provides a national framework for the sustainable use of biomass for power generation, transport fuels, heating, materials, and industrial processes (Department for Energy Security & Net Zero, 2023a). It adopts a "best-use" principle by prioritising limited biomass resources for sectors with high abatement potential and also recognises the role of BECCS in achieving net removals of greenhouse gases (Committee on Climate Change, 2018; Department for Energy Security & Net Zero, 2023a). Although industrial biomass use is acknowledged, there is still no explicit pathway for metallurgical applications such as blastfurnace injection (Department for Energy Security & Net Zero, 2023a). Moreover, the strategy also highlighted sustainability safeguards by enforcing stricter life cycle greenhouse gas accounting, carbon-intensity limits, and chain-of-custody certification across future schemes (Department for Energy Security & Net Zero, 2023a). These requirements currently apply primarily to the power and heat sectors and have not yet been extended to the metallurgical biomass sector. This represents a lack of clear compliance and incentive mechanisms for steelmaking (Department for Energy Security & Net Zero, 2023a).

In the UK, local biomass availability is a significant constraint. In 2021, the UK imported approximately 9.1 million tonnes of wood pellets, primarily from the United States, with smaller volumes coming from Europe (Forest Research, 2022; Department for Energy Security & Net Zero, 2023a). The Climate Change Committee forecasted an increase in dedicated energy crop area to approximately 700,000 hectares by 2050. However, these are dependent on constraints from land competition, biodiversity, and food security (Department for Energy Security & Net Zero, 2023a). As a result, large-scale blast furnace biomass injection would still rely heavily on imported certified feedstock.

Furthermore, recent subsidy reforms have added further uncertainty. A company called Drax, which operates four biomass-fired units at its North Yorkshire power station, relies heavily on government subsidy support. The company went under scrutiny regarding the sustainability of the wood pellets imports it uses, the validity of certification schemes, and forest management practices in supplier regions. In February 2025, the UK Government announced the company's subsidy support will be reduced by roughly half over the 2027-2031 period (Committee of Public Accounts, 2025; Reuters, 2025). While these changes improve accountability, they increase risk, and the industrial biomass users will be required to meet stricter sustainability criteria as part of the policy changes.

At present, no dedicated UK policy supports biomass as a blast furnace reductant. The Industrial Energy Transformation Fund (IETF) offers competitive grants for energy-efficiency improvements, fuel-switching, and carbon-capture readiness in manufacturing, but does not prioritise metallurgical biomass (UK Government, 2021b). For the UK Emission Trading Scheme (ETS), eligible biogenic CO_2 is considered zero-rated for compliance purposes. However, there is no additional credit for biomass combustion unless the implementation is combined with carbon capture and storage or removal (Department for Energy Security & Net Zero, 2025). Therefore, the feasibility of near-term biomass injection in blast furnaces is relatively low, given the combination of limited domestic supply, stricter sustainability criteria, and the absence of sector-specific support.

By contrast, hydrogen policy in the UK is more established. The UK Hydrogen Strategy (2021) is implemented through the Hydrogen Production Business Model and the Net Zero Hydrogen Fund (Hydrogen UK, 2023). The industrial-cluster strategy further supports H_2 deployment. Clusters such as HyNet in North-West England and the East Coast Cluster in Teesside and the Humber integrate low-carbon H_2 production with shared pipeline networks, geological carbon dioxide (CO_2) storage, and co-located industrial users. (HyNet North West, 2025; UK Government, 2025c). This setup lowers infrastructure risk for plants in the clusters but could leave steelworks outside these hubs facing higher costs and logistical delays for H_2 supply and CCS access (UK Government, 2025c).

A Carbon Border Adjustment Mechanism (CBAM) is set to take effect in January 2027, covering emissions from carbon-intensive imports, such as iron and steel. CBAM could improve the competitiveness of low-carbon steelmaking, although issues remain regarding benchmark definitions, double-counting risks, and overlap with ETS obligations (UK Government, 2025b).

Despite progress, barriers remain for low-carbon steel technologies. UK industrial electricity prices are among the highest in Europe, which reduces hydrogen's cost competitiveness compared to fossil fuels. Schemes such as the British Industry Supercharger and the IETF provide partial relief, but long-term price stability for renewable electricity is unresolved (UK Steel, 2023). Moreover, the current steel-sector strategy prioritises large-scale transitions to electric-arc furnaces and hydrogen-based direct reduction, leaving limited attention to transitional steps, such as partial H_2 injection in existing blast furnaces (UK Government, 2025a).

In summary, UK policy provides a clearer long-term pathway for industrial decarbonisation via hydrogen and CCS, backed by defined funding and regional-cluster planning (UK Government, 2021a, 2025a). Biomass as a blast furnace reductant remains less supported, constrained by land availability, tighter sustainability rules, and shrinking subsidies for large-scale power biomass (Department for Energy Security & Net Zero, 2023a; Committee of Public Accounts, 2025). Overall, hydrogen aligns more closely with the national decarbonisation strategy, while biomass would need targeted incentives and stronger sustainability safeguards for large-scale metallurgical use.

2.2 Blast Furnace Operation

2.2.1 Overview of Blast Furnace Operation

The blast furnace (BF) is a counter-current shaft reactor that plays a critical role in integrated steelmaking. Its core purpose is to produce molten iron from iron ores, which is further processed into steel. In terms of material input, iron-bearing materials, coke, and fluxes are charged from the top of the blast furnace, while air is injected through tuyeres located at the lower part of the furnace (Geerdes et al., 2015; Cameron et al., 2019). Depending on the size of the BF, daily molten iron production ranges from approximately 4000 to 12,000 tonnes per furnace. The process is operated continuously with very high productivity, typically exceeding 95% availability.

As of March 2025, approximately 95% of global iron reduction is achieved via the BF route, with the remaining 5% contributed through the direct reduced iron (DRI) process (Global Energy Monitor, 2025a). Within the same year, over 1000 blast furnaces were in operation globally, offering a combined production capacity of 1475 million tonnes per year. Most of these blast furnaces are located in China (Global Energy Monitor, 2025b). Furthermore, Global Energy Monitor (2025a) reports that there are no plan to retire 89% of the operating blast furnace capacity, which strongly indicates the continued global reliance on the BF route.

2.2.2 Input and Output Streams

In typical operation, the burden is composed of alternating layers of sinter, pellets, lump ore, and coke. Pulverised coal (PC) is injected at the tuyeres along with a hot blast that is enriched with oxygen. Modern blast furnaces generally operate with coke rates between 286 and 320 kg/tHM and PCI rates of 170 to 220 kg/tHM. (Geerdes et al., 2015; Suopajärvi et al., 2018; Cameron et al., 2019). The main outputs include hot metal tapped at 1450 to 1550 °C, slag in the range of 150-300 kg/tHM, and blast furnace gas (BFG) at volumes of 1600-2000 nm3/tHM (Geerdes et al., 2015; Cameron et al., 2019)with an energy content of 3.5 to 5 MJ/m^3 (Musiał, 2020).

The material input and output streams involved in the production of one tonne of hot metal are presented in Figure 5.

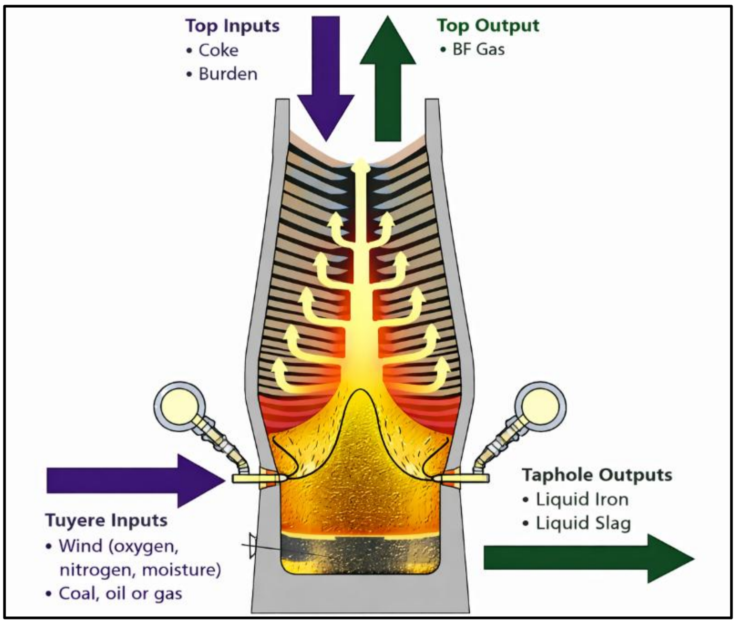

Figure 5: Inputs and Outputs of a Typical Blast Furnace (image adapted from Geerdes et al.,2015).

The typical quantities of material inputs and outputs required for producing one tonne of hot metal are summarised in Table 3.

Table 3: Typical Mass and Volume Flows of the Blast Furnace per tHM (Geerdes et al., 2015; Suopajärvi et al., 2018; Cameron et al., 2019)

Input/output	Quantity	Unit
Iron-bearing burden	1450-1600	Kg
Coke	286-320	Kg
Pulverised coal	170-220	Kg
Fluxes (limestone, dolomite)	200-250	Kg
Slag	150-300	Kg
Blast Furnace Gas	1600-2000	Nm^3

Iron-Bearing Materials

Iron oxides are primarily introduced as hematite (Fe_2O_3), which enters the blast furnace in the form of sinters, pellets, and lump ore. The physical appearance of the three main forms of iron-bearing materials is sinter, pellets, and lump ore, as illustrated in Figure 6 (Geerdes et al., 2015)

Figure 6: Physical Appearance of Iron-Bearing materials (Sinter, Pellets, and Lump Ore) (adapted from Geerdes et al., 2015)

The use of sinter is more prevalent in Europe and Asia, whereas pelletised burden is common in North America and Scandinavia (Geerdes et al., 2015). Lump ore, although cheaper, is of lower quality and is typically used in small proportions, around 10 to 15%. All iron oxide materials contain silica (SiO_2) and other impurities, and they differ in particle size, iron content and production methods as illustrated in Table 4 (Cameron et al., 2019).

Table 4: Properties and Production Methods of Iron-Bearing Burden Materials (Cameron et al., 2019)

Iron form	Mass of Fe (%)	Size (mm)	Production Method
Pellet	64	8-16	Produced by heating finely ground and beneficiated ore.
Sinter	57	10-45	Produced by heating non-beneficiated ore fines and other solids.
Lump Ore	62-67	50	Crushed for large pieces of iron ore to smaller size.

Coke

Coke is the second key material charged from the top and is produced by heating metallurgical coal in the absence of oxygen through a process known as pyrolysis. The process removes volatile matter, leaving a porous, carbon-rich material. The typical physical appearance of coke used in blast furnace operation is shown in Figure 7 (Geerdes et al., 2015).

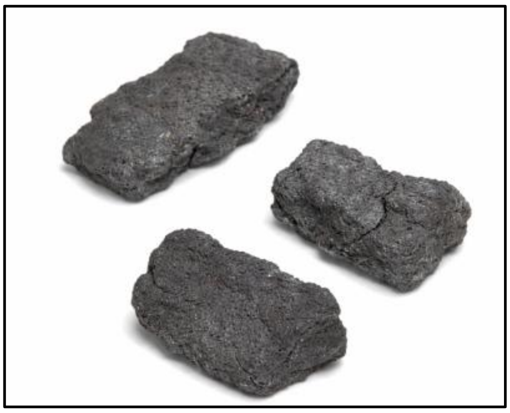

Figure 7: Physical Appearance of Coke (image adapted from Geerdes et al., 2015)

The typical diameter of coke is 50–60 mm. The coke has high thermal reactivity, adequate strength to avoid crushing inside the furnace, and the ability to combust rapidly at elevated temperatures. Furthermore, coke is indispensable not only because it serves as a fuel and reductant, but also because it forms a strong and porous matrix that ensures the permeability of the bed, allowing upward gas flow and downward liquid drainage (Geerdes et al., 2015; Suopajärvi et al., 2018; Cameron et al., 2019). This structural role makes coke irreplaceable in conventional blast furnace operation. To fulfil this function, coke must withstand temperatures exceeding 2000°C, compressive loads from the burden column, and chemical attack from CO_2 and alkali vapours without disintegrating (Geerdes et al., 2015; Cameron et al., 2019).

In addition to these physical roles, coke also plays thermal and chemical functions. Coke produces the heat needed for melting and providing carbon monoxide (CO) for the reduction of iron oxides. The carbon that dissolves into hot metal during this process is crucial for achieving the proper carbon content required for steelmaking. Auxiliary reductants such as pulverised coal, natural gas, and heavy oils are injected through the tuyeres to reduce dependence on coke. Among these, pulverised coal is the most widely used due to its lower cost, with coke priced at USD 250 per tonne and pulverised coal at USD 115 per tonne in 2017 (Cameron et al., 2019). The partial substitution of coke by pulverised coal reduces total operating costs. However, this substitution is limited because pulverised coal cannot replicate coke's structural role as a permeable load-bearing matrix, nor can it fully provide the carburisation function needed to enrich molten iron with carbon. For this reason, pulverised coal can only serve as an auxiliary reductant and must be injected through the tuyeres. Similarly, alternative reductants such as charcoal may reduce dependence on pulverised coal, but they cannot fully replace coke without altering the fundamental operation of the blast furnace. In the blast furnace, the combined burden-bearing, permeability, reducing, and carburising functions of coke emphasise its irreplaceable structural and chemical role (Geerdes et al., 2015; Cameron et al., 2019). To date, no other reductant has been able to simultaneously provide the permeability and carburisation functions required of coke.

The chemical composition of typical high-quality metallurgical coke, on a dry basis, is summarised in Table 5.

Table 5: Typical Chemical Composition of Metallurgical Coke on a Dry Basis (Cameron et al., 2019).

Element	Percentage in dry basis (%)
Fixed Carbon	87-92
Nitrogen	1.2-1.5
Ash	8-11
Sulphur	0.6-0.8
Volatile Matter	0.2-0.5

Fluxes

Fluxes are one of the raw materials and are introduced into the furnace, including limestone ($CaCO_3$) and dolomite, which decompose to produce CaO and MgO, respectively. These basic oxides combine with acidic impurities, such as silica and alumina, to form a fluid molten slag, which is tapped from the hearth along with molten iron.

Blast Furnace Products

The BF produces three key products, including molten iron (also known as hot metal or raw iron), slag, and blast furnace top gas (BFG) (Cameron et al., 2019).

Molten Iron

The main product of BF is molten iron. It is cast at 1500 degC through the tap hole located near the bottom of the BF. The typical elemental composition of hot metal tapped from the blast furnace is presented in Table 6.

Table 6: Typical Elemental Composition of Pig Iron (Cameron et al., 2019)

Elemental	Mass Percentage (%)
Iron (Fe)	94.4
Carbon (C)	4.5
Silicon (Si)	0.6

Mn (Manganese)	0.4
P (Phosphorus)	0.06
S (Sulphur)	0.03
Titanium (Ti)	0.01

Slag

The slag is produced in a blast furnace alongside molten iron. It contains only a minimal amount of iron, which is a key indicator of efficient blast furnace operation. Maintaining slag basicity within the range of 0.9 to 1.1 is vital to ensure that gangue materials from iron ore and coke ash are effectively removed. This basicity range also reflects the slag's capacity to absorb alkalis that may otherwise accumulate in the furnace, as well as sulfur, therefore preventing these impurities from being transferred into the molten iron. Once solidified, slag is commonly utilised in secondary applications such as road aggregate and cement production (Cameron et al., 2019).

Top Gas

The third primary output of the blast furnace is the blast furnace top gas (BFG), which exits the furnace through the top cones. BFG is typically recovered and reused within the plant to improve overall energy efficiency. Its applications include heating the blast furnace air, supplying heat to other furnaces across the steelworks, generating low-pressure steam, and producing electricity. The typical composition of BFG is presented in Table 7 (Cameron et al., 2019).

Table 7: Typical Volume Percentage Composition of Blast Furnace Gas (Cameron et al., 2019)

Gas	Volume (%)
Carbon Monoxide (CO)	23
Carbon Dioxide (CO_2)	22
Hydrogen (H_2)	3
Water (H_2O)	3
Nitrogen (N_2)	49

The significant volumes of slag and blast furnace gas produced as by-products in BF indicate that alternative reductants such as pulverised coal and heavy oil will influence not only direct CO_2 emissions, but also slag chemistry and energy recovery potential.

2.2.3 Reduction Mechanisms

Reduction is one of the key processes that occurs inside the blast furnace. It consists of a cascade of reactions across different thermal zones. In the upper shaft, indirect reduction predominates, where carbon monoxide (CO) and hydrogen (H_2) reduce hematite (Fe_2O_3) to magnetite (Fe_3O_4), then to wüstite (FeO), and finally to metallic iron. These endothermic reactions occur between 500 °C and 1150 °C and significantly contribute to the furnace heat balance (Geerdes et al., 2015). The reduction process inside BF is illustrated in Figure 8.

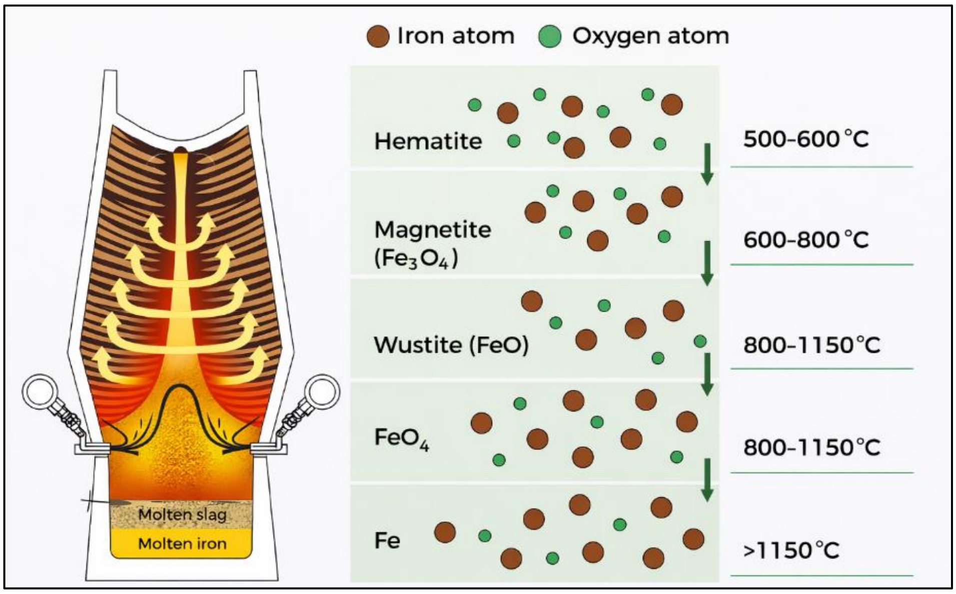

Figure 8: Schematic Presentation of Reduction of Iron Oxide and Temperatures
(image adapted from Geerdes et al., 2015)

As the burden descends into the cohesive zone, permeability decreases, and direct reduction of FeO by solid carbon becomes increasingly essential. This is facilitated by the Boudouard reaction ($CO_2 + C \rightarrow 2CO$), which is highly endothermic and generates CO to sustain reducing conditions. The combustion of coke and injected coal produces the raceway adiabatic flame temperature (RAFT), which must be sustained within 2000 to 2200 °C to provide sufficient thermal energy for both iron and slag melting, as well as overall reduction reactions. The principal chemical reactions that occur during blast furnace operation are listed in Table 8, along with their corresponding thermal effects (Geerdes et al., 2015; Cameron et al., 2019).

Table 8: Principal Chemical Reactions in the Blast Furnace (Geerdes et al., 2015; Cameron et al., 2019)

	Reaction	Description	Heat of reaction
1	C (solid) + O_2 (gas) ➔ CO_2 (gas)	Carbon is oxidised by air/oxygen to produce CO_2. This reaction happened in front of the tuyere and is highly exothermic.	-395 MJ/kg
2	CO_2 (gas) + C (solid) ➔ 2CO (gas)	The carbon dioxide (CO_2) reacts with carbon to produce carbon monoxide (CO). This is the principal reducing gas of the blast furnace, and the reaction is endothermic.	+165 MJ/kg
3	0.5Fe_2O_3 (solid) + 1.5 CO (gas) ➔ Fe (solid) + 1.5CO_2 (gas)	The reducing gas, carbon monoxide, reacts with hematite (Fe_2O_3) to produce solid iron. This reaction is exothermic.	-20 MJ/kg
4	Fe (solid) + C (solid) ➔ Fe (liquid) + C (alloy)	The reaction is followed by the formation of molten iron when solid iron (Fe) reacts with carbon. This reaction is exothermic.	NA

2.2.4 Impact of Injected AR on the BF Operation

In blast furnace operation, the injection of alternative reductants has played an essential role in improving the technical performance and commercial viability of ironmaking. From a technical perspective, injected reductants are mainly used to partially substitute coke and, therefore, reduce coke consumption. Although the general approach to inject auxiliary reductant through the tuyeres is similar across each reductant type, the operational impacts differ depending on the physical and chemical characteristics of the injected material (Cameron et al., 2019).

Several key process parameters determine the maximum permissible injection rate of alternative reductants. Firstly, the race adiabatic flame temperature (RAFT) needs to remain above the minimum value required to maintain stable reduction reactions. This value depends on reductant composition and the quality of raw materials introduced to the furnace. An adequate RAFT ensures the complete combustion of injected fuel and produces sufficient thermal energy to sustain gasification and reduction reactions in the lower furnace (Geerdes et al., 2015; Wang et al., 2015; Cameron et al., 2019).

Secondly, the increase in injection rate can raise the total gas volumes in the lower zones, thereby increasing the pressure drop across the burden and reducing permeability. This effect needs to be carefully managed through adjustments in burden distribution, particularly the layering of coke and iron ore to maintain uniform gas flow and prevent channelling (Geerdes et al., 2015; Cameron et al., 2019). Thirdly, the top gas temperature must be kept above the dew point limit to prevent condensation and accumulation of moisture in the gas line. In practice, a top gas temperature between 110°C and 130°C is maintained to prevent condensation of water vapour and aid the removal of volatile species such as zinc. The removal of zinc from the burden requires high temperatures above 900 °C, where zinc oxides can be reduced and vaporised to help prevent zinc deposition and associated operational instability in the upper part of the blast furnace and the gas cleaning system (Geerdes et al., 2015; Cameron et al., 2019).

The operational impacts of the blast furnace vary significantly between different fuels and reductants. For example, natural gas has high H_2 content and a lower carbon concentration than pulverised coal. Therefore, its injection tends to lower the RAFT because the combustion of H_2 produces less heat than the combustion of carbon due to hydrogen’s lower adiabatic flame temperature and higher specific heat of water vapour produced during combustion. However, industrial experience has shown that the blast furnaces can still operate in stable mode at a lower RAFT value around 1900°C, compared with the typical 2050°C to 2200°C observed for pulverised coal injection (PCI). This is because H_2-containing injectants, such as natural gas or H2, promote faster and more efficient indirect reduction reactions. These reactions compensate for the lower combustion temperature by increasing overall reduction kinetics and gas utilisation efficiency (Geerdes et al., 2015; Yilmaz et al., 2017; Cameron et al., 2019).

For pulverised coal injection, operational challenges may occur when the injection rate exceeds approximately 150 kg per tonne of hot metal (tHM). At higher rates, the incomplete combustion of coal and excessive gas generation can hinder permeability and increase the resistance to gas flow through the burden. Therefore, O_2 enrichment is typically used to address the issues by improving combustion efficiency and maintaining the required RAFT. However, although O_2 enrichment can reduce the specific gas volume inside the furnace, it can also lead to a lower top gas temperature. Hence, maintaining an appropriate heat and mass balance is crucial to prevent the top gas temperature from approaching the dew-point limit. Overall, the effectiveness of alternative reductant injection depend on the optimisation of interdependent parameters; RAFT, gas flow, pressure drop, O2 enrichment, and top gas temperature to achieve lower coke rates while maintaining furnace stability and hot metal quality (Geerdes et al., 2015; Wang et al., 2015; Cameron et al., 2019). Table 9 summarises the key operational parameters that influence the injection of alternative reductants in blast furnace operation.

Table 9: Key Operational Parameters Affecting the Injection of Alternative Reductants in the Blast Furnace

Parameter	Typical Range/Limit	Technical Significance
Raceway Adiabatic Flame Temperature (RAFT)	1900 to 2200°C	Minimum temperature is required to ensure complete combustion and stable reduction. Natural gas operation can remain stable near the lower limit due to improved H_2 reduction.
Top Gas Temperature	110 to 130°C	Maintain above dew-point to prevent condensation and ensure dry gas cleaning. Support zinc volatilisation and prevent build up.
Pressure Drop	Increases with gas volume, managed operationally	Higher gas flow from injectants increases pressure drop; controlled by burden distribution, coke size, and ore/coke ratio.
O_2 enrichment in Blast	1-5 vol%	Improve combustion and RAFT, enable higher injectant rates. Excessive enrichment can reduce top gas temperature.

2.2.5 Production Statistics and Efficiency Measures

Blast furnace ironmaking is considered the most expensive process in integrated steel production. Among all raw materials, coke is the most expensive. It has been reported that the cost of producing pig iron accounts for approximately 75% of the cost of producing cast steel. In 2019, the investment cost to build a new blast furnace complex was USD 600 million for a facility with an annual capacity of four million tonnes (Cameron et al., 2019).

Several strategies have been implemented to enhance performance and mitigate emissions. These include the use of recycled steel scrap, partial substitution with direct-reduced iron, utilisation of self-fluxing sintered ore and pellets, and the reutilisation of by-products such as slag and BFG. These measures provide incremental gains in reducing CO_2 emissions and improving efficiency (Geerdes et al., 2015; Cameron et al., 2019).

However, none of these options eliminates the fundamental reliance on coke, which remains both structurally and chemically irreplaceable. The literature consistently concludes that while the blast furnace is technically efficient, it is also structurally carbon-intensive. This confirms the importance of research into alternative reductants, which can reduce emissions without compromising the operational integrity of the blast furnace.

2.3 Alternative Reductants in Ironmaking

Alternative reductants have been widely proposed as a decarbonisation strategy to reduce dependence on coke and pulverised coal. A variety of candidates have been studied, which include biomass-derived reductants such as charcoal, wood pellets, and switchgrass, as well as refuse-derived fuels like subcoal. In addition, hydrogen has also been explored as a potential gaseous reductant. While the depth of literature on these alternative reductants varies, most studies rely on static process modelling and simplified assumptions, with limited pilot-scale validation and almost no assessment tailored to the UK context. The following subsections review each alternative reductant in detail to examine technical feasibility, environmental performance, and economic and practical challenges.

2.3.1 Charcoal

Charcoal has been the most extensively studied biomass-based reductant and is widely considered the most technically promising solid alternative reductant. Charcoal is produced through slow pyrolysis at temperatures above 400°C, has a high carbon content and low ash content, making it an efficient substitute for coke (Suopajärvi et al., 2018; Leão et al., 2023). Charcoal typically has a carbon content of 80.51% with a calorific value between 28.5-30 MJ/kg (Wang et al., 2015). These properties make it a promising substitute for both coke and pulverised coal injection (PCI). However, its lower density and high porosity pose challenges in large-scale industrial applications (Suopajärvi et al., 2012). Figure 9 presents an image of charcoal.

Figure 9: Charcoal as a Solid Biomass-Derived Reductant

The ultimate and proximate analysis of charcoal is shown in Table 10 (Wang et al., 2015).

Table 10: Ultimate and Proximate Analysis of Charcoal (Wang et al., 2015)

C	wt%	80.51
H	wt%	3.18
N	wt%	0.12
S	wt%	0.02
O	wt%	10.08
Moisture	wt%	4.28
Ash	wt%	1.81
Bulk density, dry	kg/m^3	230-260
Calorific value.	MJ/kg	28.5-30

Numerous modelling and simulation studies highlight the potential of charcoal to deliver significant reductions in greenhouse gas emissions. Ng et al. (2010) estimated that charcoal injection could reduce GHG emission by 23.5% using static heat and mass balance modelling in a Canadian context. Furthermore, Wang et al. (2015) simulated the substitution of 166.7 kg/tHM charcoal for 155 kg/tHM PCI, reporting a 28% reduction in CO_2 emissions. Feliciano-Bruzual and Mathews. (2013) concluded that up to 200-220 kg/tHM of charcoal could be injected and can reduce emissions by as much as 40%, based on data from literature and industry. Beyond environmental benefits, Babich et al. (2010) found that charcoal injection can decrease slag formation by 18-31%, while de Castro et al. (2013) reported an improvement in productivity of up to 25% when 100 kg/tHM of charcoal was injected alongside 150 kg/tHM PCI with O_2 enrichment.

Despite these advantages, several critical limitations are evident in the literature. First, most studies are based on static simulations that oversimplify blast furnace operation, thus neglecting factors such as raceway stability, fluctuations in coke reactivity, and impacts on hot metal chemistry. Although tuyere injection of charcoal is technically more feasible than top-charging since it bypasses the need for mechanical strength, charcoal's other characteristics, such as high porosity, low bulk density, and distinct combustion behaviour, require careful control of race adiabatic flame temperature (RAFT) to maintain stable operation (Mousa et al., 2016). Second, the industrial application of charcoal has been constrained mainly to small blast furnaces in Brazil, which operate under different burden mixes and raw material conditions compared to those in European plants (Leão et al., 2023). In contrast, large European furnaces require a strong reductant to sustain high productivity, more complex burden conditions (lower iron grades and higher gangue levels), and stricter permeability requirements (Geerdes et al., 2015; Cameron et al., 2019). Third, economic feasibility remains a critical challenge. Charcoal prices benchmarked across major hot metal producing countries ranged from USD270 to USD570/tonne, significantly higher than coal ranging between USD117 to USD135 (Feliciano-Bruzual et al., 2013). However, the study did not account for the more recent volatility in the biomass market or competition from the energy sector in Europe. In addition, the scale of biomass required is also rarely considered. Although the use of residues rather than primary wood could lower costs and reduce land use pressures, large-scale supply to even a single UK blast furnace would present considerable supply and sustainability challenges. In the case-study UK steel plant, annual hot metal production is 5 million tonnes (Euro Metal, 2024) . Assuming that 0.14 tonnes of charcoal is required per tonne of hot metal (Ng et al., 2010), the plant would need approximately 700,000 tonnes of charcoal per year. If 1 tonne of charcoal requires 2.7 tonnes of eucalyptus wood (Leão et al., 2023), this would correspond to an annual eucalyptus demand of 1.9 million tonnes. Based on the eucalyptus productivity of 12 tonnes per hectare (Biomass Connect, 2026), the land area required to supply the charcoal for blast furnace operation would be approximately 1584 km^2. This is roughly equivalent to the area to Greater London (City Population, 2026). Therefore, it is necessary for the charcoal to be imported into the UK for use in BF operation due to this significant requirement and lack of land availability.

While charcoal remains the most technically promising solid biomass-derived reductant, the literature overstates its feasibility and underplays operational, economic, and supply-chain barriers. Pilot-scale trials in large integrated blast furnaces under European conditions are therefore urgently needed to further verify its potential.

2.3.2 Wood Pellets

Wood pellets are another biomass-derived option that have been explored for feasibility in blast furnace ironmaking. Pelletisation is a key process in wood pellet production. This process involves drying, grinding, compressing, and cooling the biomass to improve its energy content and handling properties compared to raw biomass as illustrated in Figure 12 (Wei, Mellin, Yang, Mefos, et al., 2013). The carbon content of wood pellets is 46.2 wt% and the calorific value is typically d17 MJ/kg (Wang et al., 2015). These characteristics make them more suitable for storage, transport, and injection compared to unprocessed biomass. Figure 10 presents an image of wood pellets.

Figure 10: Wood Pellets as a Biomass-Derived Solid Fuel (image adapted from Wei, Mellin, Yang, Mefos, et al., 2013)

The process flow of wood pellet production is as follows.

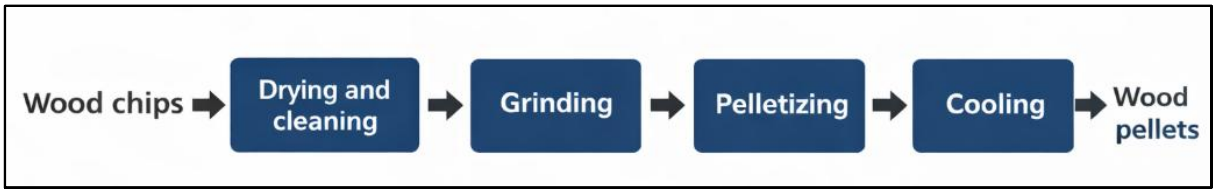

Figure 11: Process Flow of Wood Pellet Production (adapted from Wei, Mellin, Yang, Mefos, et al., 2013)

The ultimate and proximate analysis of wood pellets is shown in Table 11 (Wang et al., 2013, 2015).

Table 11: Ultimate and Proximate Analysis of Wood Pellets (Wang et al., 2015)

C	wt%	46.20
H	wt%	5.67
N	wt%	0.09
S	wt%	0.01
O	wt%	38.97
Moisture	wt%	8.60
Ash	wt%	0.46
Bulk density, dry	kg/m^3	>600
Calorific value.	MJ/kg	>16.9

Wood pellets have been studied for their viability as a partial replacement for pulverised coal (PC) injection in blast furnaces. Wang et al. (2015) modelled the substitution of wood pellets in a Swedish blast furnace and reported that only 20% of fossil PCI could be replaced, which corresponds to a modest reduction of around 5.7% in direct emissions. Although the study also suggested annual energy savings of 168.9 GWh, the environmental benefits remain low compared to charcoal. Additionally, the study did not consider the impact of wood pellet injection on the blast furnace top gas calorific value, which is crucial for energy recovery through combined heat and power systems in integrated steel plants.

Furthermore, economic assessments also raise concerns and have not been covered in the literature. Pelletisation introduces additional processing costs, which can reduce cost competitiveness with fossil PCI (Visser et al., 2020). The feasibility of using wood pellets in ironmaking was primarily investigated in Scandinavian contexts, where forestry residues are abundant and bioenergy infrastructure is well-developed (Wang et al., 2015). This limits their applicability in the UK, where the supply of wood pellets is already constrained and subject to significant demand from the power generation sector (Mayo, 2025). Moreover, the environmental implications of sourcing pellets from primary wood plantations have not been adequately assessed, which raises concerns over land use change and sustainability.

Overall, wood pellets provide logistical convenience and improved storage properties, but their lower carbon content can limit their substitution potential. Furthermore, the literature also lacks a robust background for feasibility in large-scale implementation. Therefore, their role is likely to be limited to partial substitution under specific conditions.

2.3.3 Switchgrass

Switchgrass (Panicum virgatum) is a perennial grass with high yields, and adaptability to a wide range of soil and climates, and relatively low input requirements (McLaughlin et al., 2005; Keshwani et al., 2009; IEA Bioenergy, 2011). It is native to temperate regions of North America and its suitability as a biofuel crop has been assessed in the US, Canada, Europe, and China (Adler et al., 2006; Ameen et al., 2019). However, its potential application in blast furnace injection has been considered in only a small number of studies (Ng et al., 2010; Khasraw et al., 2024). Figure 12 presents an image of switchgrass.

Figure 12: Switchgrass as Potential Alternative Reductant (image adapted from Hoffman Nursery, 2016)

Raw switchgrass has unfavourable properties as a reductant. This is due to its low calorific value (17.4 MJ/kg), well below coal (31 MJ/kg) or heavy oil (40 MJ/kg) (Khasraw et al., 2024). Besides, it has a bulk density of only 115-182 kg/m3 and contains high levels of moisture and ash (Mani et al., 2006; Ng et al., 2010; Khasraw et al., 2024). These characteristics make direct injection infeasible without pre-treatment. The typical composition of switchgrass is summarised in Table 12.

Table 12: Ultimate and Proximate Analysis of Switchgrass (Mani et al., 2006; Ng et al., 2010; Khasraw et al., 2024)

C	wt%	47.27
H	wt%	5.31
N	wt%	0.51
S	wt%	0.10
O	wt%	43.5
Moisture	wt%	11.9
Ash	wt%	5.76
Bulk density, dry	kg/m^3	115-182 kg/m3
Calorific value.	MJ/kg	17.4

Thermochemical upgrading can enhance switchgrass properties. Sadaka et al. (2014) showed that carbonisation at 400°C increased fixed carbon from 22.5% to 44.9%, raised calorific value from 17.8 to 21.9 MJ/kg, and reduced volatile matter from 72.1% to 43.9%. These improvements improve grindability and storage while reducing transport costs (Khasraw et al., 2024). Nevertheless, this additional processing adds costs and energy inputs, and therefore affects competitiveness as an alternative reductant.

The environmental benefits of switchgrass as a reductant appear limited. Ng et al. (2010), using mass and heat balance simulations, reported that substituting PCI with switchgrass reduced emissions by only 5.4%, the lowest among the biomass options assessed. No pilot-scale or industrial trials have been conducted to validate its combustion behaviour, effects on raceway adiabatic flame temperature (RAFT), or impacts on hot metal quality. The reported production cost of switchgrass, based on US conditions and excluding upgrading, pelletisation, and long distance transport to European markets is $65 per oven-dry tonne (IEA Bioenergy, 2011). Given that switchgrass is not widely cultivated in the UK and land competition with food is likely, its large-scale adoption appears impractical.

In summary, although switchgrass exhibits agronomic advantages and has been widely studied as bioenergy crop, its unfavourable properties, absence of pilot-scale trials, and weak supply chain render it impractical as a direct reductant for UK blast furnace operations.

In this research, switchgrass is included for two specific reasons. First, it represents a primary, unprocessed biomass that has not undergone thermochemical upgrading. Its inclusion enables assessment of whether further processing, such as torrefaction, is necessary before biomass can deliver meaningful environmental benefits as a blast furnace reductant. In this respect, switchgrass is retained in the scenario development as a representative primary biomass feedstock, allowing comparison with secondary biomass, namely charcoal, and illustrating the influence of different biomass pathways on environmental impacts within the LCA framework. Second, switchgrass has previously been investigated as a potential reductant by researchers linked to the case-study UK steel plant, who indicated that upgrading would be required before its use in metallurgical applications. Therefore, including switchgrass in the present LCA also provides continuity with the initial feasibility assessment of biomass application in iron and steelmaking reported by Khasraw et al. (2024). These findings can help inform future material selection decisions.

2.3.4 Subcoal

Refuse-Derived Fuels (RDFs) have emerged as potential alternatives to biomass-based reductants because they can mitigate land-use pressures while offering relatively high calorific values. One of the most promising RDFs is Subcoal, a high-quality fuel derived from non-recyclable waste streams such as paper, plastics, textiles, and wood with biogenic content of 44-55% (Veer, 2022). It has a calorific value of around 22 MJ/kg and a bulk density of approximately 500 kg/m3. This makes it comparable in energy terms to low-grade coals.

Subcoal has already been successfully deployed in energy-intensive industries such as cement, and it has also been tested in coal-fired power stations (N+P Group, 2022). It is commercially produced by the N+P Group at facilities in the Netherlands (120 kt/year) and the UK (140 kt/year). An assessment by Ingenia estimated that substituting 1 tonne of fossil fuel with Subcoal could reduce approximately 1.6 tonnes of CO_2 (N+P Group, 2022). The ultimate and proximate analysis of subcoal is shown in Table 13 (Foster, 2022; Veer, 2022).

Table 13: Ultimate and Proximate Analysis of Subcoal (Foster, 2022; Veer, 2022)

C	wt%	47.91
H	wt%	6.74
N	wt%	0.58
S	wt%	0.08
O	wt%	21.74
Moisture	wt%	5.01
Ash	wt%	17.96
Bulk density, dry	kg/m^3	500
Calorific value.	MJ/kg	22

Subcoal is available in various sizes, ranging from 4-16 mm with lengths between 15-40 mm. It is also available in pellets, granules, and milled forms (N+P Group, 2022). Research into Subcoal as a blast furnace reductant remains scarce. A thermodynamic study by Ojobowale (2024) suggested that subcoal injection could be feasible due to its high volatile matter and reactivity, but also highlighted challenges such as lower fixed carbon and higher activation energy requirements compared to PCI. Furthermore, handling poses another barrier due to its fibrous and heterogenous nature which can complicate injection, and require additional pre-treatment for homogenisation. Methods such as torrefaction and hydrothermal carbonisation can be utilised to enhance uniformity but reduce reactivity and increase cost. The study recommended blending subcoal with coal, highlighting its economic and environmental benefits, but careful ash monitoring and chemistry need to be implemented (Ojobowale, 2024). However, the gap remains since the study did not quantitatively estimate the emissions reduction of subcoal vs a conventional reductant.

Moreover, subcoal contains relatively high ash content (about 18 wt%) compared to PCI which may pose risks by increasing slag volume and refractory wear. However, this aspect has not been thoroughly investigated. Although Subcoal offers advantages in terms of reduced land-use impacts compared to biomass and has a proven application in the cement industry, its suitability as a reductant in blast furnace ironmaking remains largely untested, especially with respect to its environmental performance.

2.3.5 Hydrogen

Hydrogen (H_2) has gained importance as a potential gaseous reductant for blast furnace ironmaking. Global H_2 demand reached 97 Mt in 2023, with associated production emitting approximately 920 Mt CO_2 (International Energy Agency, 2024). Demand is dominated by the refining and chemical industries, with China accounting for one-third of global use. Between 2019 to 2024, H_2 supply remained dominated by fossil-based methods, particularly steam methane reforming (SMR), although projections suggest that low carbon H_2 technologies will supply up to 35-40% of demand by 2030 (International Energy Agency, 2024).

H_2 production is typically described using colour terminology. Grey H_2 is produced via steam methane reforming (SMR) of natural gas and has GWP values of 11-13 kg CO_2-eq/ kg H_2, dominated by the reforming process itself (Ozbilen et al., 2011; Cetinkaya et al., 2012; Mehmeti et al., 2018; Antonini et al., 2020; Bukold et al., 2020; Sphera Solutions GmbH., 2021). Brown H_2, produced by coal gasification exhibits a higher GWP of around 19-24 kg CO_2-eq/ kg H_2 (Mehmeti et al., 2018; Vickers, 2019; Bartlett et al., 2020). Furthermore, green H_2 from electrolysis powered by renewable sources typically ranges from 1 to 5.1 kg CO_2-eq/kg $H_{2,}$ while electrolysis using fossil-dominated electricity mixes can exceed 30 kg CO_2-eq/kg $H_{2.}$(Cetinkaya et al., 2012; van Cappellen et al., 2018; Mehmeti et al., 2018; Bukold et al., 2020). Moreover, blue H_2 produced via SMR with carbon capture and storage (CCS), has a reported impact of 0.6 to 4.7 kg CO_2 eq/kg H_2 (van Cappellen et al., 2018; Antonini et al., 2020; Bukold et al., 2020), although Howarth and Jacobson (2021) argued that values may be higher (11to 22 kg CO_2-eq/kg H_2) when fugitive emissions are included. These variations highlight the sensitivity of results to system boundaries and assumptions. The distinction between colours is summarised in Table 14 and illustrated in Figure 13 (Maniscalco et al., 2024).

Table 14: Hydrogen Production Methods - Colour Classification and Process Descriptions (Maniscalco et al., 2024)

Type of H_2		**Description**
Grey H_2		Produced by steam methane reforming (SMR) with direct CO_2 emissions.
Green H_2		Generated through electrolysis powered by renewable sources (wind, solar, and hydro).
Blue H_2		Produced by SMR, utilising CO_2 captured through carbon capture techniques.
Yellow H_2		Produced by grid-connected electrolysis.
Turquoise H_2		Produced by methane pyrolysis, resulting in the production of H_2 and solid carbon.
Brown H_2 (also known as grey H_2)		Generated by coal gasification, followed by the syngas process and gas purification.
Pink H_2		Produced by electrolysis powered by nuclear energy

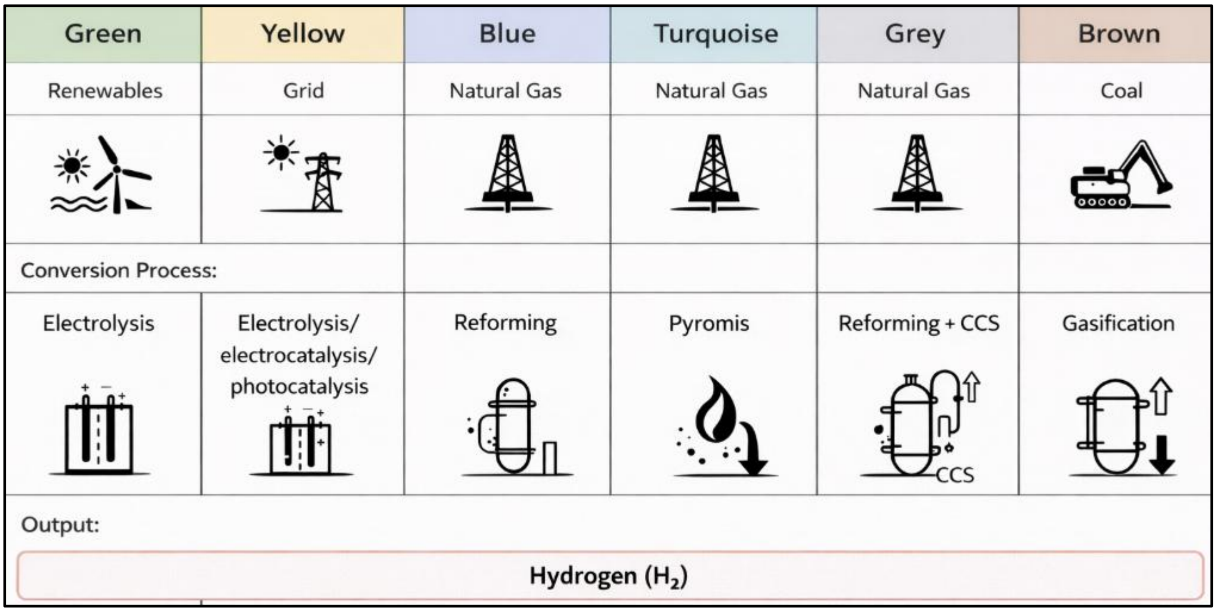

Figure 13: Overview of H2 Production Pathways (image adapted from Maniscalco et al., 2024)

In ironmaking, H_2 has been studied more extensively in direct reduction (DR) processes than in blast furnaces. A DR unit reduces iron ore to sponge iron using H_2 or natural gas, whereas blast furnaces produce liquid metal using solid alternative reductants, making both processes fundamentally different (Suer et al., 2022b). Given that blast furnaces still account for around 70% of global iron production, H_2 injection in this context requires close examination.

Early studies by Barnes (1975) and Astier et al. (1982) suggested that injecting 9-42 kg H_2/tHM can replace 27-140 kg/tHM of coke, but these works did not quantify CO_2 reductions. Later, modelling by Nogami et al. (2012) indicated that injecting 44 kg H_2/tHM at 1200°C reduced coke consumption to 324 kg/tHM. More recent assessments have specifically considered CO_2 mitigation. Schmole (2016) reported a reduction of 292 kg CO_2/tHM with 40 kg H2/tHM injection, while Yilmaz et al. (2017) achieved a comparable reduction of 289 kg CO_2/tHM, with only 27.5 kg H_2/tHM injection, by preheating H_2 to 1200°C. Ugarte et al. (2023) reported a 52 kg CO_2/tHM reduction with a 35 kg H_2/tHM injection. These discrepancies highlight the sensitivity of results to modelling assumptions.

Several weaknesses were identified from the literature. Most studies are based on simplified static models that do not account for dynamic furnace behaviour, slag chemistry, or hot metal quality. Upstream burdens from H_2 are often not included, meaning that grey H_2 injection could offset direct emission reductions at the furnace by shifting impacts upstream. Economic feasibility is also rarely addressed, although it is known that H_2 production costs, particularly for green H_2 under UK electricity prices represent a major barrier.

In summary, H_2 injection demonstrates clear technical potential to reduce coke consumption and associated emissions in blast furnaces. However, the evidence gathered is limited by its reliance on static modelling, which excludes full life cycle impacts, and a lack of robust economic analysis. These gaps are significant for the UK, where energy costs are high and H_2 deployment remains at an early stage. Therefore, this research provides a UK-contextualised assessment of H_2 as an alternative reductant by evaluating both grey and green pathways within the framework of life cycle assessment.

2.3.6 Summary of Alternative Reductant

Throughout this review, several alternative reductants have been identified, including charcoal, subcoal, wood pellets, switchgrass, grey H_2, and green H_2. For scoping assessment linked to Research Question 1, charcoal, wood pellets, and subcoal were selected for initial consideration. Charcoal was chosen because it is the most widely studied in the literature and consistently identified as a promising alternative reductant for blast furnace applications ((Babich et al., 2010; Feliciano-Bruzual et al., 2013; de Castro et al., 2013; Wang et al., 2015; Suopajärvi et al., 2018; Leão et al., 2023). Wood pellets were included because they have also been discussed in literature, although they are generally less prominent than charcoal (Wang et al., 2015; Suopajärvi et al., 2018). Furthermore, subcoal was included because in addition to its relevance, it had also been explored in previous research activities at the case-study UK steel plant (N+P Group, 2021; Ojobowale, 2024).

From this initial scoping assessment, charcoal emerged as the most suitable reductant among the options considered. Building on the findings from Research Question 1, and in line with evolving literature and agreement from industrial sponsor, Research Question 2 focused on the assessment of charcoal, switchgrass, grey H_2 and green H_2 against conventional reductants (further details are provided in Section 3.2.1). This allows a broader comparison across both solid and gaseous reductant pathways while also capturing the differences in technology maturity, environmental performances, and practical deployment considerations relevant to the UK steel sector. The inclusion of both grey H_2 and green H_2 also enabled the study to reflect contrasting H_2 pathways, representing higher-impact and lower-impact environmental cases.

2.4 Life Cycle Assessment Framework

Life cycle assessment (LCA) is defined as a compilation and evaluation of the inputs, outputs, and potential environmental impacts of product systems through their life cycle (International Standard Organisation, 2022a, 2022b). The relevance of LCA has grown substantially in the context of industrial decarbonisation, particularly in emissions-intensive sectors such as iron and steelmaking. The assessment enables a comprehensive analysis of environmental impacts and trade-offs across various environmental categories by considering both upstream and downstream effects.

Besides, LCA enable the generation of robust evidence to support decision-making for clearer production strategies.

The foundation of LCA is developed by the ISO 14040 and ISO 14044 standards, which define four interconnected phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. These standards provide methodological clarity, transparency, and reproducibility, which are essential for conducting high-quality and comparable LCA studies (Rebitzer et al., 2004; International Standard Organisation, 2022a, 2022b). The literature strongly highlights the importance of adhering to those standards to ensure consistency across studies, comparability of results, and alignment with best practices in environmental evaluation (Hauschild et al., 2015; Laurent et al., 2020). The LCA framework, which includes goal and scope definition, inventory analysis, impact assessment and interpretation, is illustrated in Figure 14.

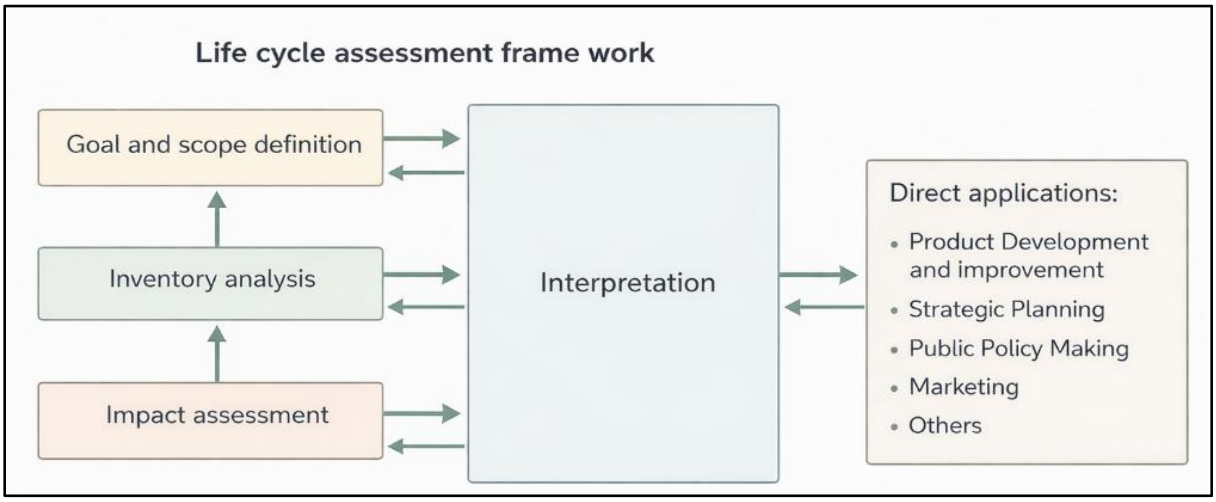

Figure 14: Life Cycle Assessment (LCA) Framework (Muralikrishna et al., 2017)

Many LCA studies have been conducted on steelmaking to evaluate its environmental impacts. There are many benefits of LCA for the steel industry. Firstly, LCA allows the steel industry to quantify the environmental impacts. Additionally, LCA enables steel producers to identify environmental hotspots, allowing for improvements in areas with the most significant potential for environmental benefits ('Life Cycle Assessment (LCA) explained - PRé Sustainability', 2024). LCA also allows benchmark performance to ensure continuous improvement and sustainable practices within sectors ('Life cycle assessment and embodied carbon - SteelConstruction.info', 2024). Lastly, LCA can help the steel industry promote transparency and show its environmental commitment ('Life Cycle Assessment | EcoAct', 2024). The LCA framework is described as follows.

Goal and Scope Definition

Defining the goal and scope is the crucial starting point of any LCA study. Based on ISO 14040 and ISO 14044, this phase requires specifying the intended application to provide the reasons for conducting the assessment, identifying the target audience, and describing the system to be analysed (International Standard Organisation, 2022a, 2022b). The functional unit serves as the basis for all calculations and comparisons. This ensures that results are expressed relative to a clearly defined reference flow. In steel-related LCA, the functional unit is commonly defined as one tonne of steel product (Norgate et al., 2007; Burchart-Korol, 2013; Renzulli et al., 2016; Liu et al., 2020). In blast furnace ironmaking LCA, the commonly used functional unit is one tonne of hot metal (Chen et al., 2015; Leão et al., 2023). The system boundary also needs to be explicitly stated to present which processes are included. Cradle-to-gate boundaries are widely applied in ironmaking studies to capture all upstream processes up to the point at which the product leaves the process. These include the extraction of raw materials, energy use, transportation, and on-site emissions (Leão et al., 2023). Transparent boundary setting is crucial to prevent errors and hidden environmental burdens (International Standard Organisation, 2022a).

Inventory Analysis

The life cycle inventory (LCI) phase involves consolidating and quantifying all material and energy flows that enter and leave the system under study (International Standard Organisation, 2022a, 2022b). In practice, inventory datasets are typically a combination of multiple sources.

Primary data is data sourced directly from industrial operations and is most valuable for foreground processes because it improves the specificity and accuracy of the evaluation. Secondary data is commonly gathered from established databases such as Ecoinvent and GaBi to represent background processes and ensure consistency and comparability across the system boundary (Arbor, 2024; Ecochain, 2025). In addition, LCI datasets may utilise values from published literature when direct measurements or database averages are lacking, as well as proxy data from analogous processes or technologies where no better alternatives are available (Bjørn et al., 2018; International Standard Organisation, 2022a, 2022b). Although secondary data, literature, and proxy data enhance system completeness, they often introduce uncertainty due to outdated assumptions, methodological inconsistencies, or a lack of regional representativeness (Bjørn et al., 2018; Zargar et al., 2022). The pedigree matrix method, developed by Weidema and Wesnaes (1996), is commonly applied to assess data quality and address the limitations. This pedigree method evaluates five dimensions: reliability, completeness, temporal correlation, geographical correlation, and technological correlation, where each dimension is scored to reflect the uncertainty levels associated with it. (Weidema et al., 2013).

Impact Assessment Method

Life cycle impact assessment (LCIA) converts life cycle inventory data into potential environmental impacts by using scientifically derived characterisation models as defined in ISO 14040 and ISO 14044. The LCIA methods have undergone significant changes over the past three decades in response to various regional priorities, modelling, philosophies, and policy requirements.

Among the LCIA methods, ReCiPe 2016 Midpoint (H) has become one of the most widely applied globally in both academic research and industry assessments. This is because it provides a balanced combination of scientific robustness, transparency, and interpretability (Huijbregts et al., 2016). The midpoint approach evaluates environmental mechanisms at an intermediate stage of the cause-and-effect chain. For example, it measures the mass of SO_2 emissions that contribute to acidification potential. This mid-stage approach helps avoid the significant subjectivity found in endpoint models, which quantify potential damage to areas of protection, such as human health, ecosystems, and resource availability. Hence, this makes midpoint indicators particularly suitable for comparing industrial scenarios (Hauschild et al., 2015). Furthermore, this method consists of 18 midpoint categories such as climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity (cancer), human toxicity (non-cancer), photochemical ozone formation, particulate matter formation, ionising radiation, agricultural land occupation, urban land occupation, water consumption, and fossil resource scarcity. These midpoint categories are used to quantify environmental impacts at the midpoint level before they are aggregated into endpoint damage categories. The overview of the link between midpoint and endpoint categories is presented in Figure 15 (Huijbregts et al., 2016).

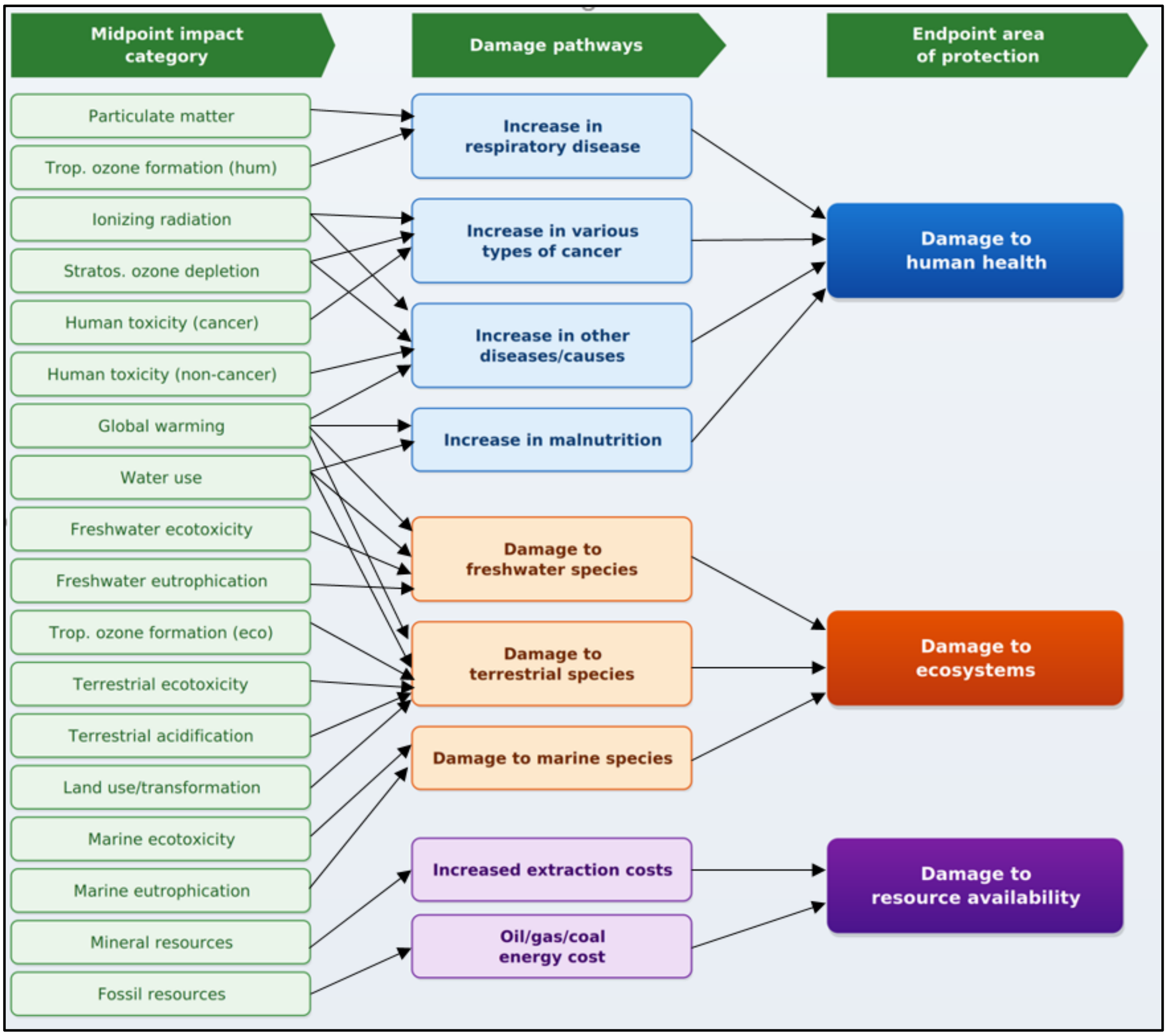

Figure 15: Overview of the ReCiPe 2016 Midpoint and Endpoint Impact Categories (image adapted from Huijbregts et al., 2016)

For this research, only five categories were prioritised, such as global warming (climate change), land use, fossil resource scarcity, mineral resource scarcity, and water consumption. This is because these categories are highly relevant to blast furnace ironmaking decarbonisation and can be influenced by the choice of reductants (Leão et al., 2023). Additionally, these categories capture the dominant emission profiles and enable the evaluation of trade-offs between impact categories. The description of the five impact categories is summarised in Table 15 (Huijbregts et al., 2017).

Table 15: Description of Selected ReCiPe 2016 Midpoint (H) Impact Categories Used in This Study (Huijbregts et al., 2016)

Impact Categories	Unit	Description
Global warming Potential (GWP)	kg CO_2 eq	This indicates the potential for global warming due to the emission of greenhouse gases, including CO_2, CH_4, N_2O, HFC, and PFC, among others.
Fossil resources scarcity (FRS)	kg oil eq	An indicator of the potential future burden of resources that contain hydrocarbons based on the current depletion rate. This includes volatile materials (e.g., methane, gasoline) and non-volatile materials (e.g., anthracite coal).
Mineral resource scarcity (MRS)	kg Cu eq	An indicator of the potential future burden of mineral resource extraction based on the current depletion rate due to human activities.
Land use (LU)	m^2a crop eq	An indicator of the transformation and occupation of land due to human activities, including habitat loss, soil degradation, and biodiversity decline.
Water consumption	M^3	An indicator that measures net freshwater taken from the surface, groundwater, or rainwater sources that is consumed and not returned to the same water sources.

2.5 Life Cycle Assessment in Steelmaking

Steelmaking has been one of the most intensively studied industries using life cycle assessment (LCA) due to its high energy consumption, dependence on fossil reductants, and significant greenhouse gas footprint. The BF-BOF route has received particular attention, as it remains the dominant production pathway globally and is the primary contributor to the emissions (Hornby et al., 2021). Numerous cradle-to-gate studies have been published, covering categories such as global warming potential (GWP), acidification potential (AP), eutrophication, and resource use.

Norgate et al. (2007) conducted one of the more comprehensive studies, which evaluated the environmental impacts of multiple primary metals, including lead, zinc and steel, using a cradle-to-gate LCA. Their results demonstrated that higher-grade ores reduce environmental impacts by lowering gangue content, but the study excluded the burden of scrap use and did not allocate impacts to co-products such as slag, and therefore limiting comparability.

Burchart-Korol (2013) studied steel production in Poland using the ReCiPe midpoint method. The GWP reported was 2.5 kg CO_2-eq/kg steel without accounting for slag credits, and 1.7 kg CO_2-eq/kg steel when slag co-products were credited. This research improved on Norgate et al. by considering co-products but like many studies, excluded the environmental burden of scrap inputs.

Neugebauer and Finkbeiner (2012) introduced a multi-recycling approach in which a hot-rolled coil produced via the primary BF-BOF route was recycled five times. Impacts were distributed equally across life cycles, demonstrating the importance of recycling assumptions. Co-products such as slag, electricity, benzene, and tar were credited but again the allocation procedures were not systematically justified. Therefore, the study raised questions about comparability with other studies.Renzulli et al. (2016) analysed steel slab production in an integrated Italian steel plant, applying mass and economic allocation for by-products. Their reported GWP was 1.6 kg CO_2-eq/kg steel, lower than most other studies. This was mainly due to higher credit given to BF gas, BOF gas, and slag. However, scrap burdens were not included, reflecting a common gap across literature.

Olmez et al. (2016) assessed multiple steel products in Turkey and reported that GWP and respiratory inorganics were the dominant impacts. This study included recycling considerations, highlighting the environmental benefits of scrap use compared to primary production.Furthermore, Liu et al. (2020) evaluated Chinese steelmaking using the IMPACT 2002 method and expanded the assessment to multiple categories including human health, ecosystem quality, and resource depletion. The study confirmed that hot metal production is a major environmental hotspot and is aligned with the conclusion of earlier studies that increased scrap utilisation significantly reduces environmental impacts.

Backes et al. (2021) studied German steel production using CML 2001 method and reported a GWP of 2.1 kg CO_2-eq/kg hot-rolled coil. Although co-products were credited, the study excluded the burden of scrap, consistent with the methodological gaps highlighted earlier. Table 11 summarises key cradle-to-gate LCA studies of BF-

BOF steel production, noting differences in impact assessment methods, treatment of co-products, and reported GWP values.

Comparison of Allocation Methods and Co-product Crediting in Prior LCA Studies

The significant methodological difference across the studies is in the treatment of co-products and recycled materials, particularly slag and scrap steel. Allocation methods vary broadly, with some studies applying mass and economic allocation, while others utilised system expansion or crediting approaches. For example, Burchart-Korol. (2013) and Renzulli et al. (2016) exhibited significant reductions in GWP when slag was credited, but did not apply burdens to scrap inputs. Similarly, Norgate et al. (2007) and Backes et al. (2021) did not account for the burden of scrap use, thereby limiting comparability with studies that include recycled content. Neugebaur and Finkbeiner (2012) proposed a multi recycling mode but did not justify their allocation of impacts across product life cycles. The inconsistencies found between studies highlight the need for transparent and harmonised accounting for co-products and recycled materials, as differences in allocation choices can significantly influence environmental impacts.

Table 16 summarises the studies discussed in this section. The variation in allocation procedures, scrap assumptions, and crediting methods across studies poses challenges to directly comparing environmental impacts. In this research, these challenges are addressed with clearly defined allocation rules, specific credit assumptions, and a harmonised LCA framework, as detailed in Section 3.2.

Table 16: Cradle-to-Gate LCA Studies on Steel Production via the BF-BOF Route

Author(s) and Year	Region	Product	Impact Method	GWP (kg CO_2 eq/kg steel)	Consideration of Allocation to Co-products
Norgate et al., 2007	Global	Steel	Not stated	2.3	Not considered
Burchart-Korol., 2013	Poland	Steel	Recipe Midpoint (H)	2.5 (without slag credits) 1.7 (with slag credits).	Credits given for co-products.

Neugebauer & Finkbeiner., 2012	Germany	Hot-rolled coil	CML 2016	1.0	Credits given for co-products.
Renzulli et al.,2016	Italy	Steel	ILCD	1.6	Credits given for co-products.
Olmez et al.,2016	Turkey	Hot rolled coil	IMPACT 2002+	Not stated	Not considered
Liu et al.,2020	China	Steel	IMPACT 2002+	0.358	Credits given for co-products.
Backes et al.,2021	Germany	Hot-rolled coil	CML 2001	2.1	Credits given for co-products

2.6 Life Cycle Assessment in Ironmaking

Although the blast furnace process is recognised as the primary source of emissions in integrated steelmaking, life cycle assessment (LCA) studies specifically for blast furnace ironmaking with a functional unit of one tonne of hot metal remain notably limited. Much existing research on blast furnace ironmaking decarbonisation has predominantly focused on process simulations, rather than comprehensive environmental assessment grounded in LCA frameworks. The blast furnace process accounts for the highest fossil fuel consumption and CO_2 emissions in an integrated steelmaking process (Geerdes et al., 2015; Cameron et al., 2019).

Norgate and Jahanshahi (2011) assessed the primary metal production using cradle-to-gate boundaries. The assessment revealed that the blast furnace stage exhibited a global warming potential (GWP) of over 1.8 kg CO_2-eq per kg hot metal, with sinter preparation and coke combustion identified as the main hotspots. However, co-products and scrap burdens were excluded, thereby limiting comparability and underestimating potential credits from by-products (Norgate et al., 2011). These omissions are inconsistent with ISO 14044 guidance, which recommends transparent allocation methods or system expansion to account for multifunctional processes

Leão et al. (2023) conducted a cradle-to-gate LCA of hot metal production in Brazil, explicitly applying a functional unit of one tonne of hot metal. The study highlighted the role of carbon sources and co-product utilisation, comparing conventional coke-based and charcoal-based ironmaking scenarios. The outcomes revealed notable GWP reductions for charcoal scenarios, influenced by carbon source mix, transport distances, and the allocation of environmental credits to co-products such as blast furnace top gas and slag (Leão et al., 2023). While the study utilised detailed system boundaries and transparent co-product crediting aligned with ISO 14044, the scenarios were constrained to Brazil-specific supply chains and material inputs, limiting generalisation to other regional contexts.

Suer et al. (2022) evaluated multiple decarbonisation options for blast furnace operation, which include H_2 injection and partial substitution of coke with pre-reduced burden materials such as direct-reduced iron (DRI). The analysis revealed that H_2 injection could reduce cradle-to-gate GWP by up to 200 kg CO_2 eq per tonne of hot metal. However, the review did not provide a consistently defined functional unit across the multiple scenarios included and did not fully disclose the upstream assumptions for H_2 production. Therefore, these gaps reduce transparency and limit direct comparison with other LCA studies (Suer et al., 2022a).

Kankanamge Dona et al. (2025) conducted a systematic review of LCA studies that explored the feasibility of H_2 and/or biomass sources in the iron and steel production process. For iron production, the review reported a wide range from -41 to 2799 kg CO_2 eq per tonne of hot metal. The review emphasised that the variability of GWP was attributed to methodological inconsistencies in the definition of functional units, system boundaries, and allocation or crediting approaches across the literature (Kankanamge Dona et al., 2025). This highlights an urgent need for harmonisation, especially in adopting system expansion, or providing transparent justification for allocation as recommended by ISO 14044 (International Standard Organisation, 2022b).

2.7 Summary and Gaps in Literature

In summary, these studies demonstrated that considerable attention has been made to explore alternative reductants for blast furnace ironmaking, particularly charcoal, wood pellets, switchgrass, subcoal, and H_2 (Ng et al., 2010; Wang et al., 2015; Yilmaz et al., 2017; Leão et al., 2023; Khasraw et al., 2024; Ojobowale, 2024). These studies consistently show the potential of substitution to reduce direct carbon emissions, but the extent of these reductions and the practical feasibility vary significantly between reductants.

Charcoal emerges as the most technically promising solid reductant due to its high fixed carbon content, low ash, and sulphur levels, with modelling studies reporting substantial reductions in CO_2 emissions when substituted for PCI (Suopajärvi et al., 2018). However, its low-density high porosity, and poor crushing strength pose operational challenges. In addition, outdated and region-specific economic data weaken claims of feasibility (Leão et al., 2023). Large-scale application in the UK would also be constrained by limited biomass supply chains and competition from other sectors (Department for Energy Security & Net Zero, 2023a).

Wood pellets and switchgrass have been considered as alternatives but both demonstrate more modest decarbonisation potential. Wood pellets offer logistical advantages through higher bulk density and easier handling. However, their relatively low carbon content limits substitution capacity (Wang et al., 2015). Switchgrass has poor fuel properties and limited cultivation in the UK, although it has agronomic advantages and low production costs in North America (Ng et al., 2010; IEA Bioenergy, 2011).

Subcoal, as a refuse-derived fuel, offers a different pathway by converting non-recyclable waste stream into alternative fuels, and partially displacing fossil reductants (Ojobowale, 2024). Although promising in terms of circular economy benefits and already deployed in cement kilns, its higher ash content, fibrous nature, and no previous trials in blast furnaces mean that its feasibility remains largely untested (Veer, 2022).

H_2 has received growing attention as a reductant because in theory it emits water vapour instead of CO_2 during iron ore reduction. Studies consistently show its potential to reduce coke consumption and emissions, particularly when heated (Yilmaz et al., 2017). However, most of the assessments conducted are based on static modelling and upstream production burdens are often excluded, and economic feasibility under current conditions remains highly uncertain. These gaps are crucial in the UK context, where H_2 costs are among the highest in Europe and supporting infrastructure is still in development (The International Council on Clean Transportation, 2024; WSS Energy Consulting, 2025).

Beyond the assessment of individual reductants, the literature also reveals several broader methodological limitations. Most studies rely on static heat and mass balance modelling, which neglects the dynamic behaviour of large blast furnaces and the influence of reductants on slag chemistry and hot metal quality. LCA studies have been applied extensively to conventional BF-BOF steelmaking, but very few focus solely on ironmaking. Only a limited number consider alternative reductants, and none provide a comparative assessment of both solid and gaseous reductants within a consistent LCA framework. Additionally, existing studies are also limited in scope. Assessments typically focus on global warming potential and do not account for broader categories, such as land use, water consumption, and resource depletion. In addition, only a few studies evaluate data robustness or test the influence of input variations on the results. Moreover, the allocation of impacts to co-products is inconsistent and rarely justified. These methodological weaknesses constrain comparability across studies and, therefore, reduce the reliability of conclusions.

Finally, the regional context of most published work is not directly transferable to the UK. Studies have predominantly focused on countries such as Brazil, Sweden, Canada, Poland, Germany, Italy, China, and Turkey, where raw material availability, energy systems, and industrial conditions differ significantly. The absence of a UK-contextualised assessment is a significant gap, particularly given the ongoing transformation of the local steel industry, the high cost of electricity, and policies developed to align with Net Zero targets.

This research addresses these gaps by conducting a comprehensive assessment of alternative reductants for blast furnace ironmaking in the UK. It integrates cradle-to-gate life cycle assessment with economic and practical considerations for the top two most promising reductants. Besides, this research includes data quality evaluation and sensitivity analysis to ensure robustness. This research provides new evidence on the feasibility of decarbonising blast furnace ironmaking under UK-contextualised conditions, comparing both solid and gaseous reductants within the same framework, and therefore fills critical gaps in the literature.

CHAPTER 3

3.0 METHODOLOGY

This chapter describes the methodological framework used in the research and explains how each component supports the assessment. It outlines the preliminary screening method for solid reductants and then presents the life cycle assessment approach, including the definition of the goal and scope, the justification of the functional unit, and the system boundaries used in the study. The chapter also details the development of the inventories, the impact assessment method, the data quality evaluation using the pedigree matrix method, and the structure of the sensitivity analysis.

This chapter outlines the methodological framework developed to evaluate the environmental, economic, and practical feasibility of alternative reductants in blast furnace ironmaking with particular relevance to the UK context. As established in Chapter 2, although numerous studies have explored low-carbon alternatives such as charcoal, H_2, and waste-derived fuels, many remain fragmented, utilise inconsistent life cycle boundaries and lack sufficient regional specificity. Moreover, very few have systematically addressed the influence of data uncertainty and modelling assumptions, which are crucial to ensure robust conclusions. Therefore, the aim of this chapter is to develop a structured, multi-stage methodology that incorporates screening, life cycle modelling, data quality evaluation, and sensitivity analysis to produce a comprehensive assessment and outcomes.

This methodology is structured into four sections, each corresponding directly to the research objectives identified in Section 1.2 and listed as follows.

- **Section 3.1- Assessment of Solid Alternative Reductant.**
    - This section establishes a high-level screening of three solid reductants: charcoal, Subcoal, and wood pellets against metallurgical coke as the baseline, considering efficiency, environmental and economic factors.
    - A multi-criteria scoring method approach is applied to take into account those three factors. The purpose of this assessment is to provide evidence-based justification for selecting the most promising solid reductant for further analysis in the LCA.
- **Section 3.2 - Life Cycle Assessment.**
    - This section forms the core of this research and the purpose is to provide a comparative environmental performance between solid and gaseous reductants in accordance with the ISO 14040 and ISO 14044 standards. This section outlines the LCA methodology applied to five reductant scenarios:
        - Coke with pulverised coal (baseline case)
        - Coke with charcoal
        - Coke with switchgrass
        - Coke with grey H_2
        - Coke with green H_2

    - The system boundary is identified as a cradle-to-gate functional unit of 1 tonne of hot metal (tHM) and ReCiPe Midpoint (H) is used as impact assessment methods.
    - Furthermore, an economic evaluation was conducted on the top two best-performing alternative reductants identified from LCA results. The aim is to identify cost competitiveness, a critical factor for practical implementation in the steel industry.
- **Section 3.3 - Data Quality Assessment**
    - This section describes the pedigree matrix scoring approach used to assess the quality of inventory data.
    - Five indicators: reliability, completeness, temporal correlation, geographical correlation, and technological correlation are systematically assessed. Scores are assigned based on dataset origin, representativeness, with detailed justifications provided.
    - This step strengthens the transparency and robustness of the results, particularly when alternative datasets are used due to limited primary data availability.
- **Section 3.4 - Sensitivity Analysis**
    - This section outlines the sensitivity analysis framework developed to test the influence of key input variations on the modelling outcomes.
    - Sensitivity parameters were established based on hotspots identified from LCA outcomes. Among the various parameters considered are the coke production region, transport distances, iron-bearing sources, and dataset substitutions. Each parameter is analysed individually to examine its effect on selected environmental indicators. In accordance with ISO 14044 requirements, sensitivity analysis is essential to ensure that the results and comparative conclusions remain robust under alternative assumptions.

Altogether, these four sections provide a coherent framework for determining which alternative reductants demonstrate the most credible and impactful decarbonisation potential for UK blast furnace applications.

It should be noted that Section 3.1 and Section 3.2 examine different sets of alternative reductants because they reflect different stages of the research. Section 3.1 presents an early-stage screening of selected solid reductants to identify promising candidates for further assessment. In this stage, three solid alternative reductants; charcoal, subcoal, and wood pellets were evaluated against the coke baseline across three criteria: technical performance, environmental performance, and economic performance. This assessment was conducted in 2022 and 2023. At that stage, the literature review identified charcoal and wood pellets as potentially relevant alternative reductants (Norgate et al., 2009, 2012a; Wei, Mellin, Yang, Wang, et al., 2013; Wang et al., 2015; Suopajärvi et al., 2017; Orre et al., 2021; Leão et al., 2023). Charcoal is widely discussed in the literature, whereas wood pellets have received more limited attention, despite being considered a potentially feasible option. Subcoal was also included because it was being investigated by the case-study UK steel plant through a separate EngD project (Ojobowale, 2024). Therefore, the reductants considered in the first stage of the research reflected both the available literature at the time and the priorities are aligned with industry sponsor.

By contrast, Section 3.2 presents the final set of scenarios used in the full LCA. This stage expands the assessment to include both solid and gaseous reductants. Charcoal was retained based on the results of the screening exercise presented in Section 3.1. Switchgrass was included because it had been assessed by the case-study UK steel plant, with findings indicating that it would require upgrading before it could be used in metallurgical applications (Khasraw et al., 2024). In addition, its inclusion enables comparison between switchgrass as a primary biomass and charcoal as a secondary biomass. As the literature and international industry trials developed, hydrogen was also introduced as an alternative reductant in the final scenario set (Yilmaz et al., 2017; Tata Steel, 2023; Nippon Steel, 2025). Both grey hydrogen and green hydrogen were assessed to illustrate how different hydrogen production pathways influence environmental impacts. Overall, this progression reflects the development of the research from an initial screening of solid reductants to a broader comparative framework aligned with the final research questions.

Table 17 provides an explicit mapping of thesis sections to the research questions that guide this research.

Table 17: Mapping of Research Questions to Corresponding Thesis Section.

Research Question	Addressed In
RQ0 - Scoping	**Methodology**: Section 3.1 **Results and Discussion**: Section 4.1
RQ1 - Environmental performance	**Methodology**: Section 3.2, Section 3.3, Section 3.4 **Results and Discussion**: Chapter 5 and Chapter 6
RQ2 - Economic feasibility	**Methodology, Results and Discussion**: Section 5.1.8
RQ3 - Practical deployment	**Results and Discussion**: Chapter 5.1.7 and Section 7.1

3.1 Assessment of Solid Alternative Reductants

This section outlines the methodology used to evaluate the feasibility of charcoal, subcoal, and wood pellets as solid alternative reductants in blast furnace ironmaking. The aim is to assess the most feasible solid alternative reductant for blast furnace ironmaking and to further examine the environmental impacts with an LCA method methodology outlined in Section 3.2. This assessment was conducted during the first year of research and serves as a high-level evaluation. The methodology comprised four primary assessments listed in Table 18.

Table 18: Assessment Types and Objectives for Evaluating Solid Alternative Reductants in Blast Furnace Ironmaking

Section	Assessment Type	Objective
3.1.1	Efficiency Analysis	To determine the amount of reductants needed to produce one tonne of hot metal using the mass balance approach.
3.1.2	Environmental Analysis	To estimate the environmental impacts of using reductants to produce one tonne of hot metal based on greenhouse gas emissions factors.
3.1.3	Cost Analysis	To evaluate the cost of reductants to produce one ton of hot metal.
3.1.4	Multi-Criteria Scoring Assessment	Scoring is used to assess efficiency, environmental impacts, and cost for each scenario.

Scenario Design

Table 19 presents five different scenarios, each with varying reductant compositions. The baseline scenario assumes the use of 100% coke as the reductant, representing conventional blast furnace ironmaking. In reality, coke is used as the primary reductant, and pulverised coal is used as an auxiliary reductant. This simplification by assuming use of 100% coke is used at this stage to enable a more focused, high-level analysis.

Table 19: Scenarios for Alternative Reductant Utilisation in Blast Furnace Hot Metal Production

Scenario	Scenarios	Descriptions
Scenario 1	Base Scenario	100% Coke is used. This serves as the baseline for the study, reflecting conventional blast furnace operation.
Scenario 2	Full coke replacement	100% of the coke mass is replaced with charcoal
		100% of the coke mass is replaced with subcoal
		100% of the coke mass is replaced with wood pellets
Scenario 3	80% of coke mass is replaced by an alternative reductant.	80% of the coke mass is replaced with charcoal
		80% of the coke mass is replaced with subcoal
		80% of the coke mass is replaced with wood pellets
Scenario 4	50% of coke mass is replaced by an alternative reductant.	50% of the coke mass replaced with charcoal
		50% of the coke mass replaced with subcoal
		50% of the coke mass replaced with wood pellets
Scenario 5	20% of coke mass is replaced by an alternative reductant.	20% of the coke mass replaced with charcoal
		20% of the coke mass replaced with subcoal
		20% of the coke mass replaced with wood pellets

Table 20 presents the wet-basis composition of coke and alternative reductants examined in this research. These compositions were determined using ultimate analysis and moisture data from several studies.

Table 20: Wet Basis Composition of Coke, Charcoal, Subcoal, and Wood Pellets Used in Assessment.

Composition (wt%)	**Percentage by weight (%)**			
	(Geerdes et al., 2015; Suopajärvi et al., 2018)	(Wang et al., 2015)	(Foster, 2022)	(Wang et al., 2015)
	Coke	**Charcoal**	**Subcoal**	**Wood Pellets**
C	85.5	80.51	47.91	46.20
H	0.38	3.18	6.74	5.67
N	0.38	0.12	0.58	0.09
S	0.67	0.02	0.08	0.01
O	0.48	10.08	21.74	38.97
Moisture	5	4.28	5.01	8.60
Ash	8.5	1.81	17.96	0.46
Total	100.00	100.00	100.00	100.00

3.1.1 Efficiency Assessment

The first assessment to evaluate the feasibility of alternative reductants in blast furnace ironmaking is efficiency analysis, which was done solely based on mass balance calculations. The purpose is to determine the amount of carbon required to reduce iron ore (Fe_2O_3) to produce 1 ton of hot metal (Fe). The findings will enable a comparative analysis of the efficiency of the reductants based on their capability to supply carbon.

Rationale for Mass Balance Approach

A blast furnace operates primarily by reducing iron ore to hot metal using carbon. In a conventional blast furnace, reductants, such as coke and pulverised coal, supply the carbon. Given the role of carbon as a key reactant, a mass balance is utilised to estimate the amount of coke, charcoal, subcoal, and wood pellets required for iron ore reduction. The mass balance is established based on two fundamental reactions:

a) Reduction of iron ore (Fe_2O_3) to hot metal (Fe) by carbon monoxide (CO)

- This reaction determines the amount of CO needed to reduce iron ore (Fe2O3) to hot metal (Fe).

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad \text{(Reaction 1)}$$

b) Formation of carbon monoxide (CO) from carbon.

- This reaction demonstrates the relationship between solid carbon (C) and carbon monoxide (CO) production.

$$C + 1/2\ O_2 \rightarrow CO \quad \text{(Reaction 2)}$$

Using both reactions 1 and 2 and the stoichiometric relationship, the required amount of carbon and the mass of the alternative reductant required for each scenario can be calculated.

Assumptions and Simplifications

The following assumptions were used in the calculation to maintain a straightforward mass balance approach.

- The focus is purely on mass conservation with heat balance and other factors excluded.
- The carbon is assumed to undergo complete combustion, which means all carbon in the reductants is available to form CO.
- Ash and moisture content impacts on carbon efficiency are excluded.
- Auxiliary reductants like pulverised coal are excluded.

Calculation Steps

The following steps, summarised in Table 21, were used to calculate the reductant required to produce 1 tonne of hot metal. Scenario 1, which uses 100% coke, was used as an example.

Table 21: Calculation Steps for Reductant Requirement in Hot Metal Production

	Calculation Descriptions	Calculations for Scenario 1
Step 1	Determine the amount of hot metal (Fe) produced in kmol. ▪ The mass balance is conducted to evaluate the production of 1 tonne of hot metal. ▪ Convert mass of hot metal (Fe) to moles using the molar mass relationship. $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$	Given: Production of 1 tonne (1000 kg) of Fe. Molar mass of Fe = 55.85 kg/kmol. Calculation: Kmol of Fe = Mass of Fe (kg) / Molar mass of Fe (kg/kmol) Kmol of Fe = 1000 / 55.85 = 17.91 kmol
Step 2	Calculate the required amount of iron ore (Fe_2O_3) ▪ Evaluate the amount of Fe_2O_3 needed based on reaction stoichiometry.	From stoichiometry, two kmol of Fe is produced per 1 kmol of Fe_2O_3. Reaction: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ Calculation: Kmol of Fe_2O_3 = 17.91 / 2 = 8.96 kmol
Step 3	Calculate the required amount of CO for reduction. ▪ Determine the amount of CO needed to reduce Fe_2O_3 to Fe.	Reaction: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ From stoichiometry, 3 kmol of CO is required per 1 kmol of Fe_2O_3. Calculation: Kmol of CO = 3 * 8.96 = 26.88 kmol

Step 4	Calculate the carbon required to produce CO using the CO formation reaction.	Reaction: $C + 1/2\ O_2 \rightarrow CO$ 1 kmol of carbon produces 1 kmol of CO. Calculation: Kmol of Carbon = 26.88 kmol Mass of Carbon required = 26.88 kmol * 12.01 kg/kmol = 322.83 kg
Step 5	Convert the amount of carbon required into the mass of each reductant.	Given: Coke contains 85.5% carbon. Calculation: Mass of Coke = 322.83 kg / 0.855 = 377.58 kg

The results from these calculations for all scenarios are presented and discussed in Section 4.1.1.

3.1.2 Environmental Assessment

The second evaluation was conducted to determine the feasibility of solid alternative reductants through an environmental impact assessment. The environmental impacts of each scenario were analysed to assess the impacts of greenhouse gas (GHG) emissions, specifically CO_2, CH_4, and N_2O using GHG emission factors. It is vital to ensure that alternative reductants can significantly reduce GHG emissions compared to traditional reductants.

The following assumptions and limitations were used in the calculations.

- The reductant required for each scenario, estimated by the mass balance in Section 3.1.1, is used to calculate GHG emissions. Complete combustion was assumed to take place in the blast furnace. However, incomplete combustion may happen in real-world operations, leading to higher emissions.
- The GHG emission factors used for coke, charcoal, subcoal, and wood pellets are referenced from the United States Environmental Protection Agency (EPA)

website for stationary combustion sources and listed in Table 22 (United States Environmental Protection Agency (US EPA), 2025a).

- The alternative reductants were represented based on the most common fuel type in the source. Subcoal, derived from refuse-derived fuel (RDF), primarily consists of municipal solid waste (MSW), including non-recyclable plastics, paper, and other combustible materials, making the MSW emission factor the most appropriate choice for GHG calculations, aligning with standard waste-derived fuel accounting. Charcoal, produced through wood carbonisation, originates from wood-based biomass. Hence, the "Wood and Wood Residuals" category was selected for accurate emissions estimation. Similarly, wood pellets also fall under the "Wood and Wood Residuals" category as they are made from compressed sawdust.
- The values provided from the source were originally in different units and have been converted to kg of emissions per kg of reductant for more straightforward interpretation.
- These factors were deduced based on average values, and may not fully include variations in reductant quality, operating conditions, and other influencing factors.

Table 22: GHG Emission Factors for Coke, Charcoal, Subcoal, and Wood Pellets (United States Environmental Protection Agency (US EPA), 2025a)

Reductant	Category Selected	CO_2 Factor	CH_4 Factor	N_2O Factor
		kg CO_2/kg of reductant	kg CH_4/kg of reductant	kg N_2O/kg of reductant
Coke	Coking coal	3.11	0.00030	0.000044
Charcoal	Wood and Wood Residuals	1.81	0.00014	0.000069
Subcoal	Municipal Solid Waste (MSW)	0.99	0.00035	0.000046

Wood Pellets	Wood and Wood Residuals	1.81	0.00014	0.000069

- Other gaseous emissions such as CO, SO_2, NO_x, and H_2 are excluded from the assessment.

The omission may result in an underestimation of the overall environmental impacts.

- GHG emissions are reported in carbon dioxide equivalent (CO_2e) units to provide a standardised approach to compare the environmental impacts of GHG gases. The total GHG emission (in CO_2 equivalent) is calculated based on the total sum of CO_2 emission, CH_4 emission (converted to CO_2 equivalent), and N_2O emission (converted to CO_2 equivalent). The emissions of CH_4 and N_2O are converted into CO_2 equivalent by multiplying them by the latest respective GWP values sourced from the US EPA website. Table 23 presents the 100-year GWP for CH_4 and N_2O as sourced from the US EPA website (United States Environmental Protection Agency (US EPA), 2025b).

Table 23: Global Warming Potential (GWP) Factors for CH_4 and N_2O on a 100-Year Basis (United States Environmental Protection Agency (US EPA), 2025b)

Gas	100-Year GWP
CH_4	25
N_2O	265

Calculation Steps

The following steps were used to calculate the GHG emissions to produce 1 ton of hot metal. Scenario 2, which uses an alternative reductant to replace 100% of the coke mass, was used as an example.

Table 24: Calculation Steps for Estimating GHG Emissions Using Alternative Reductants

	Calculation Descriptions	Calculations for Scenario 2
Step 1	Determine Fuel Mass Flow Rate	For Scenario 2, 400.98 kg of charcoal is required to replace 100% of coke mass to produce 1 ton of hot metal.

Step 2	Estimate CO_2 Emissions	CO_2 emissions (kg CO_2)= Reductant required (kg) × CO_2 emission factor (kg CO_2/kg reductant) CO_2 emissions (kg CO_2)= (400.98 kg charcoal) x (1.81 kg CO_2/kg charcoal) = 725.77 kg CO_2
Step 3	Estimate CH_4 Emissions	CH_4 emissions (kg CH_4)= Reductant required (kg) × CH_4 emission factor (kg CH_4 kg reductant) CO_2 emissions (kg CH_4)= (400.98 kg charcoal) x (0.00014 kg CH_4 /kg charcoal) = 0.056 kg CH_4 Convert CH_4 emissions into CO_2 equivalent: CH_4 emissions (CO_2e) = CH_4 emissions (kg) × GWP (25) CH_4 emissions (CO_2e) = (0.056 kg CH4) x (25) = 1.4 kg CO_2e
Step 4	Estimate N_2O Emissions	N_2O emissions (kg N_2O)= Reductant required (kg) × N_2O emission factor (kg CH_4 kg reductant) N_2O emissions (kg N_2O)= (400.98 kg charcoal) x (0.000044kg N_2O /kg charcoal) = 0.018 kg N_2O Convert N_2O emissions into CO_2 equivalent: N_2O emissions (CO_2e) = CH_4 emissions (kg) × GWP (265)

		N_2O emissions (CO_2e) = (0.018 kg CH4) x (265) = 4.77 kg CO_2e
Step 5	Calculate Total CO_2 Equivalent Emissions	Total CO_2e emissions (kg) = CO_2 emissions + CH_4 emissions (CO_2e) + N_2O emissions (CO_2e) Total CO_2e emissions (kg) = 725.77 kg CO_2 + 1.4 kg CO_2e + 4.77 kg CO_2e = 731.94 kg CO_2e

The results from these calculations for all scenarios are presented and discussed in Section 4.1.2.

3.1.3 Economic Assessment

An economic evaluation was conducted to assess the feasibility and competitiveness of using alternative reductants in blast furnace ironmaking compared to the conventional reductant. Cost assessment is essential as it represents a key criterion for the steel industry to implement green solutions effectively. The evaluation to estimate the total reductant price was done based on specific assumptions and limitations. Even though the calculations are simplified and done to provide a high-level assessment, they provide a sufficiently reliable basis for a comparative assessment between scenarios.

The following assumptions and limitations are considered for the cost assessment.

- Total cost of reductants
  - The total cost of reductants is calculated as the sum of market price and transportation costs. Market fluctuations are excluded for simplicity.
  - The market price of reductants is converted to British pounds using the exchange rate to reflect and align with the location of the study. The exchange rates of (1 USD = 0.774 ; 1 EUR = 0.839 GBP) as of 2025

are used (XE Currency Converter, 2025). Market conditions and price volatility, as well as currency fluctuations, are not considered.

- The total cost is inflation-adjusted using the Bank of England’s inflation calculator to reflect the value in the year 2023 to be consistent with the LCA timeline (Bank of England).
- The market prices for all reductants are presented in Table 25.

Table 25: Market Prices and Inflation-Adjusted Costs of Alternative Reductants

Reductants	Original Cost (per tonne, in original currency)	Reference Year	Market Price (£/tonne, converted)	Inflation-Adjusted Market Price for Year 2023 (£/tonne)	References
Coke	$ 197	2025	152	143	(GMK Center, 2025)
Charcoal	$ 470	2025	364	342	(Alibaba.com, 2025)
Subcoal	€ 80	2022	67	72	(Veer, 2023)
Wood Pellets	$ 241	2023	187	187	(IndexBox, 2023)

- Suppliers Location and Port Selection
    - The suppliers’ locations for coking coal, charcoal, and wood pellets were selected based on the top producer exporting these reductants to the UK, as sourced from websites. While reductants may be imported from multiple locations within the UK, only a single supplier location for each material was considered for simplicity.
    - Departure ports are selected based on supplier proximity, port capacity, and established supplier route.
    - The subcoal supplier is located in Teesside, UK, as sourced from N+P Group (N+P Group, 2022).
    - A UK port serving the steel plant was designated the arrival port for all shipment.
    - All cost figures reflect bulk industrial quantities rather than retail or small order-pricing.
    - The summary of suppliers' locations is presented in Table 26.

Table 26: Transport Modes and Logistics of Alternative Reductants

Raw Material	Transport Mode	Departure Location/Port	Arrival Port	References
Coke	Sea	Port Kembla, Australia	UK port	(Statista, 2025)
Charcoal	Sea	Port of Durban, South Africa		(Observatory of Economic Complexity (OEC), 2024)
Subcoal	Road (Truck)	Teesside, UK		(N+P Group, 2022)
Wood Pellets	Sea	Port of Greater Baton Rouge, United States		(Biomass Magazine, 2024)

Transportation Cost

- Transportation costs were estimated based on sea routes between the departure and arrival ports for coking coal, charcoal, and wood pellets. Although road transport is typically involved in delivering raw materials from their source to the departure port, this aspect was omitted to simplify calculations.
- Since subcoal is sourced within the UK (Teesside), its transportation cost was estimated based on road delivery by truck.
- The transportation costs for coke, charcoal, and wood pellets were calculated based on container shipping rates and fuel densities
- For coking coal, charcoal, and wood pellets, the transportation cost was calculated using container shipping rates and fuel density data:
    - The cost of transporting a 20-foot standard container was obtained from an online shipping cost estimation tool, considering the shipping distance between the departure and arrival ports (Searates by DP World, 2025).
    - The container has a total volume capacity of 33 m^3 (Sea Rates by DP World, 2025)
    - The densities of coking coal, charcoal, and wood pellets were sourced from Engineering Toolbox (Engineering Toolbox, 2003).
- The density of subcoal is obtained from the N+P group representative (Veer, 2022).

- The transportation costs for each reductant were estimated based on container shipping rates, material densities, and shipping distances.

The final transportation cost is presented in Table 27.

Table 27: Transport Costs of Alternative Reductants

Raw Material	Transport Mode	Departure Location/Port	Arrival Port	Transport Cost per Tonne (£/tonne)
Coke	Sea	Port Kembla, Australia	UK port	479
Charcoal	Sea	Port of Durban, South Africa		313
Subcoal	Road (Truck)	Teesside, UK		48
Wood Pellets	Sea	Port of Greater Baton Rouge, United States		170

The total cost of reductants per ton, comprising the market price and transport costs, is detailed in Section 4.1.3.

3.1.4 Multi-Criteria Scoring Assessment

A multi-criteria scoring assessment was done to evaluate the feasibility of using alternative reductants and to identify the optimal reductant and the ideal percentage for coke mass replacement. The assessment was conducted based on three primary aspects: efficiency, environmental impacts, and economic viability. These balanced, well-rounded assessments ensure that the advantages and constraints of each reductant are comprehensively analysed.

Table 28: Assumptions and Criteria for Multi-Criteria Scoring Assessment

Criteria	**Description**
Efficiency	Measured by the amount of reductant required to produce 1 tonne of hot metal as outlined in Section 3.1.1.
Environmental Impacts	Assessed based on total GHG emissions as described in Section 3.1.2.

Economic Viability	Evaluated through the total reductants price as summarised in Section 3.1.3.

The results calculated from the efficiency, environmental impacts, and economic assessment are presented in Section 4.1.4

Scoring Assessment

The percentage deviation from the base scenario was calculated to quantify the difference between using alternative reductants and the base scenario. The base scenario represents the use of 100% coke.

Equation 1 is used to determine the percentage deviation:

$$\text{Percentage of Deviation (\%)}: \frac{(Measured\ Value - Reference\ Value)}{Reference\ Value} \times 100\% \qquad \text{(Equation 1)}$$

Table 29 presents the percentage deviation calculated for all the scenarios.

Table 29: Percentage Deviation in Efficiency, Environmental Impact, and Cost across Coke-Replacement Scenarios

Scenario	Percentage of Coke Mass Replaced with AF (%)	Reductant	Amount of Reductant Required (kg)	Total Greenhouse Gases (%)	Total Reductant Price (%)
Scenario 1 (Baseline)	NA	Coke	NA	NA	NA
Scenario 2	100%	Charcoal	6%	-38%	12%
		Subcoal	78%	-42%	-66%
		Wood Pellets	85%	8%	6%
Scenario 3	80%	Charcoal	5%	-30%	10%
		Subcoal	63%	-34%	-52%
		Wood Pellets	68%	7%	5%
Scenario 4	50%	Charcoal	3%	-19%	6%
		Subcoal	39%	-21%	-33%
		Wood Pellets	42%	4%	3%
Scenario 5	20%	Charcoal	1%	-8%	2%
		Subcoal	16%	-8%	-13%
		Wood Pellets	17%	2%	1%

Scoring Methodology

A 1-10 rating scale was applied to improve granularity in scoring. Higher scores represent improved outcomes than the baseline scenario (100% coke). The scoring system was determined by establishing a percentage threshold and assigning scores separately for the three primary assessments.

The establishment of the percentage threshold and scores for the amount of reductant required was presented in Table 30.

Table 30: Methodology for Establishing Percentage Thresholds and Scoring Levels in Multi-Criteria Assessment.

	Calculation Descriptions	Calculations for Scenario 2
Step 1	Define the Range of Percentages	Identify the minimum and maximum percentage values for the dataset. Range = Max Percentage − Min Percentage Example: If the percentage range is from −66% to 14%: Range = 14% − (−66%) = 80%
Step 2	Determine the Number of Score Levels	Select the total number of scoring levels. A typical scale uses 1 to 10, meaning the percentage range is divided into equal intervals. Segment Size = Range ÷ Number of Scores Example: For a range of 80% and 10 scores: Segment Size = 80 ÷ 10 = 8%
Step 3	Establish Percentage Threshold Ranges	Start from the minimum percentage and incrementally add the segment size to determine threshold ranges. The first threshold starts from the minimum percentage. Each subsequent threshold increases by the segment size. The last threshold must end exactly at the maximum percentage. Ensure no overlap in values between adjacent ranges. Example: Minimum Value = −66% Maximum Value =14%

		Segment Size = 8% Thresholds are calculated as: Level 1: −66% to −59% Level 2: −58% to −51% Level 3: −50% to −43% ... continue until the last level reaches 14% (maximum percentage).

Based on guidance outlined in Table 30, percentage thresholds for the three criteria assessed, such as efficiency, environmental, and economic, were established as follows.

Percentage threshold and scoring for efficiency:

Table 31: Percentage Threshold Ranges and Corresponding Scores for Efficiency Assessment

Percentage Threshold Range	Score
1% to 8%	10
9% to 17%	9
18% to 25%	8
26% to 34%	7
35% to 42%	6
43% to 50%	5
51% to 59%	4
60% to 67%	3
68% to 76%	2
77% to 85%	1

Percentage threshold and scoring for environmental impacts:

Table 32: Percentage Threshold Ranges and Corresponding Scores for Environmental Impact Assessment

Percentage Threshold Range	Score
-42% to -38%	10
-37% to -33%	9
-32% to -28%	8
-27% to -23%	7
-22% to -18%	6
-17% to -13%	5
-12% to -8%	4

-7% to -3%	3
-2% to 2%	2
3% to 8%	1

Percentage threshold and scoring for economics:

Table 33: Percentage Threshold Ranges and Corresponding Scores for Economics Assessment

Percentage Threshold Range	Score
-66% to -59%	10
-58% to -51%	9
-50% to -43%	8
-42% to -35%	7
-34% to -27%	6
-26% to -19%	5
-18% to -11%	4
-10% to -3%	3
-2% to 5%	2
6% to 14%	1

The results of the multi-criteria scoring assessment are presented and discussed in Section 4.1.4.

3.2 Life Cycle Assessment

This section outlines the methodology used to conduct life cycle assessment (LCA) of alternative reductants in blast furnace ironmaking, adhering to ISO 14040 and ISO 14044 standards (International Standard Organisation, 2022a, 2022b). The methodology was structured to ensure clarity, transparency, reproducibility, and credibility, supporting a comparative assessment of five reductant scenarios that reflect both current industrial practice and emerging decarbonisation options in the UK context. The methodology incorporates best practices and recommendations from peer-reviewed literature, international LCA guidance documents, and industry reports to guarantee that assumptions, boundaries, and analytical selection are clearly justified.

3.2.1 Goal and Scope Definition

The primary goal of this LCA is to evaluate and compare the cradle-to-gate environmental impacts of alternative reductants such as charcoal, switchgrass, grey H_2 and green H_2 in blast furnace ironmaking, benchmarked against the conventional practice of coke and pulverised coke injection (PCI).

This comparative approach was specifically chosen to address a significant gap in the literature, where most previous studies have only assessed a single alternative reductant. In addition, the study was conducted to provide a UK-contextualised context, as there are currently no studies that assess the feasibility of alternative reductants for ironmaking in the UK. Therefore, the analysis provides robust evidence to support both academic discussion and industrial decision-making on sustainable steel production by incorporating the UK supply chain, energy mix, and technological landscape.

Scenario Definitions

This research investigates five reductant scenarios for blast furnace ironmaking in the UK as presented in Table 28. These scenarios were selected to represent a comprehensive coverage of established, emerging, and experimental pathway options currently under consideration within the steel decarbonisation roadmaps (Ng et al., 2010; Norgate et al., 2012b; Suopajärvi et al., 2013; Yilmaz et al., 2017; Leão et al., 2023; Rumsa et al., 2025). The five scenarios evaluated through LCA are discussed as follows.

- **Scenario 1 (coke and pulverised coal):** This scenario serves as the baseline, representing conventional ironmaking with coke and pulverised coal.
- **Scenario 2 (coke and charcoal):** This scenario is created to further examine the feasibility of charcoal from an LCA perspective. Charcoal, a secondary biomass (biomass that has been upgraded), has high fixed carbon content and established industrial applications, particularly in Brazil and is supported by numerous studies (Norgate et al., 2012a; Suopajärvi et al., 2013, 2017; Feliciano-Bruzual, 2014; Leão et al., 2023)
- **Scenario 3 (coke and switchgrass)**: This scenario evaluates the feasibility of switchgrass. Switchgrass is the primary biomass that has not been upgraded and has been explored by a study carried out by Tata Steel UK in 2024 (Khasraw et al., 2024). Additionally, switchgrass was selected due to its high bioenergy yield, drought tolerance, and suitability for cultivation on marginal land in temperate climates (IEA Bioenergy, 2011). Although extensively studied as a biofuel feedstock, its potential as a solid reductant in ironmaking remains largely unexplored.
- **Scenario 4 (coke and grey H_2):** This scenario aims to explore the feasibility of grey H_2 (produced via conventional steam methane reforming). This practice is consistent with multiple industrial trials that have happened globally and that have proved the success of H_2 in blast furnace ironmaking, such as by companies like Tata Steel (India), Nippon Steel (Japan), and ThyssenKrupp Steel (Germany) (Thyssennkrupp, 2022; Tata Steel, 2023; Nippon Steel, 2025). Grey H_2 was included in this study as a deliberate comparator to differentiate the effect of H_2 as a blast furnace reductant from the H_2 production route itself. In this scenario, grey H_2 represents a higher carbon reference case for H_2 use. In contrast, green H_2 (Scenario 5) represents a low carbon pathway. It is essential to include both to enable a clear comparison of whether environmental benefits come from reductant chemistry alone or from the upstream production pathway of H_2.
- **Scenario 5 (coke and green H_2):** Similar to Scenario 4, this scenario is used to evaluate the feasibility of H_2 used in blast furnace ironmaking. However, this scenario considers H_2 produced by renewable energy via electrolysis (powered by wind).

All the scenarios explored in this research are summarised in Table 34.

Table 34: Scenarios for Life Cycle Assessment

Scenarios	Reductants	Reductant Category	Descriptions
Scenario 1	Coke + pulverised coal (PC)	Base scenario-Fossil-based	This is the base scenario, which represents traditional blast furnace ironmaking. Coke is the primary reductant, and PC is an auxiliary reductant.
Scenario 2	Coke + charcoal	Biomass-based–traditional/solid	Coke is the primary reductant, and charcoal is used as an auxiliary reductant.
Scenario 3	Coke + switchgrass	Biomass-based – advanced/lignocellulosic	Coke is the primary reductant, and switchgrass is an auxiliary reductant.
Scenario 4	Coke + grey H_2	Fossil-derived hydrogen	Coke is the primary reductant. Grey H_2 is used as an auxiliary reductant.
Scenario 5	Coke + green H_2	Renewable hydrogen	Coke is the primary reductant. Green H_2 is used as an auxiliary reductant.

The intended application of this research is to support the development of decarbonisation strategies within the steel industry, with a specific focus on informing academic research and industrial practice. The target audiences for this research are researchers, professionals within the steel industry, and policymakers who are evaluating sustainable steel production roadmaps. The geographical coverage is a UK integrated steel plant operating the BF-BOF route, representing a typical large-scale site within the United Kingdom. The temporal coverage spans the year 2023, selected to represent the period of stable blast furnace operation at the case-study UK steel plant prior to significant operational changes in 2024. The technological coverage is focused on blast furnace ironmaking. The software used is SimaPro version 9.6.

3.2.2 Functional Unit and System Boundaries

The functional unit is defined as one tonne of hot metal (tHM) produced via blast furnace operation. Throughout this thesis, hot metal refers to the molten iron-carbon product tapped from the blast furnace, as defined in Section 1.2.1. This unit was selected to provide a consistent quantitative basis for comparison across all scenarios. In this research, the selection of one tHM as a functional unit is deliberately chosen to ensure methodological consistency, technical relevance, and comparability with prior blast furnace-specific research as discussed in Section 2.6 (Suer et al., 2022a; Leão et al., 2023; Liang et al., 2023). Although “per tonne of crude steel” is commonly used in integrated steelmaking LCA studies (Burchart-Korol, 2013; Renzulli et al., 2016; Backes et al., 2021), this research focuses specifically on blast furnace ironmaking rather than the entire BF-BOF route. The blast furnace produces hot metal, which is subsequently converted to crude steel in the basic oxygen furnace. Using crude steel as the functional unit would require including BOF operations, oxygen production, scrap addition, and alloying processes. However, these operations and processes are outside the scope of assessment and may dilute the comparison of reductant-specific impacts within the blast furnace itself. Furthermore, reductant choice directly affects blast furnace inputs and outputs (e.g coke rate, top gas composition) but has minimal influence on downstream BOF performance. By isolating the blast furnace stage, this research ensures that observed differences in environmental impacts can be directly attributed the choice of reductants, rather than variations in steelmaking operation. This approach aligns with recent blast furnace-focused LCA studies. Leão et al. (2023) used one tHM as a functional unit to compare charcoal and coke-based ironmaking in Brazil, which enables direct assessment of biomass substitution without introducing variability from BOF operations.

The system boundary is defined as cradle-to-gate, covering all processes from raw material extraction to the point where hot metal exits the blast furnace at the UK steel plant. It includes the extraction, processing, and iron-bearing materials and reductants from their source countries to the plant site. BOF steelmaking, casting, and rolling are excluded from the scope. Transport was modelled using combined road-and-sea freight distance to reflect actual UK supply-chain routes.

All on-site blast furnace operations are included, covering flux addition, reduction reactions, and utilities such as electricity, water, and natural gas consumption. Co-product handling is addressed through system expansion, where blast furnace top gas is credited for displacing on-site energy generation, and slag is credited for substituting clinker in cement production (see Section 3.2.2.1).

Particular attention was given to the representativeness and data quality. Process conditions obtained mainly from literature were systematically cross-validated using operational data from the case-study UK steel plant and further reviewed in consultation with a steel-industry expert with in-depth knowledge of the plant's operations. Key raw materials and reductants were modelled using UK supply chain datasets to ensure transparency and accuracy in the life cycle inventory. This approach ensures that the system boundary reflects industrial reality and provides a robust basis for scenario comparison.

The treatment of multifunctionality arising from the co-products is addressed in section 3.2.2.1 in accordance with ISO 14044 guidance (International Standard Organisation, 2022b).

Figures 16 to 20 show the cradle-to-gate system boundaries for hot metal production across Scenarios 1 to 5. Each diagram highlights the scenario-specific reductants in green and defines the system boundary by the dashed lines.

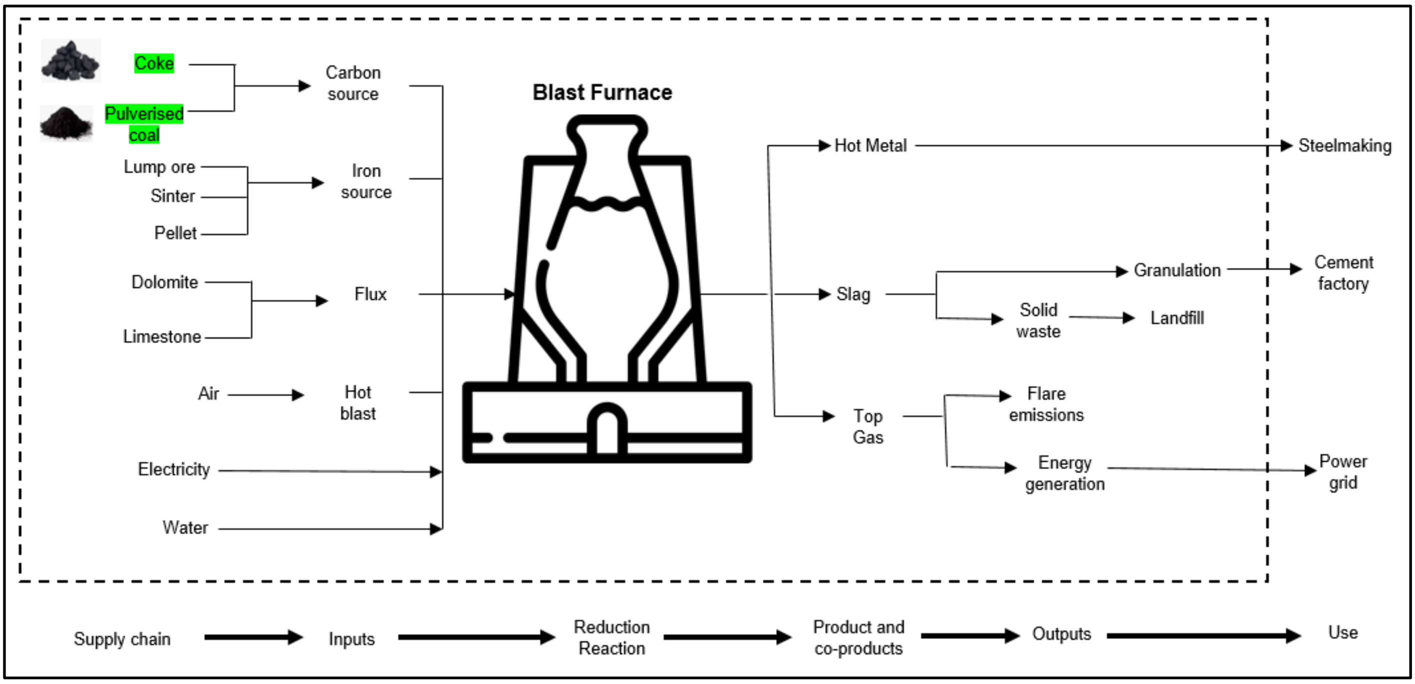

Figure 16: Cradle-to-Gate System Boundary and Material Flows for Hot Metal Production in Scenario 1 (Coke and Pulverised Coal)

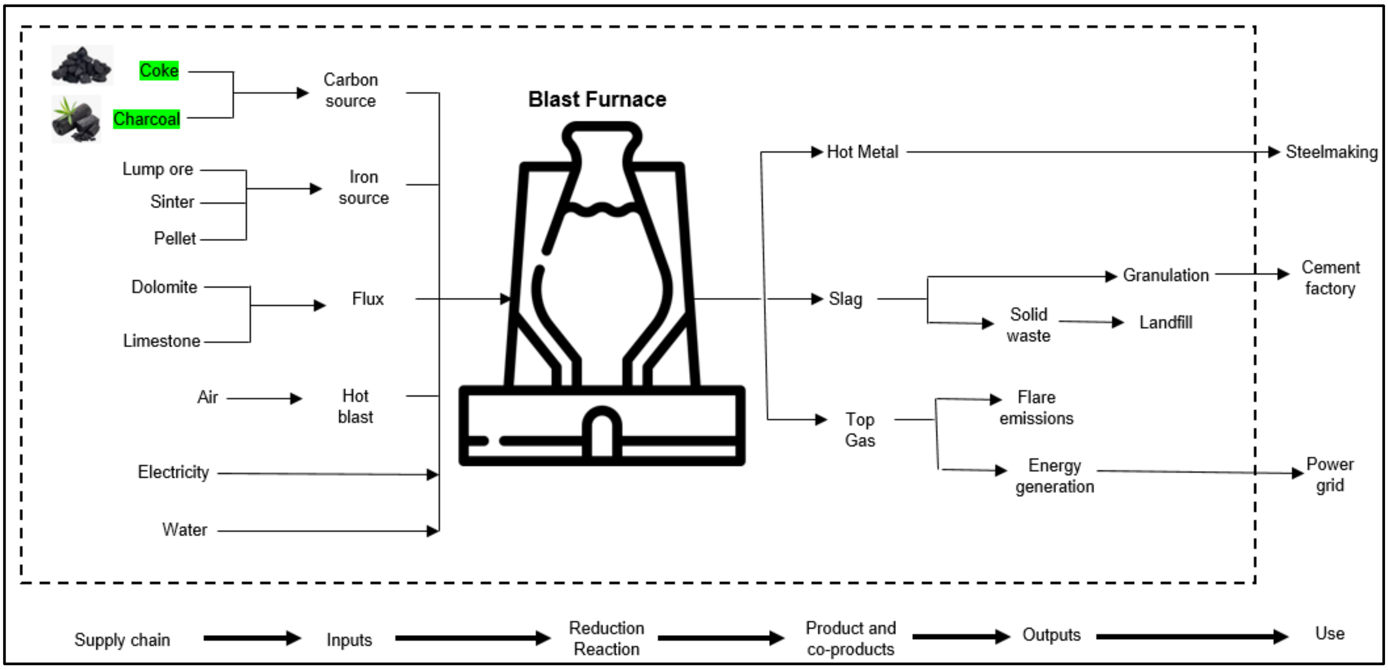

Figure 17: Cradle-to-Gate System Boundary and Material Flows for Hot Metal Production in Scenario 2 (Coke and Charcoal)

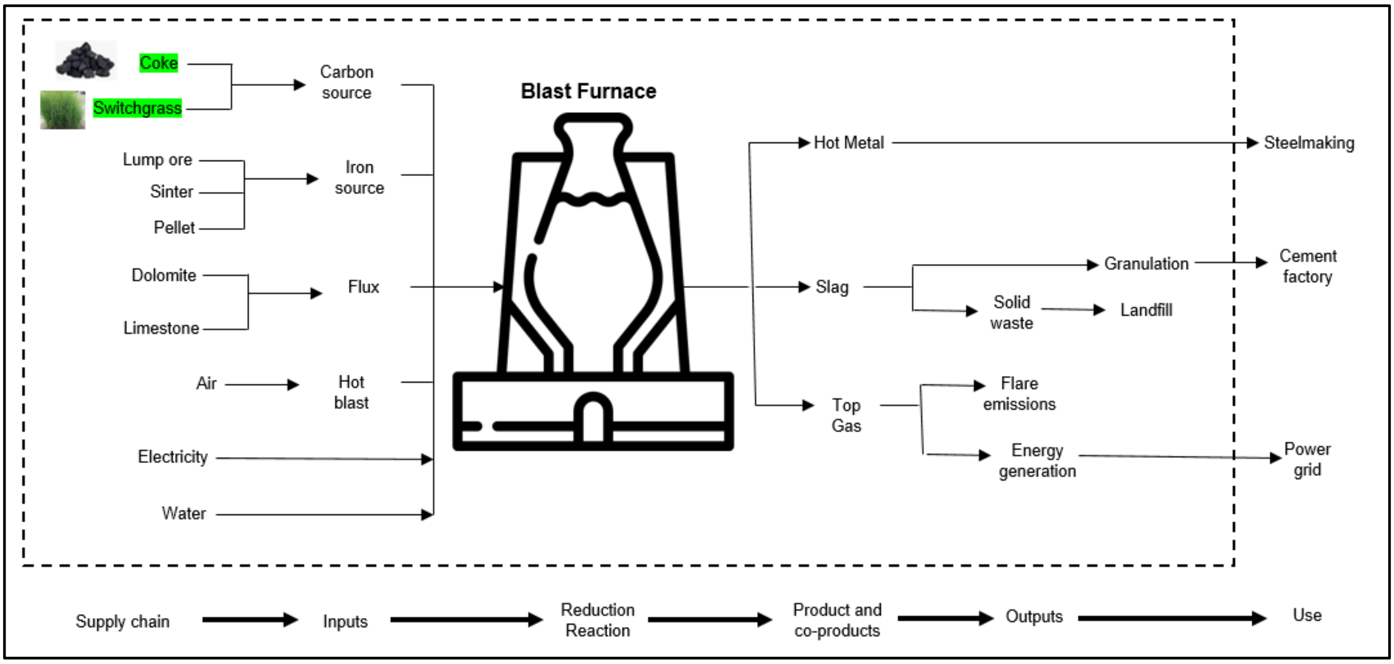

Figure 18: Cradle-to-Gate System Boundary and Material Flows for Hot Metal Production in Scenario 3 (Coke and Switchgrass)

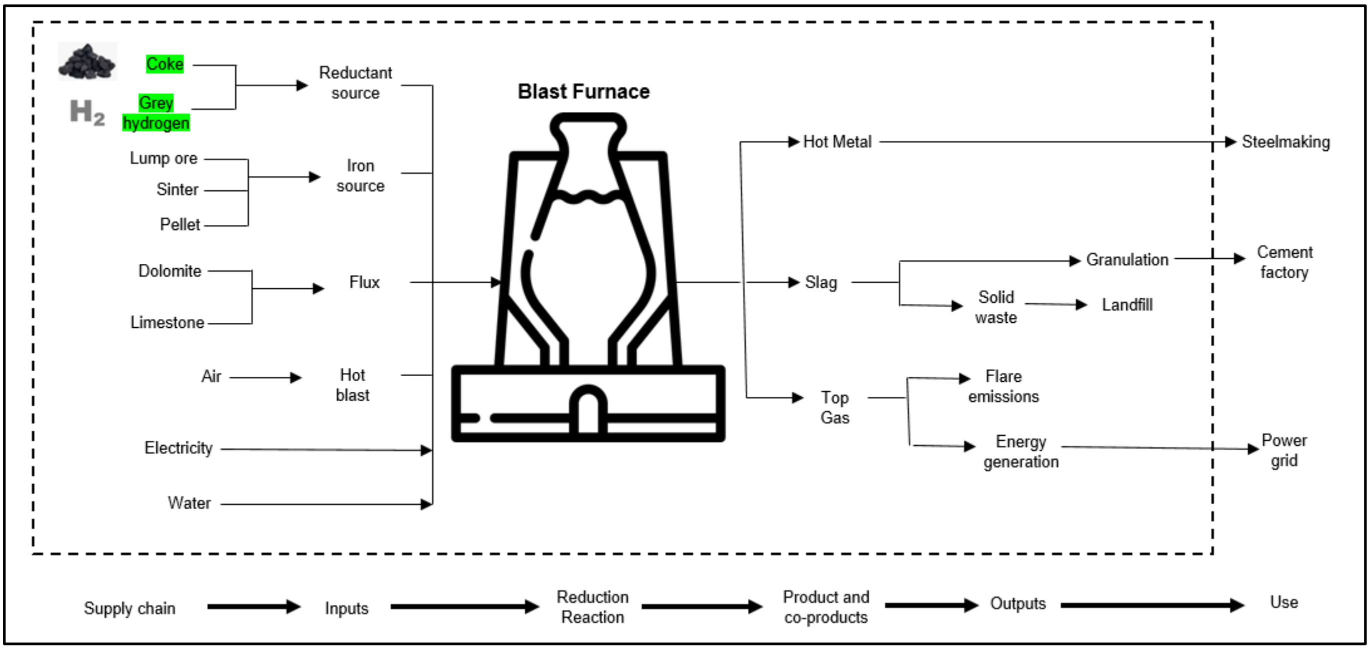

Figure 19: Cradle-to-Gate System Boundary and Material Flows for Hot Metal Production in Scenario 4 (Coke and Grey Hydrogen)

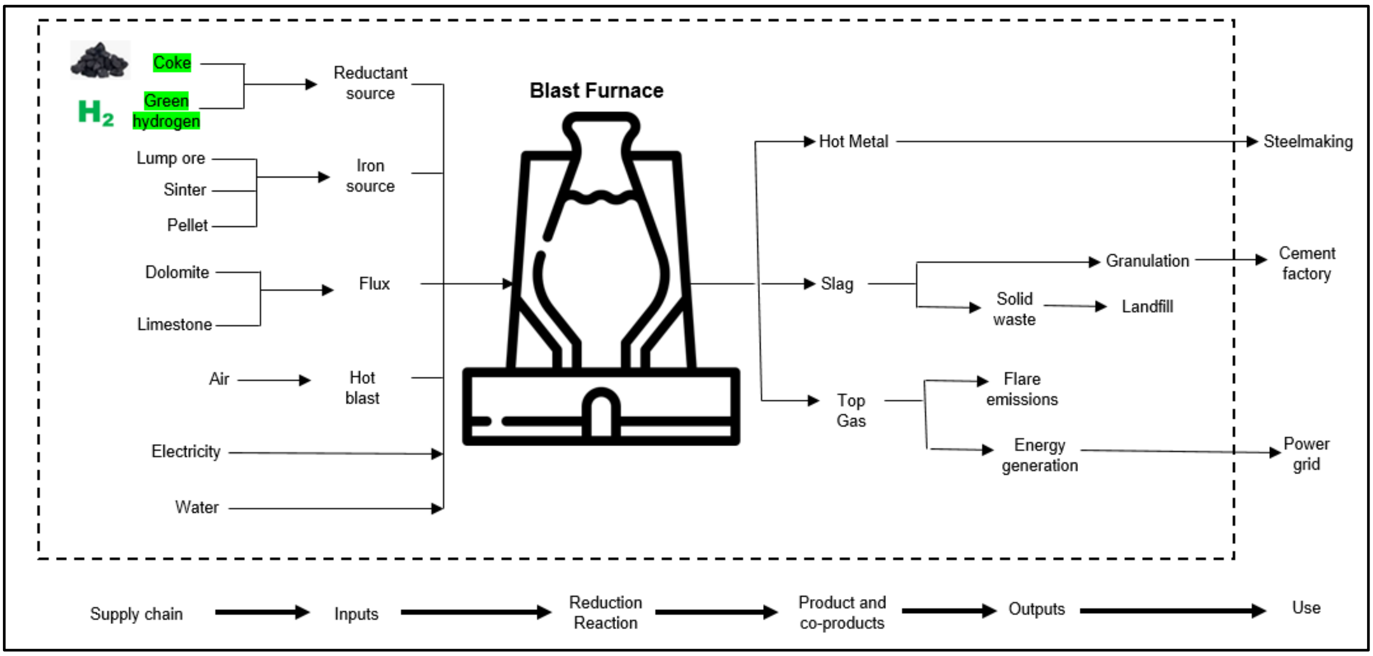

Figure 20: Cradle-to-Gate System Boundary and Material Flows for Hot Metal Production in Scenario 5 (Coke and Green Hydrogen)

Process Description

The blast furnace process begins with the preparation of feedstock, which includes iron-bearing materials (such as iron ore, iron sinter, and iron pellets) and carbon-bearing materials (e.g., coke, PCI, charcoal, and H_2). Fluxes such as dolomite and limestone are added to remove impurities. These inputs undergo a reduction reaction inside the blast furnace at high temperatures, facilitated by the injection of hot air. From the chemical reactions, liquid iron (hot metal) is produced as the main product. Slag and top gas are the co-products from the reaction. Utilities such as electricity, water, and natural gas are required for air compression, heating, material handling, and control systems. Top gas is recovered for energy generation within the plant, while slag is reused in cement production.

Treatment of Co-Products and System Expansion

The blast furnace process yields multiple products, including hot metal as the reference product and slag and top gas as co-products. This creates a multifunctionality challenge that needs to be addressed to ensure consistency and comparability of results across scenarios. The treatment of multifunctionality arising from the co-products is addressed in section 3.2.2.1.

3.2.2.1 Treatment of Multifunctionality

The blast furnace process yields multiple outputs concurrently; hot metal as the main product, blast furnace gas (BFG) and slag as co products. The multifunctionality in a process need to be addressed following a hierarchical decision framework in accordance with ISO 14044 guidance (International Standard Organisation, 2022b) as follows:

1. Subdivision or system expansion to avoid allocation wherever possible.
2. Physical allocation based on underlying physical relationship (e.g., mass, energy content).
3. Other allocation based on economic value.

In this research, subdivision as not feasible because BFG and slag are co-produced simultaneously within the blast furnace and cannot be separated through process reconfiguration without fundamentally changing the ironmaking process. Due to this constraint, system expansion was adopted as preferred approach under ISO 14044 guidance.

System expansion entails crediting the system for displacing equivalent processes or products that would otherwise need to provide similar functionality (2.0 LCA, 2014; International Standard Organisation, 2022b). In this assessment, slag can replace clinker in cement production, and BFG can displace natural gas for energy production. These avoided burdens are deducted from the total cradle-to-gate environmental impact of each blast furnace scenario.

System expansion was selected over alternative allocation methods (mass, energy, and economic) for several reasons. Firstly, this approach is consistent with steel industry practice and ISO standards. The World Steel Association recommends system expansion for multifunctional steel processes to recognise that co-products provide measurable substitution benefits (World Steel Association, 2017).

Although system expansion was preferred under Step 1 of ISO 14044, alternative approaches under Step 2 (mass allocation) and Step 3 (economic allocation) are also considered. Mass allocation is used to proportionally partition impacts based on output masses. However, this approach is not suitable since it ignores functional differences (energy in BFG versus role of hot metal) and the co-products are in different forms (solids and gas). Furthermore, energy allocation would be partitioned based on energy content. However, this approach fails to capture industrial substitution benefits, and it is challenging to define comparable energy content across products and co-products with different functions. Economic allocation is another method to partition products based on market value. For this research, the method is not suitable because BFG has no external market price, and slag prices fluctuate significantly by region and cement market conditions.

Operational data from a UK integrated steel plant for year 2023 were used to define the allocation of co-products. Blast furnace gas (BFG) is partially recovered and reused on-site for energy services, while slag is primarily sold to the cement industry as a substitute for clinker. The allocation shares for BFG use entail hot blast stove (21%), coke ovens (13%), on-site energy generation (60%), and unused losses (6%). For slag, 98% is sold to cement manufacturers to serve as a clinker substitute in cement production, with 2% remaining unused. The co-products, their main applications, and the displaced products are summarised in Table 35.

Table 35: Allocation of Blast Furnace Co Products at a UK Integrated Steel Plant and the Corresponding Displaced Products

Co Products	Usage Allocation (UK Integrated Steel Plant)	Application	Displaced Product
Blast Furnace Gas	Hot blast (21 %)	Preheating air in blast furnace stoves	Natural Gas
	Coke ovens (13 %)	Fuel for coke ovens	
	Energy generation (60 %)	On site electricity and steam generation	
	Unused (6 %)	Flaring or losses	
Slag	Cement manufacturer (98 %)	Clinker substitute in cement production	Clinker
	Unused (2 %)	Landfill	

Credits were applied for the avoided production of natural gas. Moreover, natural gas was assumed to be uniformly displaced for all external uses of recovered blast furnace gas for simplicity. Additionally, credits were applied for the avoided clinker production, which was displaced by ground granulated blast furnace slag (GGBS). The modelling assumptions, the background Ecoinvent version 3.10 datasets, and the supporting references are summarised in Table 36.

Table 36: Background Datasets for System Expansion Calculation

Co Products	Displaced Product	Ecoinvent v3.10 (APOS U) Dataset	Key Assumptions	Reference
Blast Furnace Gas	Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, U	Net calorific value of blast furnace gas is 3.4 MJ per Nm^3. All external uses are assumed to displace natural gas for simplicity	(International Flame Research Institution, 2003)
Slag (GGBS)	Clinker	Clinker {Europe without Switzerland}|	Slag substitutes clinker on a 1 to 1 mass basis.	(Cembureau, 2012)

		clinker production | APOS, U	Portland cement contains approximately 95 percent clinker by mass	

The specific quantities of BFG recovered for other uses and slag utilised as a clinker substitute for all five scenarios are summarised in Appendix A.1. The remaining BFG fraction was assumed to be flared, and the unused 2 percent share of slag was assumed to be landfilled, and this treatment was fully included within the system boundary. The avoided burdens from displaced natural gas and clinker were deducted from the total cradle-to-gate environmental impacts of each blast furnace scenario. This is through the assumption of 1 to 1 energy content displacement of blast furnace gas with natural gas, and 1 to 1 mass substitution of slag for clinker.

This research acknowledges that the choices of allocation methods can influence the comparative LCA environmental outcomes. System expansion was selected as the preferred approach in accordance with ISO 14044, as it aligns most closely with the functional and physical characteristics of blast furnace co-products. Although mass allocation, energy allocation, and economic allocation were reviewed under Step 2 and 3 of the ISO hierarchy, these methods were deemed unsuitable for the reasons outlined above. Nevertheless, alternative allocation may lead to different comparative outcomes and future work should quantitatively verify the robustness of scenario rankings under mass, energy, and economic allocation methods.

3.2.2.2 Cut-Off Criteria and System Boundary Exclusions

Cut-off refers to the exclusion of irrelevant life-cycle stages, specific processes, and elementary flows from the system model.

In the assessment, explicit cut-off criteria were established to determine which processes and material flows were included or excluded from the LCI in accordance with ISO 14044 Section 4.2.3.3 requirement for transparency in system boundary definition (International Standard Organisation, 2022b).

Processes and material flows were not included in the inventory if their individual contribution to the system was less than one percent of total mass, energy input, or predicted environmental impact. Additionally, the cumulative contribution of all excluded flows was required to remain below five percent of total system inputs and outputs. These thresholds align with commonly applied LCA practice documented in Section 6.6.3 of the European Commission's International Reference Life Cycle Data System Handbook (European Commission, 2010). The selected thresholds ensure that excluded flows do not have any impact on the conclusions of the assessment.

Capital infrastructure associated with blast furnace operation including the blast furnace itself, ancillary buildings, production machinery, and transport vehicles, was excluded from the life cycle inventory. This exclusion is justified because infrastructure-related environmental impacts are distributed over the operational lifetime of industrial facilities and the global average age of operating blast furnace is 24 years (Global Energy Monitor, 2025b). Therefore, the contribution to environmental impacts are assumed to be marginal. Furthermore, the environmental impacts were deemed negligible when prorated per tonne of hot metal across millions of tonnes produced over a facility's lifetime, the contribution is considered negligible. Moreover, this research assesses a comparative life cycle assessment in which all five reductant scenarios utilise the same blast furnace infrastructure at the case-study UK steel plant. Hence, any infrastructure-related impacts would be identical across scenarios and would cancel out in relative comparisons. Thus, the infrastructure exclusion does not affect the validity of comparative conclusions on the performance of alternative reductants.

3.2.3 Life Cycle Inventories (LCI)

This section describes the development of LCIs for each scenario, which quantify all material and energy flows, emissions, and process outputs within the cradle-to-gate boundary. Developing a transparent and robust inventory is essential for any LCA, as it allows quantification of all material and energy flows, inputs and output emissions associated with each process stage. This entails the extraction and processing of raw materials, transportation, on-site blast furnace operations at the UK steel plant, and all process outputs up to the point where hot metal exits the blast furnace. The approach taken here is consistent with established LCA methodologies in the steel sector (Burchart-Korol, 2013; Renzulli et al., 2016; Leão et al., 2023).

A hybrid data approach was employed, utilising primary data from the case-study UK steel plant wherever possible. Data from peer-reviewed literature and the Ecoinvent v3.10 database were used to fill gaps, particularly as direct operational data became limited following the decommissioning of the blast furnaces at the case-study plant in 2024. All data were harmonised to a standard functional unit of one tonne of hot metal (tHM), and scenario boundaries, assumptions, and parameter choices were kept consistent unless directly affected by the choice of reductant. Special attention was given to UK-contextualised factors, including supply-chain routes, transport distances, and utility mixes.

Each scenario is described in detail in the subsequent subsections of the thesis, explaining how the inventories were developed, which adaptations were made, and how data sources were selected and justified.

Scenario 1 (Coke and pulverised coal)

Scenario 1 serves as the baseline, representing conventional blast furnace operation using coke and pulverised coal as reductants. Foreground inventory data were primarily sourced from reputable literature by Ng et al. (2010) and supplemented with operational records from the case-study UK steel plant, as well as additional data from a peer reviewed study by Leao et al. (2023). These data are regarded as representative of European blast furnace practice and were further cross-checked against inventories of Suopajarvi et al. (2018), Geerdes et al. (2015), and Cameron et al. (2019).

Several adaptations were necessary to represent the UK context accurately. The proportions of iron-bearing materials (lump ore, pellet, and sinter) were updated using operational data from the case-study UK steel plant. International transport distances for key raw materials (reductants and iron-bearing materials) were calculated using Google Maps and a Sea Rate Distance Calculator (Sea Rates by DP World, 2025) to match current supply routes to the UK steel plant. Raw material origins and percentages are based on the most recent UK trade statistics (refer to Table 37), which take into account the top three importers. Road transportation was modelled exclusively using lorries, due to the lack of consistent rail data.

Energy and water inputs were represented using UK-contextualised datasets from the Ecoinvent database. Where emissions and utility use data were missing, values were taken from Leao et al. (2023) or reviewed in consultation with an expert familiar with the operations of the case-study UK steel plant (Holliman, 2025). Water emissions are excluded for all scenarios since there are no robust data and the values are considered negligible (Leão et al., 2023). Foreground process flows are listed in Table 37, while background datasets are listed in Table 38. All assumptions, calculations, and UK-contextualised parameter choices are documented for transparency and reproducibility.

Table 37: Foreground Inventory Data for Scenario 1 – Coke and Pulverised Coal as Reductants

Categories	Data	Value	Unit	Source	Remarks
Inputs	Iron lump ore	196	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron pellet	393	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron sinter	921	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Coke	370	kg	Ng et al., 2010	Use conversion 28.6 MJ/kg in SimaPro
	Pulverised coal	140	kg	Ng et al., 2010	
	Dolomite	35	kg	Ng et al., 2010	
	Limestone	35	kg	Ng et al., 2010	
	Air	1413	kg	Ng et al., 2010	Assume air density is 1.293 kg/m3
	Water	906.3	kg	Leao et al., 2023	
	Electricity	111.4	kW	Leao et al., 2023	
	Transport (road)	3070	t.km	Manual calculation	Google Maps was used to estimate the road distance to transport raw materials from the importers to the UK port.
	Transport (sea)	29978	t.km	Manual calculation	The Sea Distance Calculator estimated the

					distance by sea to transport raw materials from the importers to the UK port.
Output (Reference Product)	Pig Iron (Functional Unit)	1000	kg	NA	
Output (By/co-products)	Slag	250	kg		
	Top Gas	1660	Nm3	Ng et al., 2010	
Emissions to the air	CO_2 (Fossil)	762.5	kg	Ng et al., 2010	
	CO (Fossil)	481.4	kg	Ng et al., 2010	
	H_2	5.4	kg	Ng et al., 2010	
	N_2	1037.5	kg	Ng et al., 2010	

Background inventory datasets used for Scenario 1 are presented in Table 38.

Table 38: Background Inventory Datasets for Scenario 1

	Item	**Intermediate and Elementary Flows in Ecoinvent version 3.10**
Inputs	Lump ore	Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | APOS, U
	Pellet	Iron pellet {RoW}| iron pellet production | APOS, U
	Sinter	Iron sinter {RoW}| iron sinter production | APOS, U
	Coke	Coke {RoW}| coke production | APOS, U
	Pulverised coal	Hard coal {RoW}| hard coal mine operation and hard coal preparation | APOS, U
	Dolomite	Dolomite {RoW}| market for dolomite | APOS, U
	Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U
	Air	Air
	Water	Water, decarbonised {GB}| market for water, decarbonised | APOS, U
	Electricity	Electricity, medium voltage {GB}| market for electricity, medium voltage | APOS, U
	Road Transport	Transport, freight, lorry 16–32 metric ton, EURO5 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U

	Sea Transport	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land trasformation	Carbon dioxide, land transformation
	CO_2 fossil	Carbon dioxide, fossil
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	CO fossil	Carbon monoxide, fossil
	H_2O	Water
	H_2	Hydrogen
	N_2	Nitrogen
	O_2	Oxygen
	Particulates	Particulate

Several assumptions were made to tailor the study to represent the UK context specifically and to compensate for gaps in data availability.

1. Data from Ng et al. (2010) showed that iron pellets contributed to around 1510 kg per tonne of hot metal, but this figure only reflected one form of iron. Since the case-study UK steel plant provided specific data on the proportions of iron-bearing materials (ore, lump, and pellets), this research used those figures. The percentages of iron-bearing materials used to produce 1 tonne of hot metal at the case-study plant are presented in Table 39. The quantities and proportions of iron-bearing materials are also identical for Scenarios 2 to 5.

Table 39: Type of Iron Form and Percentage (Tata Steel UK, 2024)

Type of iron form	Percentage (%)	Quantity (kg)
Iron lump	13	196
Iron pellet	26	393
Iron sinter	61	921
	Total	1510

2. The sourcing of primary raw materials (iron ore, coking coal, etc) has been updated to reflect imports of raw materials to the UK based on data from the UK Trade Association for 2024, necessitating revisions to the distances travelled by road and sea. The delivery location in the UK is the bulk-handling port serving the UK steel plant. The details of raw materials imported and the percentage of raw materials imported to the UK are shown in Table 40:

Table 40: Details of Raw Materials Importers and % of Imports to the UK

Raw Materials	Exporters, Countries and Percentage of Import	References
Iron-bearing materials	Norway (48%) Canada (27%) Netherlands (26)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)

Note: Percentages may not sum to exactly 100% due to rounding.

3. Electricity and water sources have been adjusted to align with specific UK conditions customised in SimaPro software.
4. Road transportation for moving raw materials from producers to the ports in the exporting countries is assumed to be via truck instead of rail to ensure consistency in the assessment for comparative purposes. This is due to a lack of data regarding rail distances and efficiencies.
5. The distances from raw material producers to the ports in the exporting countries are estimated using Google Maps.
6. The sea travel distances from the exporting countries to the UK steel plant's are calculated with the Sea Rate Distance calculator.
7. A round-trip journey was considered for road and sea transportation.

While the previous parameters were revised to adapt to UK ironmaking, the following parameters and conditions are kept the same, as described below.

- **Technological Equivalence**: The blast furnace technology, process specifications, and operating practices in Canada, as reported by Ng et al. (2010), are broadly consistent with those in the UK. This similarity applies to furnace size, efficiency levels, process parameters, and overall production methods.
- **Raw Material Quality and Quantity**: The quality, quantity, physical composition, and chemical composition of iron-bearing materials (e.g., ore, pellet, and sinter), carbon-bearing materials (e.g., coke), fluxes, and other raw materials are the same in Canada and the UK. The quantity of raw materials by Ng et al., 2010 to produce 1 tonne of hot metal is almost consistent with the value suggested by the literature and Handbook of Ironmaking (Geerdes et al., 2015; Suopajärvi et al., 2018).

- **Energy Consumption**: Energy consumption and efficiency used are the same. This includes fuel usage (coke, coal, natural gas) and auxiliary energy sources (electricity, hot blast air).
- **Process Efficiency**: Process efficiency, yield rate, losses, and waste generation are assumed to be similar in the UK.
- **Environmental Performance**: Air emissions, water usage, waste generation, and resource consumption.

Scenario 2 (Coke and charcoal)

The second scenario evaluates the environmental impact of replacing pulverised coal with charcoal as the auxiliary reductant, while coke continues to fulfil its primary role. The maximum feasible substitution ratio was established based on Ng et al. (2010), with supporting evidence from Suopjarvi et al. (2018) that benchmarked the feasibility of charcoal as an alternative reductant. This literature was chosen since it provides robust foreground data supported by simulation and has been verified with several other literatures that explore the feasibility of using charcoal as an alternative reductant, such as work done by Suopajarvi et al (2018). Besides, the data produced by Ng et al (2010) was peer reviewed and considered industry-accepted data sources and hence supports the transparency and robustness of the LCA study. In practice, process simulation using software such as AspenPlus can be used to generate foreground data. However, due to the time constraint and the larger availability of foreground data for charcoal used in blast furnaces, it is decided that this research is supposed to fill the gaps by focusing on using the LCA framework to translate foreground data generated by Ng et al (2010) into the detailed environmental impacts.

Charcoal production data were taken from Leao et al. (2023), which provides a comprehensive inventory for eucalyptus-derived charcoal produced in modern kilns. This dataset was selected because it clearly specifies feedstock composition and process energy requirements. Additionally, the dataset represents charcoal production from a single hardwood species, rather than a mix of hardwood species.

All other aspects of the process, including iron input, flux addition and site operations, remain consistent with Scenario 1, to ensure a fair comparison. Charcoal imports were modelled based on recent UK import data, with Namibia, Paraguay, and South Africa identified as the principal suppliers. Both road and sea transport distances were recalculated for these supply chains. Water and electricity supply were adapted for UK conditions.

The foreground data used in this research for Scenario 2 are summarised in Appendix B.1.1. Background inventory datasets used for Scenario 2 are presented in Appendix B.1.2.

The inventory data for producing 1 tonne of charcoal is sourced from Leao et al. (2023) and summarised in Appendix B.1.3. The dataset was chosen over Ecoinvent's because it is robust and peer-reviewed. Additionally, this research aims to investigate the impact of wood choices on emissions. The Ecoinvent data assumes production from a mix of hardwoods but does not specify the proportions of each species. Hence, it is challenging to accurately assess individual contributions to emissions. The parameters that have been revised to be UK-contextualised for Scenario 2 are listed in Appendix B.1.4.

Scenario 3 (Coke and switchgrass)

In Scenario 3, switchgrass is assessed as a replacement for pulverised coal, while coke is maintained at levels necessary for stable blast furnace operation. The process follows the same structure as in the previous scenarios, with modifications to account for the use of switchgrass as a bio-based auxiliary reductant. The maximum feasible substitute amount is derived based on Ng et al. (2010), a study selected for its robust foreground data supported by process simulation. This source was also peer-reviewed and recognised by the steel industry, enhancing the transparency and credibility of using the data. Although process simulation tools such as AspenPlus can be utilised to generate similar data, this research focuses on using the LCA framework to translate the data from Ng et al. (2010) into detailed environmental impact results due to time constraints. In addition, this approach helps to fill current gaps in assessing the use of bio-based reductants in blast furnace ironmaking. The switchgrass inventory was constructed using the Ecoinvent version 3.10 'mischantus, chopped' dataset as a proxy due to the unavailability of a robust dataset of mischantus. Miscanthus has similar agronomic characteristics and energy profiles with switchgrass and is therefore considered a suitable proxy in bioenergy and LCA studies, although differences in yield and site adaptability need to be acknowledged (McLaughlin et al., 2005; Hastings et al., 2009).

Given the absence of large-scale domestic switchgrass production, it is assumed that all switchgrass is imported from the USA, reflecting the current global supply pattern for perennial energy crops. Transport distances were recalculated accordingly, and other utility and process inputs follow UK-contextualised parameters. Any scenario-specific assumptions are also explained as follows.

The foreground data used in this research for Scenario 3 are summarised in Appendix B.2.1. Background inventory datasets used for Scenario 3 are presented in Appendix B.2.2. The parameters that have been revised to be UK-contextualised for Scenario 3 are summarised in Appendix B.2.3.

Scenario 4 (Coke and grey H_2)

Scenario 4 evaluates the use of grey H_2, produced via steam methane reforming, as a substitute for pulverised coal. The maximum feasible hydrogen substitution and all process substitutions were taken from Yilmaz et al. (2017). The methodology used by Yilmaz et al. (2017) integrates process simulations performed using Aspen Plus software, combined with FactSage/ChemApp software, and further validated based on actual operating data from a steel plant in Germany. The combination of simulation and verification approaches strengthens the reliability and representativeness of the data. Moreover, the data produced by Yilmaz et al. (2017) have been peer-reviewed, enhancing the transparency and scientific rigour needed in LCA. This assessment also addresses a notable gap where numerous studies have explored the feasibility of hydrogen use in the blast furnace process through simulation models. However, relatively few environmental impact assessments using the LCA framework have been conducted. The dataset for grey H_2 was sourced from Hren et al. (2023) due to its robustness as it is highly cited publication and peer-reviewed. Additional sources from the literature were also partially used to complete the inventory such as those from Ng et al. (2010) and Leao et al. (2023). This study provides a robust reference point for inventory development, particularly given the increase of interest in H_2 as a reductant in ironmaking.

For UK adaptation, H_2 is assumed to be sourced from domestic production, which reflects both market reality and policy direction (BOC Limited, 2025). Transport distances, energy mix, and process inputs remain aligned with the UK context. Any scenario-specific assumptions are also explained as follows.

The foreground data used in the SimaPro simulation for Scenario 4 is presented in Appendix B.3.1. Background inventory datasets used for Scenario 4 are presented in Appendix B.3.2. The foreground inventory for producing 1 tonne of grey H_2 via steam methane reforming is summarised in Appendix B.3.3. The parameters that have been revised to be UK-contextualised for Scenario 4 are summarised in Appendix B.3.4.

Scenario 5 (Coke and green H_2)

The fifth scenario considers the environmental impacts of using green H_2, specifically H_2 generated by wind-powered electrolysis as a substitute reductant. The operational parameters and substitution ratio remain identical to those used in Scenario 4, to allow direct comparison. The primary difference lies in the H_2 background dataset, which was also selected from peer-reviewed literature similar to Scenario 4 (Hren et al., 2023).

No additional international transport was assumed for green H_2, since this scenario assumes it is sourced domestically in the UK. Transport distances, energy mix, and process inputs remain aligned with the UK context. Any scenario-specific assumptions are also explained as follows

The foreground inventory datasets for Scenario 5 are presented in Appendix B.4.1. Background inventory datasets used for Scenario 5 are presented in Appendix B.4.2. The foreground inventory for producing 1 tonne of green H_2 via electrolysis powered by wind energy is summarised in Appendix B.4.3. The details of raw materials imported and % of raw materials imported to the UK for Case 5 are shown in B.4.

Scenario Summaries

Inventories across all five scenarios were harmonised to enable direct comparison. The proportions of lump ore, pellet, and sinter were based on the most up-to-date operational data from the case-study UK steel plant (2024). For all materials, supply origins and transport distances were recalculated to match the actual routes to the UK steel plant, using the most current trade data. Energy and water utilities were modelled using UK-contextualised datasets throughout. Trucks were used for all road transportation due to the unavailability of robust rail datasets. Round-trip journeys were assumed for all transport stages. System boundaries were clearly defined, covering cradle-to-gate operations. All data sources, calculation methods, and any scenario-specific assumptions are documented in this section. This approach ensures the transparency, reproducibility, and policy relevance of the results.

The summary of foreground data for all scenarios is summarised in Table 41. This summary provides a clear, side-by-side comparison with consistent operational and methodological assumptions.

Table 41: Summary of Foreground Data for All Five Scenarios.

Scenarios		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Unit**
		Coke and pulverised coal	**Coke and charcoal**	**Coke and switchgrass**	**Coke and grey H_2**	**Coke and green H_2**	
Inputs	Iron lump ore	196	196	196	196	196	kg
	Iron pellet	393	393	393	393	393	kg
	Iron sinter	921	921	921	921	921	kg
	Coke	370	364	449	389.8	389.8	kg
	Auxiliary Reductants	140 (Pulverised coal)	140 (Charcoal)	140 (switchgrass)	27.5 (grey H_2)	27.5 (green H_2)	kg
	Dolomite	35	19	35	35	35	kg
	Limestone	35	19	35	35	35	kg
	Air	1413	1413	1413	1159	1159	kg
	Water	906.3	906.3	906.3	906.3	906.3	kg
	Electricity	111.4	111.4	111.4	111.4	111.4	kW
	Transport (road)	3070	3096	3070	2928	2928	t.km
	Transport (sea)	29978	32134	28479	27377	27377	t.km
	Transportation (pipeline)	-	-	-	14	3	tkm
Output (Reference Product)	Pig Iron (Functional Unit)	1000	1000	1000	1000	1000	kg

Output (By/co-products)	Slag	250	250	250	250	250	kg
	Top Gas	1660	1654	1724	1446	1446	Nm3
Emissions	CO_2 (Fossil)	762.5	552	604.5	566.8	566.8	kg
	CO_2 (Biogenic)	-	215	190.9	-	-	kg
	CO (Fossil)	481.4	359	402.9	313.1	313.1	kg
	CO (Biogenic)	-	140	127.2	-	-	kg
	H_2	5.4	3.6	6.4	16.2	16.2	kg
	N_2	1037.5	1035.8	1036.6	892.8	892.8	kg

The summary of UK Trading Information for key raw materials imported to UK across all five scenarios is summarised in Table 42.

Table 42: UK Trading Information for Raw Material Imports

Raw Materials	Importing Countries and Percentage of Imports (%)	References
Iron Ore	Norway (48%) Canada (27%) Netherlands (26%)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)
Charcoal	Namibia (40%) Paraguay (33%) South Africa (28%)	(The Observatory of Economic Complexity, 2025b)
Switchgrass	USA (100%)	(IEA Bioenergy, 2011)
Grey H_2	UK- BOC Gas Teeside (100%)	(BOC Limited, 2025)
Green H_2	UK- Milford Haven Milway (100%)	(RWE, 2025)

3.2.4 Impact Assessment Methods

The aim of impact assessment is to estimate the significance of potential environmental impacts based on LCI results (International Standard Organisation, 2022a). This phase involves linking the inventory data from Section 3.2.3 with specific environmental impact categories to understand these impacts better. The evaluation was conducted using the ReCiPe-2016 (H) version method.

This research applies the ReCiPe-2016 midpoint (H) as the primary method. A parallel assessment using the Environmental Footprint (EF) method was not conducted because ReCiPe aligns with both the research objectives and current practice in UK LCA studies. Although the EF method is increasingly used for environmental reporting within the European Union, the UK is not bound by the EU methodological requirements following Brexit. UK industrial LCAs continue to rely predominantly on ReCiPe, and there is no regulatory or industry requirement to adopt the EF method. Therefore, the use of ReCiPe in this research aligns with established UK practice.

The ReCiPe-2016 midpoint (H) method offers several advantages. This method encompasses 18 impact categories that cover a range of environmental impacts, including climate change, resource depletion, human health, and ecosystem quality. Hence, it can provide a holistic assessment of the ironmaking environment and footprint. Besides, this method focuses on the midpoint impact that can identify the environmental hotspot in the processes before it translates into environmental damage. The midpoint approach allows the identification of hotspots in ironmaking for decarbonisation. Lastly, the ReCiPe-2016 midpoint method is also used widely. It is a standardised method which allows the comparison of results with those of other steel producers and industries that employ the same environmental assessment method (Huijbregts et al., 2016).

Only five impact categories (at the midpoint level), such as global warming potential (GWP), (also known as climate change), fossil resource scarcity (FRS), mineral resource scarcity (MRS), land use (LU), and water consumption are focused in this research since these five are the most relevant to the steel industry for decarbonisation purposes. This prioritisation does not imply that other categories, such as toxicity-related impacts, are irrelevant. The foreground inventories used in this research were developed primarily from literature and database sources (Ng et al., 2010; Yilmaz et al., 2017; Leão et al., 2023). The direct emission flow required for some impact categories was not consistently available with adequate robustness across all scenarios. Therefore, restricting the analysis to five impact categories reduces the risk of false precision while also conserving a transparent and comparable basis for scenario assessment. Table 43 describes the five impact categories used in this research.

Table 43: Impact Categories for Environmental Impacts Evaluation (Huijbregts et al., 2016) (Ecochain, 2024)

Impact Categories	Unit	Description
Global warming Potential (GWP)	kg CO_2 eq	This indicates the potential for global warming due to the emission of greenhouse gases, including CO_2, CH_4, N_2O, HFC, and PFC, among others.
Fossil resources scarcity (FRS)	kg oil eq	An indicator of the potential future burden of resources that contain hydrocarbons based on the current depletion rate. This includes volatile materials (e.g., methane, gasoline) and non-volatile materials (e.g., anthracite coal).
Mineral resource scarcity (MRS)	kg Cu eq	An indicator of the potential future burden of mineral resource extraction based on the current depletion rate due to human activities.
Land use (LU)	m^2a crop eq	An indicator of the transformation and occupation of land due to human activities, including habitat loss, soil degradation, and biodiversity decline.
Water Consumption	m^3	An indicator of freshwater consumed (through evaporation, utilisation into products, or transfer to other watersheds), measured as the volume of water withdrawn and not returned to the same watershed.

The results of the LCA assessment conducted across five blast furnace ironmaking scenarios are presented and discussed in Chapter 5.

3.3 Data Quality Assessment

High-quality life cycle inventory (LCI) data are essential for generating reliable, credible, and reproducible LCA results. Given that LCI sources can range from direct measurements to modelled estimates and generic databases, evaluating the data quality is crucial to ensure transparency in interpretation.

In this research, the Pedigree Matrix method is applied to evaluate the quality of LCI data. This approach is adapted from methodology developed by Weidema et al. (2013) for the Ecoinvent database, and is consistent with data quality requirements outlined in ISO 14044 (Weidema et al., 2013; International Standard Organisation, 2022b). The Pedigree Matrix evaluates the data against five key criteria as summarised in Table 44.

Table 44: Five Data Quality Criteria in the Pedigree Matrix Method (Weidema et al., 2013)

No	Criteria	Description
1.	Reliability	To assess whether the data are based on direct measurement, validated modelling, or assumptions.
2.	Completeness	To evaluate whether all relevant inputs, outputs, emissions, and by-products are included.
3.	Temporal Correlation	To assess the age of the data and its relevance to the period of the study.
4.	Geographical Correlation	To evaluate the relevance of the dataset to the location of the system under study (e.g., the UK).
5.	Technological Correlation	To assess how closely the technology or process described in the dataset matches the actual technology used in the system, such as the UK blast furnace.

Each criterion is scored on a scale of 1 (high quality, low uncertainty) to 5 (low quality, high uncertainty). This structured scoring allows transparent evaluation of data robustness and systematic interpretation of uncertainty.

For this research, the Pedigree Matrix approach is applied primarily to foreground data, as these are largely derived from technical reports, peer-reviewed literature, and expert input. Generic background data from Ecoinvent version 3.10 already includes embedded pedigree and uncertainty information and were therefore not reassessed. However, background data for charcoal production and hydrogen generation are included in this assessment since the data are sourced from peer-reviewed literature and are critical to the outcomes of the LCA study.

These scores provide a structured method to assess data robustness and support interpretation of data uncertainty. The scores for each criteria for each scenario were assigned based on guidance in Table 45.

Table 45: Pedigree Matrix Used to Assess Data Quality (Weidema et al., 2013)

Indicator score	**1**	**2**	**3**	**4**	**5** (default)
Reliability	Verified[5] data based on measurements[6]	Verified data partly based on assumptions *or* non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered *or* >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered *or* some sites but from shorter periods	Representativeness unknown or data from a small number of sites *and* from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown *or* distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale *or* from different technology

The foreground inventory data for all scenarios were collected from various sources. For Scenarios 1, 2, and 3, data were sourced from an industrial-linked report written by Ng et al (2010) and also from inputs provided by a representative from the case-study UK steel plant (Tata Steel UK, 2024). For Scenarios 4 and 5, the foreground data was primarily sourced from a peer-reviewed paper written by Yilmaz et al (2017), and further supported by inputs from the case-study UK steel plant.

Table 46: Sources of Foreground Data for Five Scenarios

No	Scenario	Sources of Foreground Data
1.	Coke + pulverised coal (Base scenario)	Ng et al (2010) Tata Steel UK (2024)
2.	Coke + charcoal	Ng et al (2010) Tata Steel UK (2024) Leao et al (2023)
3.	Coke + switchgrass	Ng et al (2010) Tata Steel UK (2024)
4.	Coke + grey H_2	Yilmaz et al (2017) Tata Steel UK (2024)
5.	Coke + green H_2	Yilmaz et al (2017) Tata Steel UK (2024)

The results of data quality assessment conducted across five blast furnace ironmaking scenarios are presented and discussed in Chapter 6 (Section 6.1).

3.4 Sensitivity Analysis

The sensitivity of input parameters was systematically assessed to evaluate how input variations influence the overall LCA outcomes. A series of input parameters was introduced to reflect plausible variations in material sourcing, supply chain configurations, and background datasets. These were selected based on the hotspot contributors identified in the LCA findings, as summarised in Table 47. The percentage presented in Table 47 represents each source’s contribution to total emissions (for example, a value of 51% suggests that the source accounts for 51% of overall emissions).

Table 47: Summary of Hotspot Contributors for Impact Categories in All Five Scenarios

Impact Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Coke + PC (Base scenario)	Coke + charcoal	Coke + switchgrass	Coke + grey H_2	Coke + green H_2
Global Warming Potential	Blast furnace emission (51%)	Blast furnace emission (41.4%)	Blast furnace emission (46.3%)	Blast furnace emission (31.8%)	Blast furnace emission (43%)
Land Use	Coke (39.3%)	Charcoal (73.2%)	Switchgrass (70.1%)	Coke (44.4%)	Coke (43.8%)
Fossil Resource Scarcity	Coke (67.8%)	Coke (88.8%)	Coke (91%)	Coke (87.6%)	Coke (89.1%)
Water Consumption	Coke (48%)	Coke (47.5%)	Coke (52.3%)	Coke (42.4%)	Coke (45.8%)
Mineral Resource Scarcity	Iron sinter (58.4%)	Iron sinter (58.4%)	Iron sinter (58.3%)	Iron sinter (58.4%)	Iron sinter (58%)

The LCA results show that coke was the primary hotspot across all five scenarios in terms of global warming potential (GWP), fossil resource scarcity, and water consumption. For land use, the dominant contributors are charcoal in Scenario 2 and switchgrass in Scenario 3, indicating the significant land requirements associated with biomass cultivation. Switchgrass will not be considered in the sensitivity analysis since there is no robust alternative dataset that can be used, and the environmental benefits are also low. For mineral resource scarcity, iron sinter was consistently identified as the primary hotspot across all five scenarios. These findings provide the rationale for selecting input variations to be tested in the sensitivity analysis.

Following this, a targeted set of sensitivity scenarios was developed, tailored to each impact category. For GWP, the analysis evaluates the effects of varying coke production regions (US and Germany), iron-bearing sources (100% pellets and 50:50 pellet-sinter mix), and transportation distances. Other categories, including water consumption, FRS, and MRS, were also tested under the same input changes to assess whether similar trends apply. For land use, sensitivity was evaluated by replacing the original charcoal inventory with an Ecoinvent Dataset for Scenario 2, to reflect the different hardwood species, yield assumptions, and production technologies. The summary of sensitivity scenarios is presented in Table 48.

Table 48: Sensitivity Scenarios for Each Impact Category

Impact Categories	Sensitivity Scenarios	Scenarios
GWP	Coke Production in the US	All Scenarios
	Coke Production in Germany	
	100% Iron pellet	
	50% sinter, 50% pellet	
	Shortest Transportation Distance	
	Longest Transportation Distance	
Land Use	Charcoal Inventory from Ecoinvent	Scenario 2
Water Consumption	Coke Production in the US	All Scenarios
	Coke Production in Germany	
	100% Iron pellet	
	50% sinter, 50% pellet	
	Shortest Transportation Distance	
	Longest Transportation Distance	
Fossil Resource Scarcity (FRS)	Coke Production in the US	All Scenarios
	Coke Production in Germany	
	100% Iron pellet	
	50% sinter, 50% pellet	
	Shortest Transportation Distance	

	Longest Transportation Distance	
Mineral Resource Scarcity (MRS)	Coke Production in the US	All Scenarios
	Coke Production in Germany	
	100% Iron pellet	
	50% sinter, 50% pellet	
	Shortest Transportation Distance	
	Longest Transportation Distance	

The results of the sensitivity analysis assessment conducted across five blast furnace ironmaking scenarios are presented and discussed in Chapter 6 (Section 6.2).

CHAPTER 4

4.0 RESULTS AND DISCUSSION: ASSESSMENT OF SOLID ALTERNATIVE REDUCTANTS

This chapter presents the results of the preliminary assessment of solid reductants and discusses their relative technical, environmental, and economic performance. It evaluates efficiency, indicative environmental impacts, cost considerations, and multi-criteria scores to establish the strengths and limitations of each option. The findings serve as a preliminary screening that informs the selection and interpretation of the scenarios examined in the full life cycle assessment in the subsequent chapter.

4.1 Assessment of Solid Alternative Reductants

This section presents a comparative assessment of charcoal, subcoal and wood pellets as solid alternative reductants for blast furnace ironmaking under UK-contextualised conditions. This preliminary assessment was conducted in the first year of the EngD and was designed to identify the most viable solid alternative reductant. This evaluation integrates three core dimensions: process efficiency, environmental impact, and economic viability. These dimensions are combined in a multi-criteria scoring framework to allow a structured comparison and provide transparency on the trade-off between solid alternative reductants. The results inform the selection of the most promising solid reductant for detailed cradle-to-gate analysis in subsequent stages of the research. The results are presented and discussed as follows.

4.1.1 Efficiency Assessment

Figure 21 presents the total mass of reductant required to produce 1 tonne of hot metal (tHM) across five different coke-replacement scenarios based on the methodology described in Section 3.1.1.

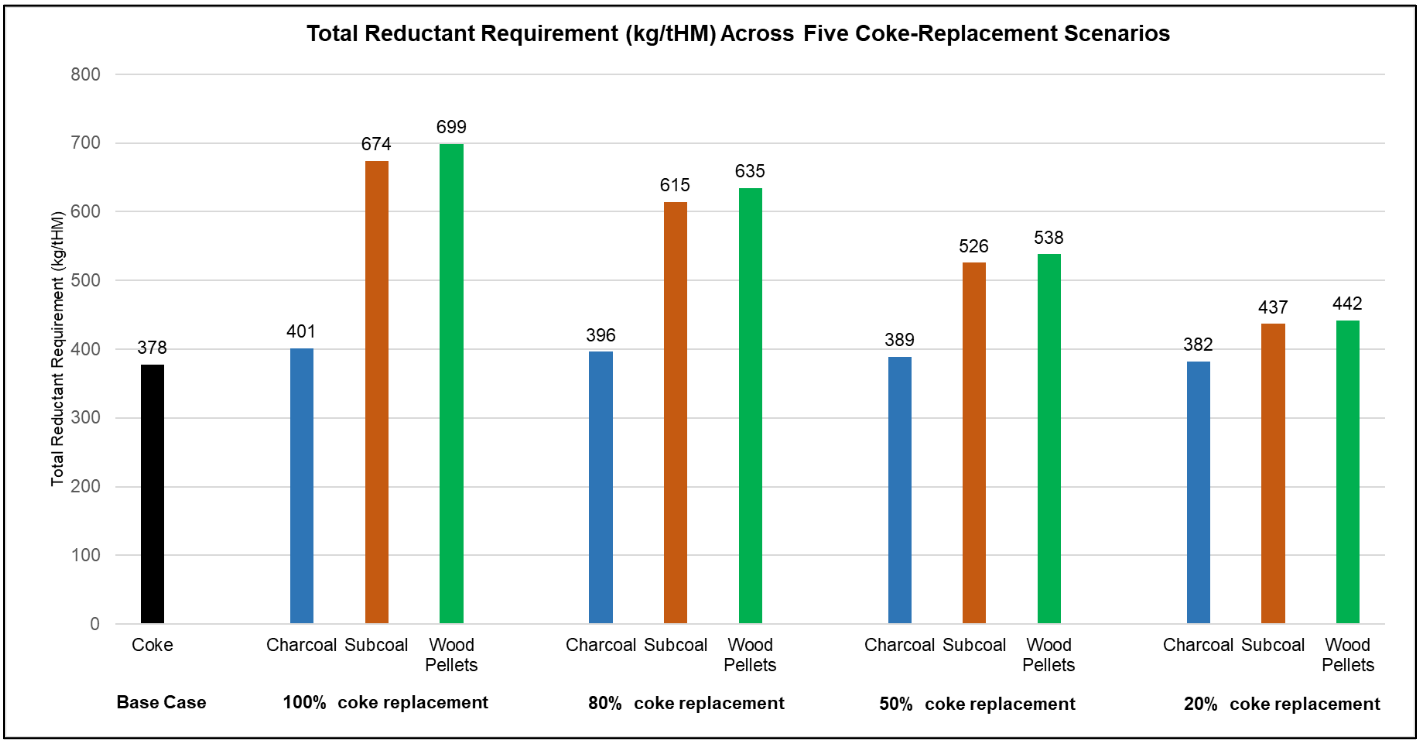

Figure 21: Total Reductant Requirement (kg/tHM) for Five Coke-Replacement Scenarios

The total amount required is estimated using stoichiometric carbon balance, assuming complete conversion of fixed carbon to carbon monoxide (CO) for the indirect reduction of iron ore, based on the following reactions: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ and $C + ½O_2 \rightarrow CO$.

For zero coke replacement, the total amount of reductant required is 378 kg/tHM. This represents the base scenario reflecting the minimum amount of coke required stoichiometrically to reduce iron ore to iron in conventional blast furnace ironmaking. In reality, a higher amount of coke is needed to account for other factors (e.g burden permeability, losses) and coke is typically used with pulverised coal injection (PCI) as an auxiliary reductant for cost-optimisation purposes (Cameron et al., 2019). When coke is fully replaced with alternative reductants, the mass requirement increases to 401 kg/tHM for charcoal. Another steep increase was observed for subcoal and wood pellets, at 674 and 699 kg/tHM respectively. Furthermore, the ordering is similar in lower coke substitution levels (80%, 50%, and 20%). At 80% coke replacement level, the total reductants required are 396, 615, and 635 kg/tHM for charcoal, subcoal, and wood pellets respectively. At 50% coke replacement, the ordering is preserved but the values are on the lower side at 389, 526, and 538 kg/tHM respectively. With 20% coke replacement, the total amount of reductants needed are the least for each AF, at 382, 437, and 442 kg/tHM for charcoal, subcoal, and wood pellets respectively. These represent the minimum amounts required from stoichiometric practices. Other factors, such as thermal efficiency, ash handling, burden permeability, and slag formation are not considered at this stage of analysis. However, in practice they need to be considered (Geerdes et al., 2015).

The most significant trend observed is that charcoal requires only a marginally higher mass than coke with an increase ranging between 1.1 to 6.1 % depending on the coke replacement ratios. The rationale behind this is primarily due to the high carbon content of charcoal (80.51 wt%) which is comparable to coke (85.5 wt%) (Wang et al., 2015; Suopajärvi et al., 2018). In contrast, subcoal and wood pellets require substantially higher masses ranging from 16 to 85% more than coke across the various substitutional levels. Subcoal contains 47.9 wt% carbon while wood pellets contain 46.2 wt%. These properties resulted in lower effective carbon availability per unit mass. Hence, a greater amount of reductant needs to be provided to meet the stoichiometric demand of Fe_2O_3 reduction. These findings are consistent with previously published studies that show that fixed carbon content is primarily the governing factor of reductant efficiency in blast furnace operation (Norgate et al., 2012b; Suopajärvi et al., 2018).

Another noticeable trend is that the mass penalty becomes more pronounced at higher levels of coke substitution. This outcome directly reflects the mass-balance effects caused from the increasing proportion of solid alternative reductants with lower carbon content. Hence, the overall charge needs to be increased linearly to maintain the required reducing capacity. Moreover, the deviation from the coke baseline with increasing substitution percentage is attributable to stoichiometric constraints in blast furnace operation.

In addition, the results consistently show that wood pellets require slightly more mass than subcoal at each substitution level. In reality, the amount of wood pellets needed might be higher because of higher oxygen and higher moisture in wood pellets (Wang et al., 2013, 2015). The presence of O_2 reduces the effective fixed carbon contribution (Vassilev et al., 2010). In contrast, subcoal which is derived from solid recovered fuel (SRF) includes a high carbon waste fraction, such as plastic and paper, which contain lower O2 and moisture even though the advantage can be partially offset with higher content of ash (Nasrullah et al., 2014; Foster, 2022).

However, it is important to note that this mass based efficiency calculation does not fully capture the real world operational limitation that may affect each reductant. Reductants with high ash content, such as subcoal, can increase slag formation and can reduce furnace permeability, operational inefficiency and higher auxiliary reductant demand (Geerdes et al., 2015). Besides, high volatile matter can undergo endothermic devolatilisation and cracking reactions in the raceway, which absorb heat, lower the adiabatic flame temperature, and also generate additional gas volume. These changes in conditions can cause a higher O_2 requirement in the blast furnace to maintain stable raceway operation, as evidenced by a study indicating that the high level of volatile matter in wood pellets reduces RAFT (Suopajärvi et al., 2018). In contrast, physical and chemical properties of charcoal particularly its high fixed carbon and low ash, make it more compatible with existing blast furnace infrastructure. Nevertheless, higher substitution levels may still require adaptation of the charging system and issues with burden permeability need to be accounted for especially with the low crushing strength of charcoal (Babich et al., 2010; Cameron et al., 2019).

In summary, Figure 21 verifies that charcoal is the most efficient solid alternative reductant in terms of mass-based carbon supply efficiency. It can be observed that the performance remains consistently close to coke across all substitution levels with only minor increases in terms of required mass. On the other hand, subcoal and wood pellets show significant mass penalty reflecting their lower carbon concentration. These findings provide a strong foundation to integrate efficiency consideration into broader sustainability assessment of alternative reductants to ensure that the primary function of a blast furnace is fundamentally met.

4.1.2 Environmental Assessment

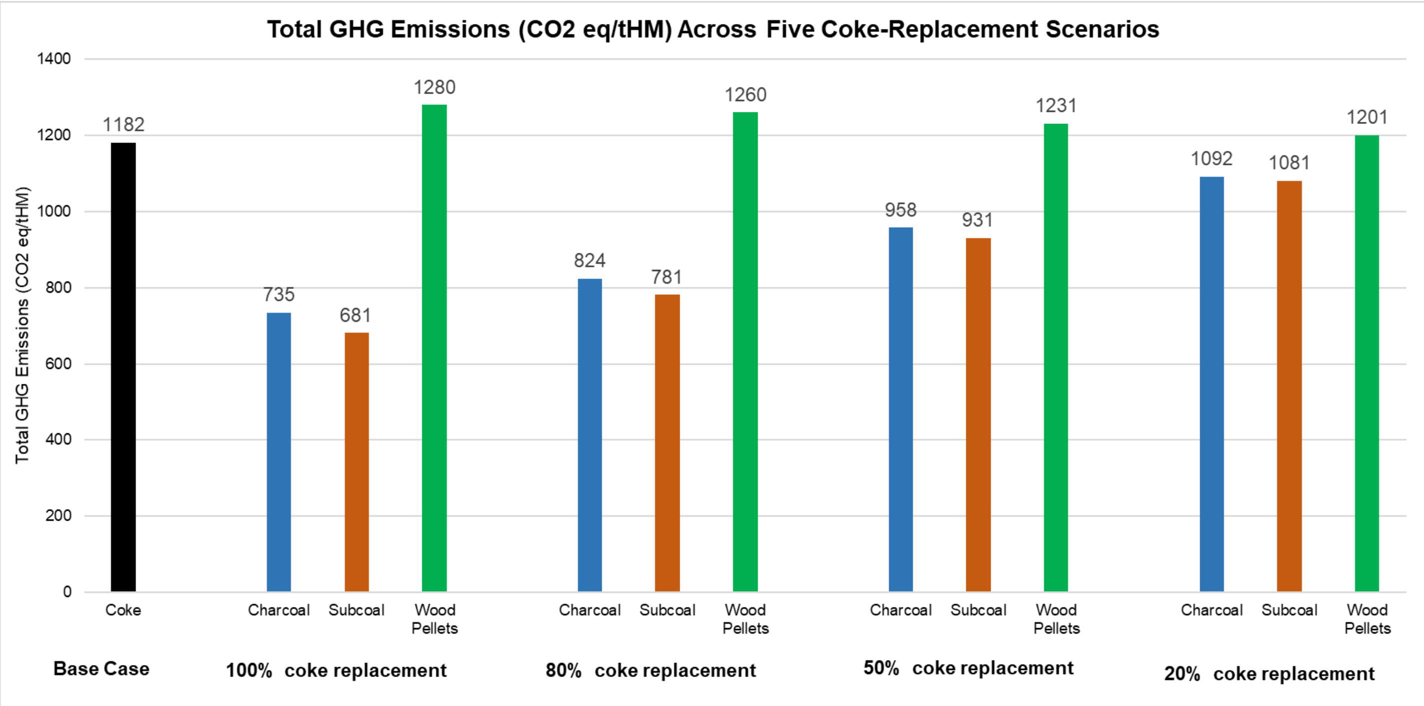

Figure 22: Total GHG Emissions (CO_2 eq/tHM) for Five Coke-Replacement Scenarios

Figure 22 demonstrates the total greenhouse gas (GHG) emissions associated with five coke-replacement scenarios, each for the production of one tonne of hot metal (tHM). These are calculated based on methodology outlined in Section 3.1.2. The total GHG emissions are reported in kilograms of CO_2 equivalent per tonne of hot metal (kg CO_2 eq/tHM), which is based solely on the direct emissions from the stationary combustion of each reductant. This includes emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), with all values converted to CO_2 equivalents using 100-year GWP of 25 for CH_4 and 265 for N_2O based on characterization data from the United States Environmental Protection Agency (United States Environmental Protection Agency (US EPA), 2025b). Emissions of CO_2, CH_4, and N_2O

were converted to CO_2-equivalents using 100-year GWP factors (25 for CH_4 and 265 for N_2O) from the USEPA, to enable comparison on a common climate impact scale. In this analysis, no upstream emissions such as those from mining, processing, drying, or transportation are included, in alignment with the defined methodology of stationary combustion factors (United States Environmental Protection Agency (US EPA), 2025a).

For the base scenario, zero replacement of coke yields a total of 1182 kg CO_2 eq/tHM from combustion-phase emissions. This figure is estimated using EPA emission factors for coking coal and assuming complete oxidation within the blast furnace. However, it is worth to note that this assessment does not take into account the significant upstream emissions related with coke production, including coal mining, methane leakage, and coking plant emissions, which are known mainly to significantly increase the total carbon intensity. The upstream emissions were excluded as the analysis is intended as a high-level assessment rather than a full life cycle assessment (Burchart-Korol, 2013; Renzulli et al., 2016; Leão et al., 2023).

Among the solid alternative reductants assessed, subcoal exhibits the lowest direct GHG emissions across all coke-replacement levels. At 100% coke replacement, the subcoal yields a total of 681 kg CO eq/tHM, a 42.4% reduction relative to the base scenario. At 80%, 50%, and 20% coke replacement levels, subcoal emissions increase to 781, 931, and 1081 kg CO_2 eq/tHM respectively. The favourable performance of subcoal is attributed to its lower stationary combustion emission factors, as calculated using the EPA category for municipal solid waste (MSW). This proxy is appropriate given subcoal's composition from non-recyclable plastics, paper, and other combustible residues (N+P Group, 2022). Despite its partial fossil content, subcoal demonstrates lower emissions per kg of reductant due to its high calorific value and lower CH_4 and N_2O emissions in stationary combustion.

Furthermore, charcoal also performs reasonably well in reducing stationary combustion emissions, even though it slightly underperforms compared to subcoal across all levels of coke replacement. At complete coke replacement, charcoal emissions reach 735 kg CO eq/tHM, indicating a 37.8% reduction from the base scenario. Partial replacement scenarios at 80%, 50%, and 20% resulted in emissions of 824, 958, and 1092 kg CO eq/tHM, respectively. Charcoal emissions are estimated using EPA emission factors for ‘Wood and Wood Residuals’, as no specific factor is listed for charcoal. Even though the CO_2 emitted during charcoal combustion is of biogenic origin, it is included in this assessment following EPA’s stationary combustion methodology, which requires the biogenic CO_2 emissions to be accounted as part of total direct emissions (United States Environmental Protection Agency (US EPA), 2025a). Charcoal has relatively low fossil-carbon content and hence contributes to lower GHG intensity. However, due to its slightly lower fixed carbon content than coke, a higher mass of charcoal is needed to achieve equivalent reducing efficiency.

In contrast, wood pellets demonstrate the highest stationary combustion emissions among the alternative reductants and surpass the base scenario at all levels of substitution. At 100% coke replacement, wood pellets yield 1280 kg CO eq/tHM GHG emission, an 8.3% increase over the base scenario. At 80%, 50%, and 20% coke replacement levels, emissions declined only slightly to 1260, 1231, and 1201 kg CO eq/tHM, which consistently remained above the base scenario. These higher emissions are primarily due to the relatively low carbon content of wood pellets (46.2 wt%) vs coke (85.5 wt%), which necessitates a significantly higher mass of wood pellets to supply the required reducing carbon in the blast furnace (Wang et al., 2015). As a result, total combustion emissions increase despite the biogenic nature of the wood pellets. It is crucial to clarify that additional emissions associated with pellet production, drying, and import transportation are excluded from this analysis, but are known to be significantly high, which can diminish the environmental viability of wood pellets in full life cycle comparisons.

The results exhibit a clear trend in stationary combustion emissions performance. From the assessment, subcoal emerges as the most effective reductant in reducing GHG emissions, followed by charcoal, while wood pellets yield higher emissions than conventional coke in blast furnace operation. These findings highlight the importance of taking into account the mass and carbon content of alternative reductants when evaluating their GHG emission impacts. Although this analysis provides a high-level insight into direct emissions from reductant combustion, it is not a replacement for a complete cradle-to-gate life cycle assessment. A detailed LCA is recommended to account for all critical aspects such as land use, water consumption, and fossil resource depletion impacts, especially in the context of the UK, where there is a gap in the understanding based on the literature review conducted throughout this research.

4.1.3 Economic Assessment

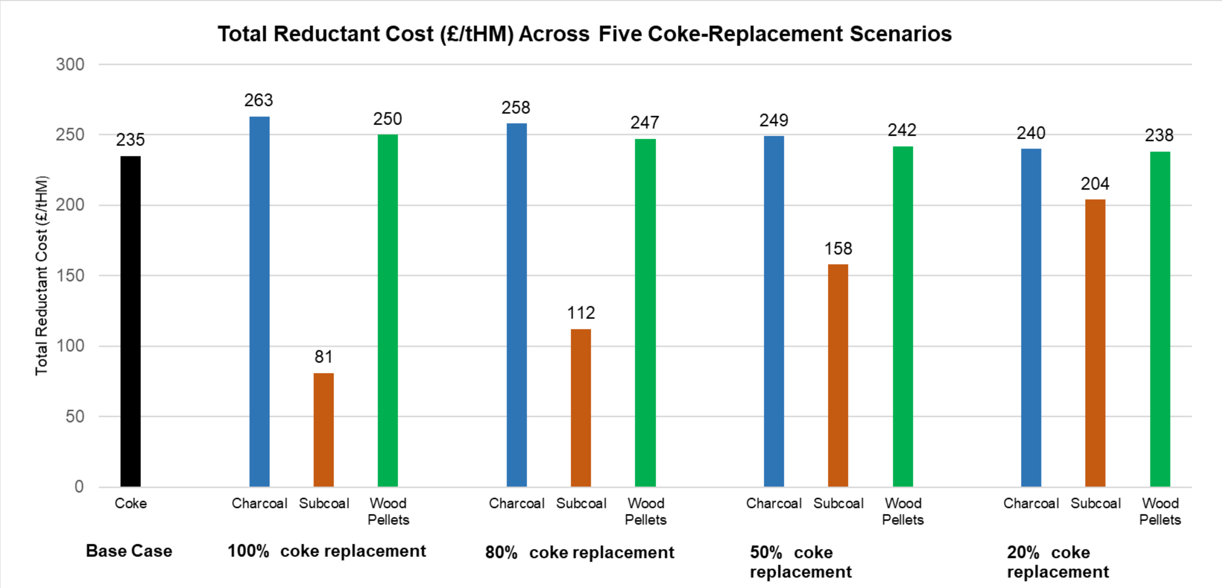

Figure 23: Total Reductant Cost (£/tHM) for Five Coke-Replacement Scenarios

Figure 23 presents the total reductant cost across five coke-replacement scenarios, expressed in pounds sterling per tonne of hot metal (£/tHM). This is calculated based on methodology outlined in section 3.1.3. The cost calculation entails both the market price and the transport cost for each reductant (importing to the UK), based on the amount needed to produce one tonne of hot metal. This quantity was obtained from the mass balance (in efficiency analysis) discussed previously in section 4.1.1. The cost assessment only takes into account direct reductant costs and excludes capital investments or downstream operational expenses. The aim is to evaluate the economic implications of replacing coke with charcoal, subcoal, or wood pellets at varying levels of replacement under current UK market conditions.

For the base scenario, the total reductant cost of using 100% coke in conventional blast furnace ironmaking is estimated to be £235/tHM. This serves as the baseline for comparison with other scenarios. Among the alternative reductants considered, subcoal consistently offers the lowest total cost across all varying coke substitution levels. In contrast, charcoal incurs the highest cost across all replacement percentages, with the economic impact most pronounced at maximum coke replacement.

At 100% coke replacement, the total cost of charcoal increases to £263/tHM, representing a 13.4% increase relative to the base scenario. This increase is mainly due to high production and transport costs. Charcoal production involves resource-intensive steps, which entail wood harvesting, pyrolysis (carbonisation) and grinding. Feliciano-Bruzual. (2014) highlights that the biomass source is the most significant single cost associated with total charcoal production in metallurgical applications (Feliciano-Bruzual, 2014). In addition, charcoal has a low bulk density, estimated to be between 300-400 kg/m3, compared to approximately 1600-1900 kg/m3 for coke (The Engineering Toolbox, 2025). In this assessment, coke was assumed to be processed in the importing country and transported to the UK. Moreover, the demand for sustainable charcoal is increasing globally, but the supply remains constrained, causing elevated market prices. These aspects collectively justify the higher cost of charcoal at all coke substitution levels (80%, 50%, 20%), which corresponds to 10.9%, 6.7% and 2.5% increases, respectively, over the base scenario.

By contrast, subcoal is the most economically viable alternative. At full coke replacement, the total cost is estimated to be £81/tHM, representing a 65.7% cost reduction compared to coke. This favourable outcome is primarily due to low production costs of subcoal at approximately £72 per tonne (adjusted to inflation) and its local availability in the UK (Veer, 2023). Subcoal is produced from solid recovered fuel (SRF), such as non-recyclable plastics, paper and biomass residues, using a relatively low-cost process (Ojobowale, 2024). Moreover, subcoal production facilities are located in Teesside, which allows short-haul transport at an estimated cost of £48/tonne. These logistics advantages, combined with low material cost, make subcoal cost-competitive even at partial substitution levels: £112/tHM at 80%, £158/tHM at 50%, and £204/tHM at 20% replacement, all of which are substantially lower than the base scenario.

Wood pellets demonstrate an intermediate cost between subcoal and charcoal. At 100% coke replacement, the total cost is £250/tHM, which is 5.9% higher than the base scenario. Although the production cost of wood pellets is moderate, around £187/tonne, the lower carbon content and moderate bulk density (650 kg/m^3) require a higher mass of pellets to deliver an equivalent reducing potential, thus increasing overall costs. Besides, wood pellets in this assessment are assumed to be imported from the United States with a sea transport of £170/tonne. In the UK, the wood pellets used by Drax (a company that uses wood pellets for electricity generation) are predominantly imported from the United States. All these factors combined make wood pellets more costly than subcoal but slightly cheaper than charcoal. At partial replacement levels, the total costs are £247/tHM at 80%, £242/tHM at 50%, and £238/tHM at 20% substitutions. It is worth noting that at 20% coke replacement, wood pellets only cost 0.8% higher than the base scenario, indicating potential feasibility in limited substitution contexts where the local wood pellet supply chain is available.

In conclusion, the analysis proves a clear cost hierarchy in which subcoal has the greatest economic benefit, followed by wood pellets at lower substitution levels. At the same time, charcoal presents the highest cost burden, especially at full or near-full replacement, which corroborates well with findings from several studies (Norgate et al., 2009; Feliciano-Bruzual, 2014). The low cost of subcoal is due to the local availability, although its long-term viability depends largely on supply stability and quality control. Charcoal is economically constrained by production complexity and transport inefficiency. Last but not least, wood pellets may be viable for partial substitution, especially when there is the availability of local supply chains.

4.1.4 Multi-Criteria Scoring

The comparative assessment of charcoal, subcoal and wood pellets as solid alternative reductants in the blast furnace was conducted in this research. The aim is to identify the most viable alternative reductant under UK market conditions. The evaluation was performed as a preliminary analysis within the first year of the EngD programme to allow a more in-depth life cycle assessment (LCA) to follow. The analysis integrates three core criteria, such as efficiency, environmental impacts, and economic viability, within a multi-criteria scoring framework. This is assuming an equal weighting applies across all criteria. This structure allows a holistic, transparent comparison. It clarifies the trade-offs between each reductant option to enable the selection of the most suitable alternative reductant for further in-depth assessment.

The summary of results obtained from assessment of solid alternative reductants via three core dimensions; efficiency, environmental, and economic are summarised in Table 49.

Table 49: Efficiency, Environmental Impact, and Economic Assessment Results across Five Coke-Replacement Scenarios

			Efficiency		**Environmental**	**Economics**
Scenario	Percentage of Coke Mass Replaced with AF	Reductant	Amount of Reductant Required (kg)		Total Greenhouse Gases	Total Reductant Price
	%		Amount of coke (kg)	Amount of alternative reductant (kg)	kg CO_2-eq	£/tonne
Scenario 1 (Baseline)	NA	Coke	378	0	1182	235
Scenario 2	100%	Charcoal	0	401	735	263
		Subcoal		674	681	81
		Wood Pellets		699	1280	250
Scenario 3	80%	Charcoal	76	321	824	258
		Subcoal		539	781	112
		Wood Pellets		559	1260	247
Scenario 4	50%	Charcoal	189	200	958	249
		Subcoal		337	931	158
		Wood Pellets		349	1231	242
Scenario 5	20%	Charcoal	302	80	1092	240
		Subcoal		135	1081	204
		Wood Pellets		140	1201	238

The summary of scores assigned for each scenario across the three parameters assessed are presented in Figure 24 and Table 50 respectively.

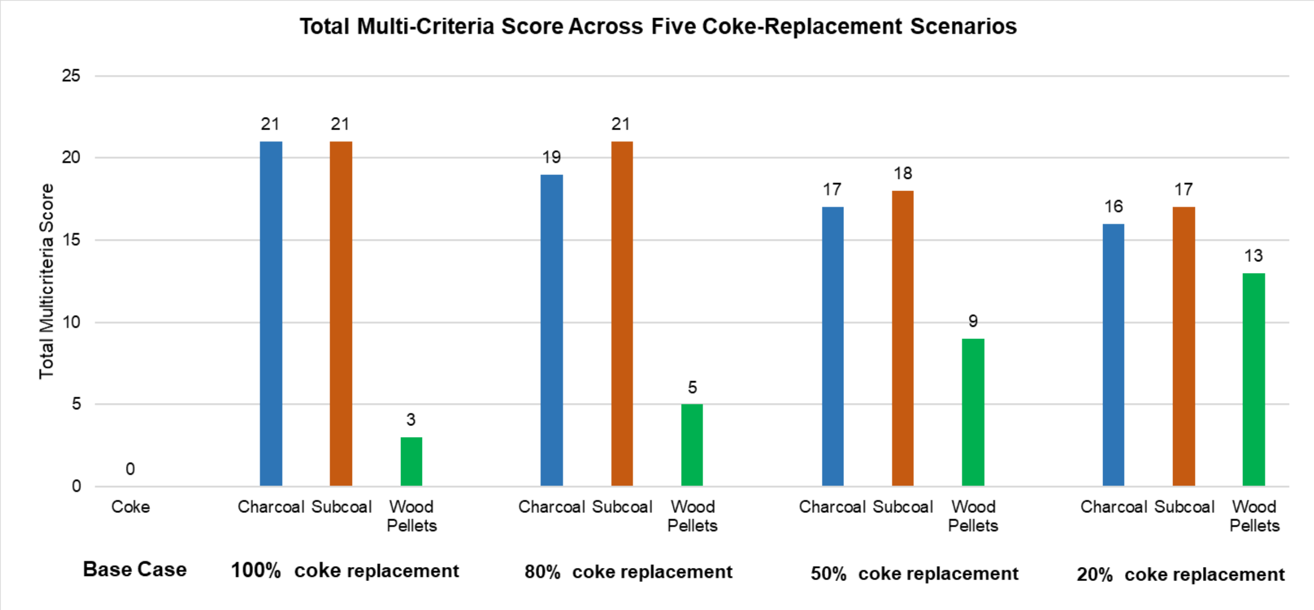

Figure 24: Total Multi-Criteria Score Across Five Coke-Replacement Scenarios

Table 50: Multi-Criteria Scoring (Equal Weighting)

Scenario	Percentage of Coke Mass Replaced with AF (%)	Reductant	Efficiency	Environmental	Economics	Total Score
			Amount of Reductant Required	Total Greenhouse Gases	Total Reductant Price	
Scenario 1 (Baseline)	NA	Coke	NA	NA	NA	NA
Scenario 2	100	Charcoal	10	10	1	21
		Subcoal	1	10	10	21
		Wood Pellets	1	1	1	3
Scenario 3	80	Charcoal	10	8	1	19
		Subcoal	3	9	9	21
		Wood Pellets	2	1	2	5
	50	Charcoal	10	6	1	17
		Subcoal	6	6	6	18

Scenario 4		Wood Pellets	6	1	2	9
Scenario 5	20	Charcoal	10	4	2	16
		Subcoal	9	4	4	17
		Wood Pellets	9	2	2	13

Table 50 presents the total multi-criteria scores across five coke-replacement scenarios, based on three criteria: efficiency (amount of reductant required per tonne of hot metal), environmental impact (total GHG emissions as CO_2 equivalent), and economic viability (total reductant cost, £/tHM). Each criterion was assigned a score on a 1 to 10 scale, where higher scores indicate better performance than the base scenario (Scenario 1). Scores from all three criteria are added to produce a total score for each reductant across five coke replacement levels to facilitate a holistic assessment.

For the base scenario (Scenario 1), no score was assigned as this serves solely as a comparative reference. For 100% coke replacement, both charcoal and subcoal achieved the highest total score of 21. Subcoal demonstrates strong performance primarily due to the lowest direct GHG emissions and the lowest cost, even though it required higher mass input. Charcoal requires less mass, which indicates higher mass-based efficiency, but the high cost offsets this benefit. Furthermore, wood pellets achieved a total score of only three, reflecting poor performance across all dimensions, which aligns well with literature by Wang et al. (2015) and Thek et al. (2012) documenting lower carbon efficiency for wood pellets (Thek et al., 2012; Wang et al., 2015).

Another notable observation is that the subcoal consistently maintained the highest scores across all replacement percentages (80%, 50%, and 20%), declining from 21 to 17 as the coke replacement percentage decreased. In addition, charcoal followed a similar trend, with scores ranging from 19 to 16. Meanwhile, wood pellets remained the least effective option, even though the total score improved at the lowest coke replacement percentage. The findings show that subcoal achieves the strongest overall performance from a purely technical standpoint, particularly when cost and emissions are taken into account, even though it requires more mass per tonne of hot metal.

4.1.5 Sensitivity analysis Under Alternative Weighting

In this section, three alternative weighting scenarios were tested to determine the sensitivity of multi-criteria scoring results to the assumption of equal weighting.

The first alternative weighting scenario was the efficiency-weighted case, in which 60% of the total weighting was assigned on efficiency, while 20% was assigned to both environmental and economic criteria. This weighting was intended to reflect an operational engineering perspective, where reductant performance is the primary concern. As shown in Table 51, the revised scores indicate that charcoal emerged as the most optimal reductant, achieving the highest overall score.

Table 51: Multi-Criteria Scoring (Efficiency-weighted Case)

Scenario	Percentage of Coke Mass Replaced with AF (%)	Reductant	Total Score
Scenario 1 (Baseline)	NA	Coke	NA
Scenario 2	100	Charcoal	8
		Subcoal	5
		Wood Pellets	1
Scenario 3	80	Charcoal	8
		Subcoal	5
		Wood Pellets	2
Scenario 4	50	Charcoal	7
		Subcoal	6
		Wood Pellets	4
Scenario 5	20	Charcoal	7
		Subcoal	7
		Wood Pellets	6

The second alternative weighting scenario was the environmental-weighted case, in which 60% of the total weighting is allocated to the environmental criteria, while 20% was assigned to both efficiency and economic performance. This weighting was intended to reflect a policy priority perspective, where emission reduction is prioritised. As presented in Table 52, the revised scores show that charcoal and subcoal emerged as the most optimal reductants under this weighting approach.

Table 52: Multi-Criteria Scoring (Environmental-weighted Case)

Scenario	Percentage of Coke Mass Replaced with AF (%)	Reductant	Total Score
Scenario 1 (Baseline)	NA	Coke	NA
Scenario 2	100	Charcoal	8
		Subcoal	8
		Wood Pellets	1
Scenario 3	80	Charcoal	7
		Subcoal	8
		Wood Pellets	1
Scenario 4	50	Charcoal	6
		Subcoal	6
		Wood Pellets	2
Scenario 5	20	Charcoal	5
		Subcoal	5
		Wood Pellets	3

The final alternative weighting scenario was the economic-weighted, in which 60% of the total weightage was assigned on economic criteria, while 20% was allocated to both efficiency and environmental performance. This weighting was intended to reflect a commercial business's perspective where cost competitiveness is a key consideration. As shown in Table 53, the revised scores indicate that charcoal and subcoal emerged as the most optimal reductants under this scenario.

Table 53: Multi-Criteria Scoring (Economic-weighted Case)

Scenario	Percentage of Coke Mass Replaced with AF (%)	Reductant	Total Score
Scenario 1 (Baseline)	NA	Coke	NA
Scenario 2	100	Charcoal	5
		Subcoal	8
		Wood Pellets	1
Scenario 3	80	Charcoal	4
		Subcoal	8
		Wood Pellets	2
Scenario 4	50	Charcoal	4
		Subcoal	6
		Wood Pellets	3
Scenario 5	20	Charcoal	4
		Subcoal	5
		Wood Pellets	3

4.1.6 Overall Summary of Multi-Criteria Scoring

Overall, it can be observed that multi criteria assessment identified charcoal and subcoal as the strongest solid alternative reductants across all scenarios. In contrast, wood pellets consistently showed the weakest performance.

Under the equal weighting approach, subcoal achieved the highest overall scores. This is mainly due to its economic and environmental performance. Moreover, charcoal also appears as strong reductant, particular in terms of mass-based efficiency, although the higher cost reduce its overall score.

For the alternative weighting scenarios, the ranking became more dependent on decision priorities. Charcoal performed best under efficiency-weighted case, whereas charcoal and subcoal performed well under environmental case, and subcoal emerged best under economic-weighted case. The results signify that the choice of subcoal and charcoal depends on whether priority is given to operational performance, emissions reduction, or commercial competitiveness.

Although subcoal exhibits technical superiority, the practical deployment in large-scale UK blast furnace operation is limited by two key challenges, which are production capacity and product consistency. The N+P Group Teesside facility has an annual output capacity close to 250,000 tonnes of subcoal per year, and it provides service to both local and European clients (N+P Group, 2021). Even though the amount of production is significant, the level of output remains modest if it is to be used as an auxiliary reductant for the UK steel industry. Furthermore, subcoal is produced from solid recovered fuel feedstocks, which can result in variability in calorific value, chemical composition, moisture and ash composition. Technologies such as torrefaction can improve uniformity, and optical sorting can ensure consistent quality but they will require extensive quality control measures for metallurgical applications that have more stringent requirements than cement industry (Holliman, 2025). Hence, this potential quality variability could cause a significant risk for stable blast furnace operation given its sensitivity to feedstock characteristics (Geerdes et al., 2015; Cameron et al., 2019).

In contrast, charcoal provides a more scalable and dependable solution. Charcoal production for metallurgical operation is established in Brazil (Leão et al., 2023), and it is produced by the controlled carbonisation of defined biomass feedstock which allows for consistent high fixed carbon content and low ash predictable reliability, both of which are crucial and ideal for blast furnace reductants (Feliciano-Bruzual, 2014). Trade data from the Observatory of Economic Complexity (OEC) indicates significant imports of charcoal into the United Kingdom worth £48.5 million in 2024, verifying the existence of flexible international supply chains and also the infrastructure to support charcoal availability (The Observatory of Economic Complexity, 2025b).

Moreover, there are established UK policy frameworks that can guide sustainable charcoal sourcing such as UK Timber Regulation and this also aligns with the objectives of the UK Biomass Strategy 2023 that promotes biomass as a crucial pathway for industry decarbonisation (Department for Energy Security & Net Zero, 2023a). In terms of cost, the expensive price of charcoal needs to be supported by grants that allows industry to integrate biomass as fuel or reductant.

In summary, although subcoal provides superior technical performance in terms of emissions and cost, the limited production capacity and concerns about consistent quality reduce its viability for medium term large scale adoption. On the other hand, charcoal provides a more practical, scalable, and policy aligned alternative. From this analysis, charcoal is selected as the preferred solid alternative reductant. Further evaluation is to be conducted through cradle-to-gate LCA to assess a more holistic environmental impact from the supply chain to the production of hot metal when charcoal is used as a reductant and also to inform future decarbonisation strategies for the UK steel sector.

CHAPTER 5

5.0 RESULTS AND DISCUSSION: LIFE CYCLE ASSESSMENT

This chapter presents the results of the cradle-to-gate life cycle assessment for all five scenarios, in which Scenario 1 serves as the baseline for conventional ironmaking and Scenarios 2 to 5 introduce alternative reductants. Across all alternative reductant scenarios, coke remains the dominant reductant, and the alternatives function only as partial substitutes. The chapter compares the environmental performance of each scenario against the baseline and examines how different reductants affect global warming potential, land use, fossil resource scarcity, water consumption, and mineral resource scarcity. It highlights the trade-offs that arise when improvement in one impact category are accompanied by increases in another. This chapter synthesises these outcomes to provide a balanced interpretation of performance across the scenarios and concludes with a discussion of the economic implications for the two most promising alternative reductants.

5.1 LCA Results

This section presents the comparative LCA results for all five blast furnace ironmaking reductant scenarios, evaluated across five midpoint impact categories such as global warming potential (GWP), fossil resource scarcity (FRS), land use, water consumption, and mineral resource scarcity (MRS). Each scenario is assessed based on the cradle-to-gate production of 1 tonne of hot metal (tHM) in the UK, with Scenario 1 (Coke and PCI) serving as the base scenario.

5.1.1 Global Warming Potential

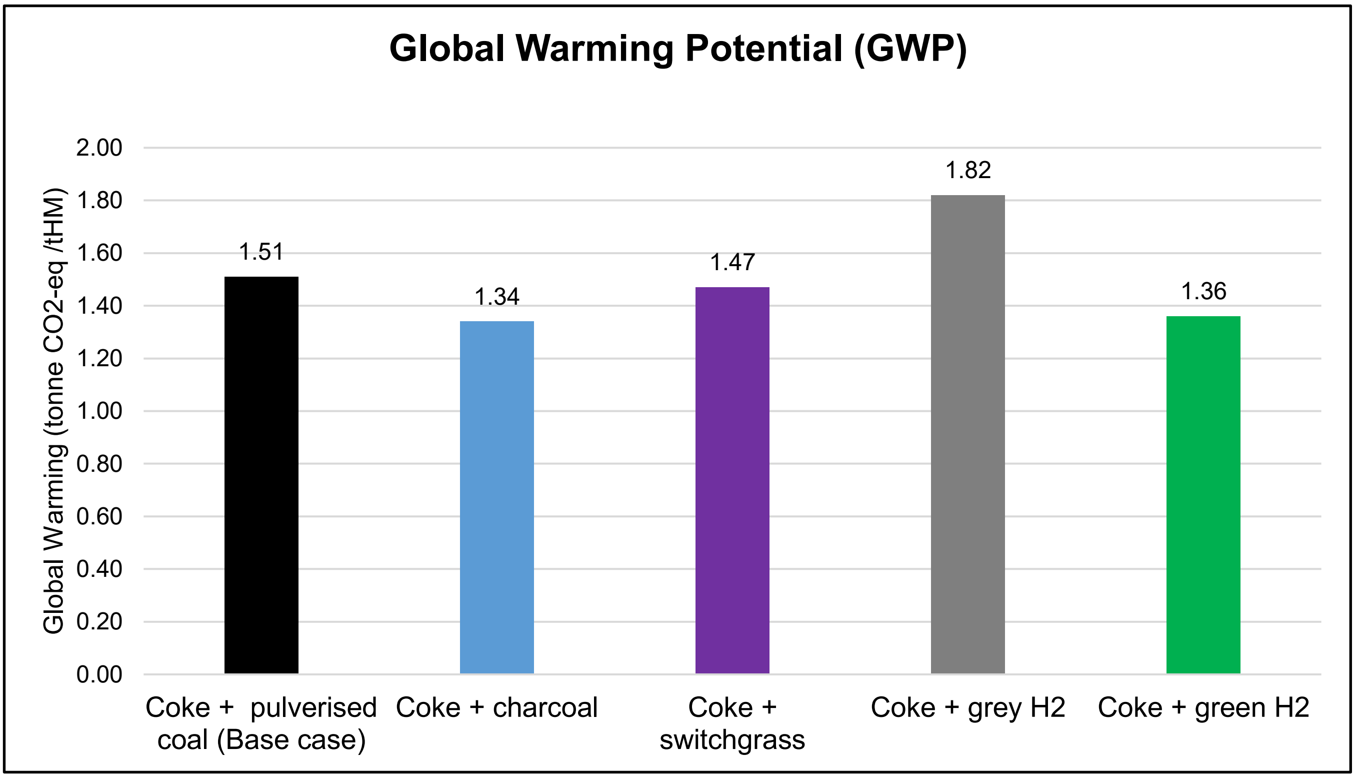

Figure 25: Global Warming Potential across Five Blast Furnace Ironmaking Scenarios

Figure 25 presents the global warming potential (GWP) results for all five blast furnace ironmaking scenarios evaluated in this research. GWP quantifies the contributions of greenhouse gases including CO_2, CH_4, N_2O, HFCs, and PFCs to climate change (Huijbregts et al., 2017).For Scenario 1 (base scenario), the GWP representing conventional blast furnace ironmaking with coke and PCI as reductants, is calculated to at 1.51 tonne CO_2 eq/tHM. This value sits comfortably within the range reported in literature for a similar industrial context. Leao et al. (2023) reported a higher figure of 1.73 tonne CO_2 eq/tHM for BF operation in Brazil due to low BF top gas utilisation rate (Leão et al., 2023). In contrast, Choi. (2013) calculated a lower GWP at 1.41 tonne

CO_2 eq/tHM under the assumption of full BF top gas recovery for other usage (e.g. utilities) (Choi, 2013). The higher the percentage of co-product utilisation (e.g BF top gas and slag), the lower the GWP allocated to the hot metal. Furthermore, the Ecoinvent version 3.10 dataset indicates a more carbon intensive global average of 1.93 tonne CO_2 eq/tHM (Ecoinvent, 2024). This is likely attributable to the data aggregation from various sources with varying operational efficiencies and higher upstream emissions. Moreover, a benchmarking study across European steel plants reported an average GWP of 1.328 tonne CO_2 eq per tonne of hot metal (Carbon Market Watch, 2022). Based on these findings, the calculated GWP for the base scenario falls within the typical range reported in the literature, supporting its validity as a reference scenario for subsequent analysis. Besides, the variation observed across the findings highlighted the importance of harmonising methodological assumptions, such as life cycle assessment methods, allocation methods, utilisation rates, and inventory choices, when conducting comparative assessments of environmental impacts in blast furnace ironmaking.

Among the alternative scenarios evaluated, the use of charcoal in Scenario 2 demonstrated the most substantial GWP reduction, achieving a decrease of 1.34 tonnes CO_2 eq, which equates to an approximately 11% reduction relative to the base scenario. Although the reduction may appear modest at the unit scale, the cumulative effect across large-scale steel production will be significant, highlighting the systemic potential of biomass integration for steel decarbonisation pathways. Charcoal is currently the most extensively studied alternative reductant for blast furnace ironmaking (Suopajärvi et al., 2017), largely due to its renewable biomass origin.

The GWP advantages reported in this assessment follow the ReCiPe Midpoint (H) treatment of biogenic carbon, which accounts for CO_2 uptake during biomass growth. However, this steady-state approach does not account for temporal dynamics, such as carbon debt arising from land use change or the length of forest rotation cycles. Therefore, the environmental benefits of charcoal are contingent on sustainable forestry practices with verified carbon sequestration rates.

Charcoal has also been used extensively for ironmaking in Brazil (Leão et al., 2023). The use of charcoal helps reduce GWP to some extent due to the carbon neutrality principle of biomass. Charcoal is derived from biomass such as wood, and CO_2 emissions associated with charcoal combustion are classified as biogenic carbon, because they represent carbon previously sequestered from the atmosphere during the tree's growth. Fundamentally, biogenic CO_2 has a lower net contribution to long-term atmospheric CO_2 levels, unlike fossil CO_2 from coke or pulverised coal (Abbasi et al., 2010). Hence, replacing fossil-based pulverised coal injection with charcoal offers a dual benefit of reducing fossil carbon emissions and lowering overall GWP. Furthermore, the upstream impacts of fossil fuel extraction add another layer of significance. Metallurgical coal mining is associated with high methane emissions, a potent greenhouse gas, with a GWP impact of 28 times that of CO_2 over 100 years (IEA, 2023; US EPA, 2024). Therefore, higher methane emissions from coal extraction contribute to a higher GWP, as the assessment in this research uses a cradle-to-gate system boundary that includes raw-material extraction.

The findings of this UK-based analysis are broadly consistent with the existing literature, which recognises the environmental advantages of charcoal used in blast furnace ironmaking. Studies such as Leao et al. (2023), Hembrom et al. (2016), Ng et al. (2010), Norgate et al (2010), Orre et al. (2021), Wang et al. (2015), Suopajarvi et al (2013), Suopajarvi et al. (2017), Khasraw et al. (2024), reported improvement in greenhouse gas and carbon emissions profiles when charcoal is employed to fully or partially replace coke and pulverised coal. However, the absolute GWP values in this research differ from several of these publications because of the lower substitution rate applied, the adoption of system expansion for co-products and the UK specific assumptions embedded in the inventory. These methodological choices resulted in outcomes that diverge from studies that assume full substitution or use narrower boundaries. This demonstrates that comparative findings in the literature are highly sensitive to system boundaries and modelling choices, and it emphasised that such differences must be interpreted with caution when assessing the relative performance of reductant pathways.

Furthermore, the use of green H_2 in Scenario 5 also demonstrated substantial potential for GWP reduction. In Scenario 5, the substitution of pulverised coal with green H_2 produced via wind-powered electrolysis reduces the GWP to 1.36 tonnes CO_2-eq, achieving around a 10% reduction from the base scenario. This reduction, second only to that achieved by charcoal, is primarily attributed to the inherent properties of green H_2. Hydrogen reduces iron oxides to iron by forming water vapour rather than carbon dioxide, unlike carbon-based reductants. This significantly lowers direct process emissions. Hydrogen also exhibits favourable thermodynamic properties such as higher calorific value, lower molecular weight, faster reduction kinetics, and superior diffusivity (Liu et al., 2021). Moreover, when H_2 is produced from renewable sources, green H_2 has a significantly lower carbon footprint between 1 and 5.1 kg CO_2-eq per kg H_2 compared to grey H_2 produced via steam methane reforming, which ranges between 11 and 13 kg CO_2-eq per kg H_2 (Suer et al., 2022b). However, the use of H_2 in blast furnace operation introduces specific thermodynamic limitations. The reduction of iron oxides using H_2 is an endothermic reaction, which causes a drop in furnace temperature and therefore increases heat demand. This constraint can be mitigated by increasing oxygen enrichment and increasing heat demand. Hydrogen reduction is reported to be more efficient above 1273 K, where it can act as a catalytic agent in facilitating the reaction. However, below this temperature, excessive heat absorption can reduce temperature and destabilise furnace operation (Lan et al., 2022). Furthermore, this thermodynamic constraint is evidenced by findings from a simulation study that showed H_2 replacement in blast furnaces is quantitatively limited (Yilmaz et al., 2017). The technical viability of green H_2 as a reductant has also been demonstrated in several industrial-scale trials globally. In Germany, ThyssenKrupp Steel launched the H_2Stahl project, initiating H_2 injection into a single tuyere in Blast Furnace 9 in 2019 at its Duisburg plant, and subsequently extending it to all 28 tuyeres in 2022. This project is reportedly aimed at reducing CO_2 emissions by 20% (Thyssenkrupp, 2022; BFI, 2025). In India, Tata Steel started H_2 injection trials at the Jamshedpur facility in 2023, with a report suggesting potential for around 7-10% CO_2 reduction (Tata Steel, 2023). In Japan, Nippon Steel achieved a staggering 43% reduction in CO_2 emissions at pilot scale, exceeding its 40% target by using heated H_2 injection to replace pulverised coal (Nippon Steel, 2025).

By contrast, grey H_2 performs poorly in this category. The use of grey H_2 in Scenario 4 showed the highest GWP of all scenarios, at 1.82 tonnes CO_2-eq, an increase of 21% over the base scenario. Grey H_2 is produced from natural gas without carbon capture and hence carries substantial upstream fossil emissions, eliminating any environmental benefits achieved by replacing pulverised coal. This outcome is consistent with assessment by the International Energy Agency (IEA), which highlighted that H_2 decarbonisation potential relied entirely on the production pathways (International Energy Agency, 2021a). This is also supported by a review conducted by Suer et al. which showed grey H_2 production itself has a significantly higher carbon footprint than blue H_2 and green H_2 due to the different production methods (Suer et al., 2022b).

Moreover, switchgrass, in its raw, unprocessed form, offers the least GWP reduction, only 3% over the base scenario at 1.47 tonne CO_2 eq. These limited environmental benefits are primarily attributed to the intrinsic properties of switchgrass, particularly its low fixed carbon content. With a carbon content of 47.3% which is significantly lower than coal at 77.7% (Ng et al., 2010), switchgrass provides inadequate carbon to sustain the reduction of iron ore within the blast furnace. As a result, additional coke needs to be introduced to meet the carbon requirements by the process, thereby increasing overall fossil fuel consumption and associated emissions (Ng et al., 2010; Khasraw et al., 2024). Furthermore, the low energy density of switchgrass reduces the thermal efficiency of the blast furnace, which can impact the raceway temperature, leading to reduced productivity and a further increase in coke demand (Khasraw et al., 2024). Hence, upgrading switchgrass through processes such as pyrolysis or torrefaction is essential to enhance its performance as a reductant, significantly improve carbon content, reduce moisture and volatile matter, and increase energy density. This rationale aligns with conclusions drawn by several studies that emphasise the importance of upgrading raw biomass before blast furnace injection (Suopajärvi et al., 2018; Khasraw et al., 2024). Moreover, numerous studies that established the superiority of charcoal (Feliciano-Bruzual, 2014; Hembrom et al., 2016; Leão et al., 2023), which is produced through biomass pyrolysis, have also emphasised the necessity of biomass pre-treatment to unlock further the full environmental and operational benefits of solid alternative reductants

5.1.2 Land Use

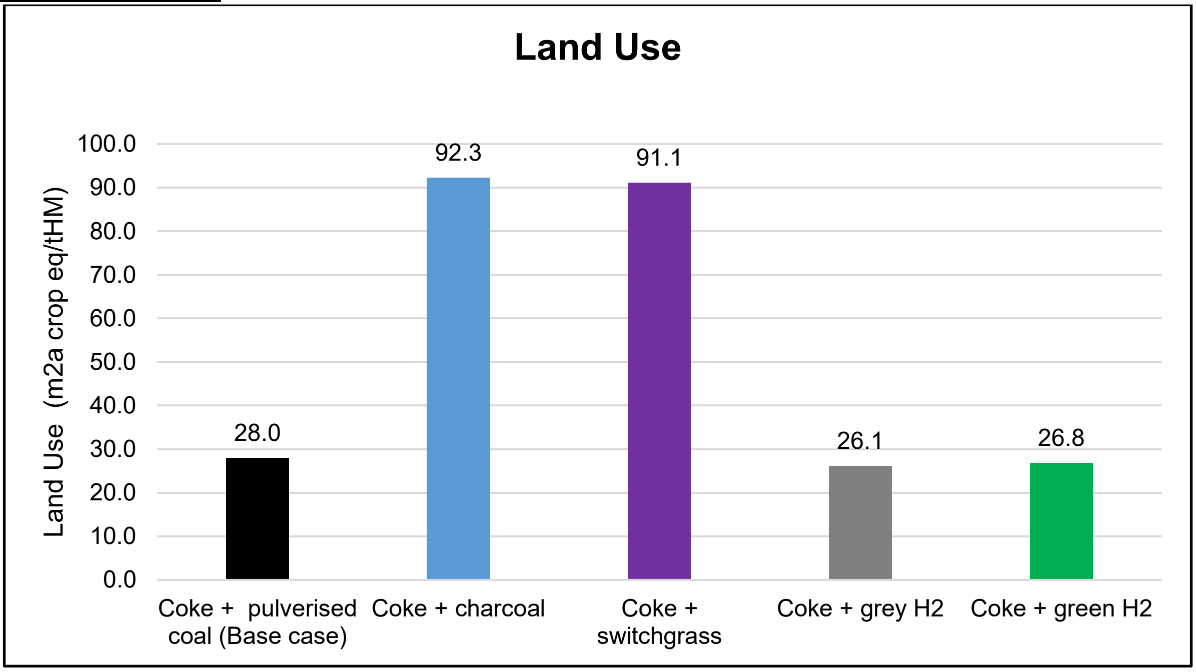

Figure 26: Land Use across Five Blast Furnace Ironmaking Scenarios

Figure 26 presents the land use results for all five assessed scenarios, each based on the production of 1 tonne of hot metal. Land use in LCA using the ReCiPe Midpoint (H) method is measured in square meters per year of agricultural crop equivalent (m^2a crop equivalent). This unit represents the annual area of productive land required to provide the energy and material inputs for a given process or product. It is used to represent both land occupation (the duration and intensity of land used for activities such as agriculture and forestry) and land transformation (the change from one land type to another, such as from forest to cropland). These land use impacts are used to represent the potential of a processing route to cause biodiversity loss, utilising specialised richness data across different land types (Huijbregts et al., 2016).

Land use results reveal a clear contrast between biomass-based and hydrogen-based reductants. Scenario 2 and Scenario 3, charcoal and switchgrass, respectively, are associated with significantly higher land occupation values at 92.3 and 91.2 m^2a crop eq/tHM, respectively. In order to contextualise the land use figures further, Scenario 2 (charcoal) yields a land occupation of 92.3 m^2a crop eq per tHM, approximately threefold higher than the baseline. For the case study UK steel plant, which produces around 5 million tonnes of hot metal annually, this corresponds to a total land occupation of around 460 km^2 per year of productive land-equivalent. This is roughly equivalent to one and a quarter times the land area of the Isle of Wight (National Character Areas, 2026). This comparison underscores why land availability is widely cited in the literature as one of the primary constraints on large-scale charcoal deployment for metallurgical applications (Norgate et al., 2012; Chidumayo et al., 2013; Suopajärvi et al., 2013; Feliciano-Bruzual, 2015; Rose et al., 2022; Leão et al., 2023).

The high value of land use for charcoal is mainly due to the massive amount of land required to grow biomass feedstock, which is predominantly eucalyptus. Eucalyptus is favoured due to its rapid growth and high productivity, particularly in suitable climates (Zhang et al., 2021). It is estimated that 2.7 tonnes of eucalyptus are required to produce 1 tonne of charcoal based on the dataset of charcoal production in Brazil (Leão et al., 2023). The trees used to produce charcoal must be planted, harvested, and regenerated over repeated cycles, which places significant pressure on land use (Okello et al., 2001). Top charcoal exporters such as Paraguay, South Africa, and Brazil are well known to have available land areas for tree plantations and a suitable climate for tree growth (Leão et al., 2023; Observatory of Economic Complexity, 2023). Such land intensiveness is recognised in multiple studies (Schulze et al., 2012; Feliciano-Bruzual, 2014) as a vital constraint for scaling-biomass-based PCI replacement in regions with limited land availability or high competition from other land uses. Since the study considers the use of charcoal in the UK, the implementation will be a challenge due to issues with land availability for biomass plantation.

Furthermore, switchgrass in Scenario 3 also exhibits similar properties to charcoal. In Scenario 3, the amount of switchgrass used as a reductant is similar to that of charcoal in Scenario 2. However, due to its lower carbon content, a higher amount of coke is required to maintain reduction efficiency. This has a negligible impact on land use as coal extraction via mining requires a minimal amount of land occupation, unlike biomass cultivation (Norgate et al., 2009; Ecoquery, 2025). Land use is calculated based on the product of land area and the time duration it is occupied, expressed in m^2a crop eq. While switchgrass can be harvested annually (Sanderson et al., 1999; Parrish et al., 2005), eucalyptus, commonly used for charcoal production, requires around 6 to 8 years of growth before harvest (Timo et al., 2015; Munis et al., 2022). Despite a faster growth cycle, switchgrass yields less energy per hectare per year, requiring larger land areas to meet equivalent energy demands compared to charcoal. This trade-off effectively balances the land-use burden between switchgrass and charcoal, thereby making the land use for Scenarios 2 and 3 comparable.

In stark contrast, the land use calculated for Scenario 4 (grey H_2) and Scenario 5 (green H_2) are almost similar to the base scenario (28 m^2a crop eq/ tHM) at 26.1 and 26.8 m^2a crop eq/tHM, respectively. These findings reflect the compact physical footprint of the SMR plant. The low land use is attributed to the nature of natural gas infrastructure, which is extracted from underground reservoirs and processed in compact industrial plants. Thus, it requires minimal land occupation or transformation compared to biomass-based reductants (Nnabuife et al., 2023). For green H_2 (Scenario 5), the land footprint of onshore wind energy is typically low, since wind turbines only occupy a small portion of the total land area (Maniscalco et al., 2024). However, a study has highlighted that wind energy installations can cause a slight loss of habitat area due to certain species avoiding areas in proximity to wind power facilities (Gasparatos et al., 2017). Furthermore, only 27.5 kg of hydrogen is needed to produce 1 tonne of hot metal in a blast furnace due to thermodynamic constraints; hence, the impacts on land use will be insignificant (Yilmaz et al., 2017).

5.1.3 Fossil Resource Scarcity

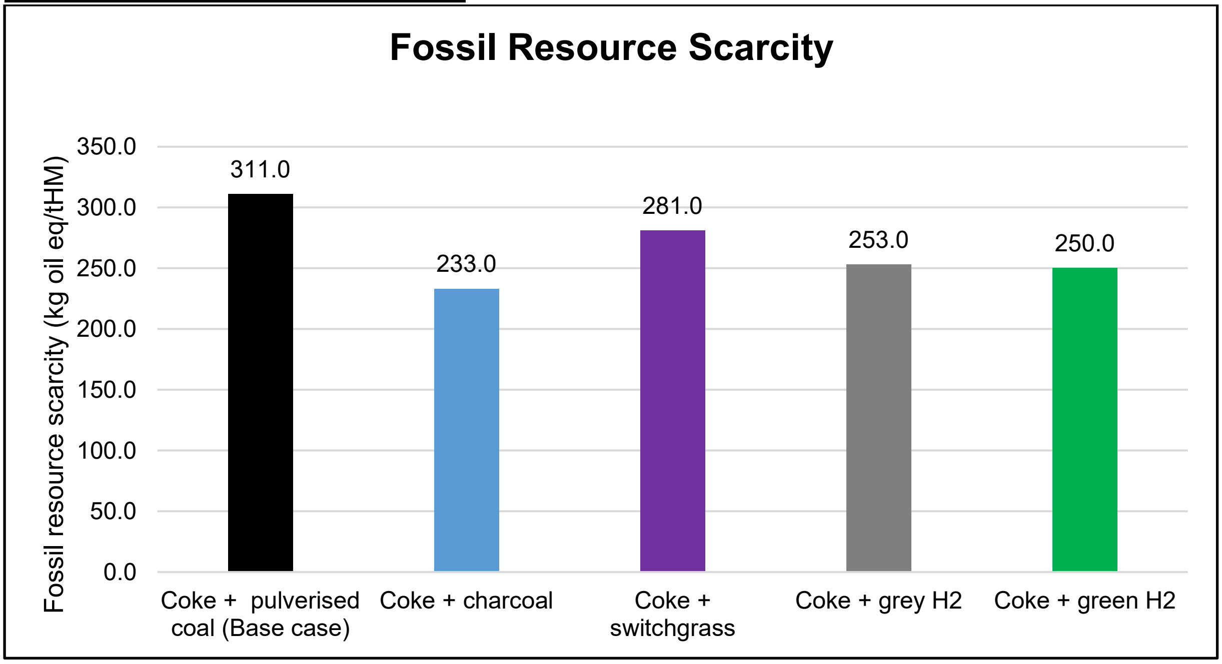

Figure 27: Fossil Resource Scarcity across Five Blast Furnace Ironmaking Scenarios.

Figure 27 presents the fossil resource scarcity (FRS) for the five assessed blast furnace scenarios, each for the production of 1 tonne of hot metal. FRS is measured in kilograms of oil equivalent (kg oil eq), as defined in the ReCiPe Midpoint (H) methodology. This parameter reflects the depletion of fossil-based energy carriers such as coal, crude oil, and natural gas, which are non-renewable and can contribute to long-term resource availability issues (Huijbregts et al., 2016). A higher value indicates a greater dependence on fossil resources and a higher reliance on non-renewable energy sources or finite resources. The base scenario (Scenario 1) represents conventional blast furnace ironmaking in the UK exhibits the highest FRS at 311 kg oil eq/tHM. Conventional blast furnace ironmaking relies highly on fossil-derived energy carriers due to the exclusive use of coke as the primary reductant and PCI derived from coal. This dependence is consistent with a wide range of literature where coke production is well documented as an energy-intensive, fossil-dependent process which involves carbonisation of coking coal at high temperatures with significant burdens from coal extraction, preparation, and transport (Geerdes et al., 2015; Cameron et al., 2019).

For Scenario 2, replacing PCI with charcoal reduces FRS by approximately 25%, with a value calculated at 233 kg oil eq. The primary contributor to FRS is coke, at 88%, and charcoal contributes minimally, at 0.1%. Although charcoal production requires some fossil input from plantation management, harvesting, transport and pyrolysis, the overall fossil footprint is still lower than that of coal-based reductant as evidenced by multiple literature findings (Suopajärvi et al., 2014; Leão et al., 2023). Moreover, these findings are also consistent with Norgate and Langberg. (2009), who reported that charcoal use could achieve significant fossil savings provided the biomass is locally sourced and processed with renewable energy inputs (Norgate et al., 2009).

Grey H_2 and green H_2, represented by Scenario 4 and Scenario 5, respectively, achieve a comparable FRS relative to the base scenario. For Scenario 4, grey H_2 reduces FRS by 19% with a value of 253 kg oil-eq/tHM. Grey H_2 is produced via steam methane reforming, which requires a high quantity of natural gas both as feedstock and energy source, highlighting the continuous dependence on fossil-based fuel (Maniscalco et al., 2024). However, the amount of fossil dependence when grey H_2 is used as an alternative reductant is still lower compared to coal (at 2.5% vs 23.9%), indicating the use of grey H_2 still helps reduce reliance on fossil-based fuels. Besides, the amount of coke needs to be slightly increased when H_2 is used as an auxiliary reductant due to thermodynamic constraints (Yilmaz et al., 2017). This, therefore, added to the FRS value. For Scenario 5, the use of green H_2 reduces FRS by around 20% with a value of 250 kg oil-eq/tHM. The primary contributor of FRS is coke at 88.8%, the same as in all the scenarios. The amount of FRS reduction is almost the same as Scenario 4 (grey H_2), but green H_2 contributes to a total FRS of 1.2% compared to grey H_2 (2.5%), a reduction of almost half. Although green H_2 is produced using renewable electricity, the overall process still uses fossil-based inputs (Bhandari et al., 2014; International Energy Agency, 2021a) , hence contributing slightly to FRS. However, similar to Scenario 4, the impacts are minimal since only a low amount of green H_2 is used and a higher amount of coke needs to be introduced due to the thermodynamic constraints of H_2 as a reductant (Yilmaz et al., 2017). Nevertheless, the use of green H_2 as an alternative reductant still offers positive benefits to the reduction in FRS.

By contrast, use of switchgrass (scenario 3) offers only a 10% reduction in FRS with a value of 281 kg oil eq/tHM. This is the weakest performance among the alternative reductants, mainly because its low carbon and energy density necessitate higher coke inputs to meet process requirements (Ng et al., 2010; Khasraw et al., 2024). This, erodes the fossil savings potential. This result reinforces the consensus in the literature that unprocessed, low-grade biomass is not suited for direct BF injection from a resource efficiency standpoint and needs to undergo upgrading, such as torrefaction or pyrolysis, to displace fossil inputs meaningfully (Suopajärvi et al., 2017).

5.1.4 Water Consumption

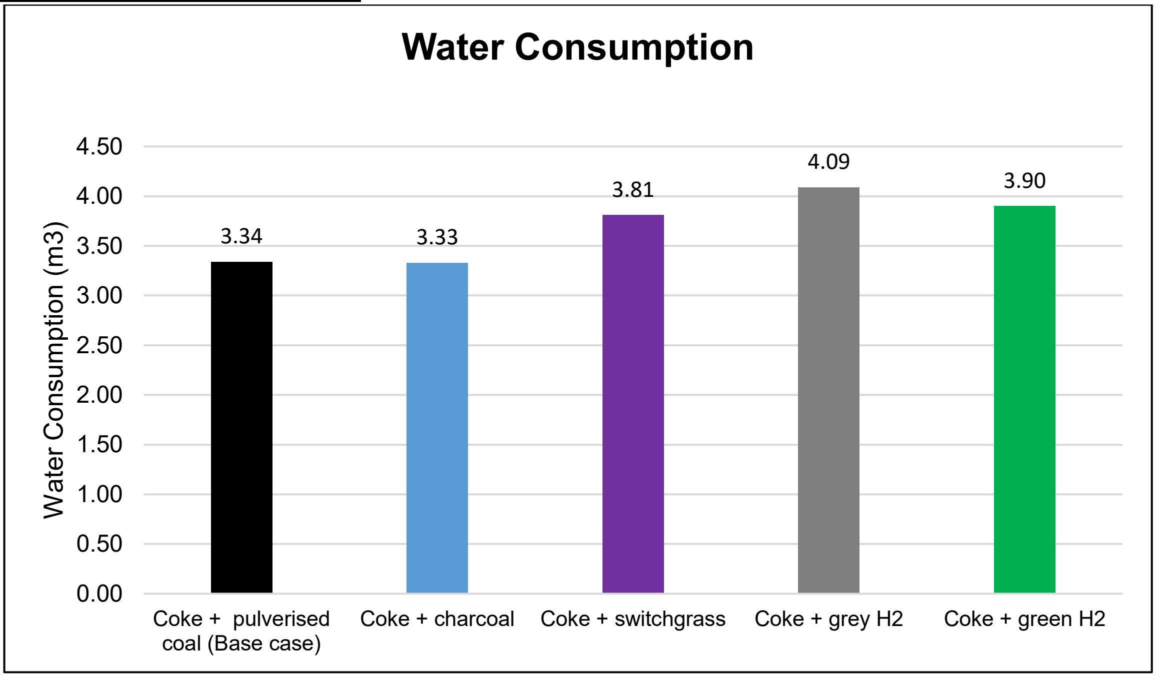

Figure 28: Water Consumption across Five Blast Furnace Ironmaking Scenarios.

Figure 28 presents the results of water consumption for all five evaluated scenarios. Water consumption, measured in cubic meters (m^3), quantifies the total amount of freshwater sourced from surface and underground resources that is permanently removed from other users or natural ecosystems, based on ReCiPe Midpoint (H) methods. In this method, only freshwater and groundwater are taken into account. This parameter is essential since it represents the potential to contribute to freshwater scarcity and regional water stress (Pfister et al., 2009; Huijbregts et al., 2017). The base scenario (Scenario 1) records a value of 3.34 m^3/tHM. This relatively moderate value is primarily contributed to by coke at 55.4% and water used in the blast furnace, at around 27.3%. Coke is made from coking coal. Coal mining and coke oven operations utilise water for coal cutting, dust suppression, slurry transport, and cooling. However, modern mining operations are commonly centralised and utilise a water recycling system, resulting in relatively lower net water consumption (Mielke et al., 2010). Moreover, blast furnace operation also requires water consumption for cooling, acting as a barrier against elevated temperatures. A blast furnace requires freshwater for indirect cooling of the blast furnace body, valve, and tuyere (Choudhury et al., 2023). Besides, water is also needed for slag granulation treatment and top gas scrubbing (Leão et al., 2023). For coke production, fresh water is needed as a coolant for wet quenching and also as direct and indirect cooling. The value obtained in this study is also lower than the one evaluated by Leao et al. (2023), primarily attributed to the different methods used to evaluate water consumption.

For Scenario 2, charcoal substitution yields virtually no change in water consumption at 3.33 m^3/tHM. This result corroborates findings by Leao et al. (2023), in which the charcoal scenario only very minimally reduced water consumption compared to conventional blast furnace ironmaking (Leão et al., 2023). Charcoal only contributed modestly to water consumption at 2.7%. The growth of the eucalyptus tree typically relies on rainfall, and irrigation is rarely used. Moreover, charcoal production is not a water-based reaction and predominantly involves heating wood in the absence of oxygen through a process called pyrolysis (Canal et al., 2020)

Scenario 3 (switchgrass) shows a 14% increase in water consumption at 3.81 m^3/tHM. This is primarily driven by the increased coke usage needed to offset the low carbon content of the feedstock. The use of switchgrass as an auxiliary reductant, even though high in quantity, only contributed minimally to overall water consumption, around 2.4%. Switchgrass is a grass that is drought-tolerant and known to utilise water and nutrients more efficiently compared to other temperate-zone crop species (IEA Bioenergy, 2011). The primary contributors to water consumption are coke, at 59.1%, and water used for the blast furnace, at 23.9%. This is consistent with Scenarios 1 and 2, and the same rationales apply.

In contrast, hydrogen-based scenarios reveal a different trend. The use of grey H_2 (Scenario 4) recorded the highest water consumption at 4.09 m^3/ tHM, 22% higher than the base scenario. The primary contribution of water consumption is through coke itself at 47.6 % with the rationale as discussed previously. However, grey H_2 itself also contributes notably to overall water consumption at 18%, the greatest compared to other alternative reductants. For grey H_2 production, natural gas reacts with steam at high temperature via the steam methane reforming process to produce H_2-rich syngas. Steam methane reforming is also a water-intensive process. This process requires a significant amount of water, both as reductant (steam), for cooling and purification. According to a study conducted by Hren et al., around 10 tonnes of steam and 18.85 tonnes of water are needed to produce 1 tonne of grey H_2 (Hren et al., 2023). This amount is significant and contributes to higher water consumption even though the amount of grey H_2 used as an auxiliary reductant is minimal due to thermodynamic constraints (Yilmaz et al., 2017). For green H_2 (Scenario 5), a water consumption of 3.9 m^3/tHM is calculated. This value is 17% higher than the base scenario, but slightly lower than grey H_2. The highest source of water consumption is from coke at 58%, which is similar to all other scenarios. Green H_2 production contributes to around 13.9% of overall water consumption, which is slightly lower than grey H_2, but higher than the biomass-based reductants evaluated in Scenario 2 and Scenario 3. A study by Hren et al showed that around 0.11 tonnes of steam and 10 tonnes of water are needed to produce 1 tonne of green H_2 (Hren et al., 2023). This overall amount is significantly lower than grey H_2. In this research, Green H_2 is produced by electrolysis powered by onshore wind energy, splitting water into H_2 and O_2.

5.1.5 Mineral Resource Scarcity

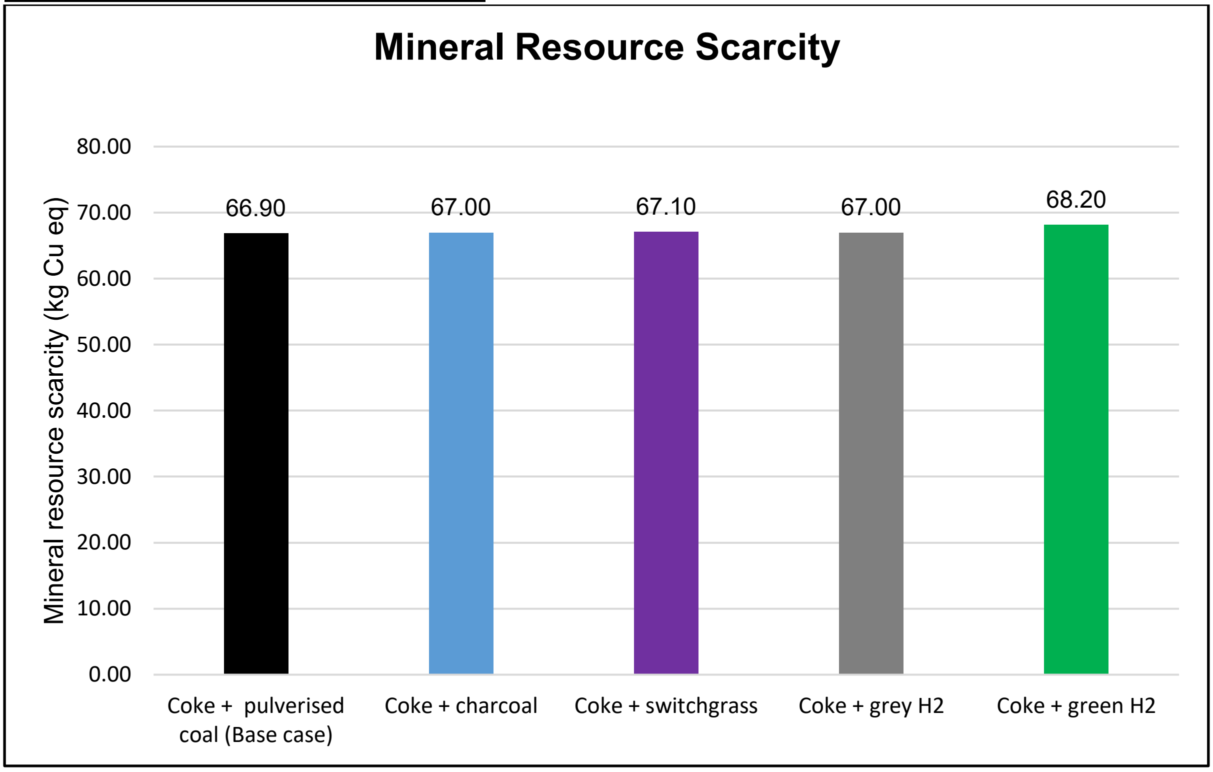

Figure 29: Mineral Resource Scarcity across Five Blast Furnace Ironmaking Scenarios

Figure 29 presents the mineral resource scarcity (MRS) results for all five assessed scenarios. The impact category is expressed in kilograms of copper equivalent (kg Cu eq) based on the ReCiPe Midpoint (H) methodology. This impact category quantifies the mineral resources critical to industrial processes like copper, cobalt, nickel, lithium, and rare earth elements (Huijbregts et al., 2016). These elements are essential for technologies, and the metric indicates long-term economic availability by taking into account energy and cost needed to access lower-grade or more remote reserves of minerals (Schneider et al., 2014; van Oers et al., 2020).

The MRS value is essentially invariant across the five scenarios, ranging from 66.9 to 68.2 kg Cu-eq/tHM, with more than 99% of total impacts attributable to iron-bearing raw materials. For Scenario 1, the primary contributors of MRS are iron sinter (58.4%), followed by iron pellets (29.6%), and iron ore (11.4%). From the assessment, coal mining and coal production have a low contribution to MRS of below 1%. These operations do not require substantial inputs of rare metals or technology critical elements consistent with a finding by Norgate et al (Norgate et al., 2007).

For Scenarios 2, 3, 4, and 5, the values of MRS are almost identical to the base scenario. This is because MRS's primary contributors are from iron-bearing sources (ore, sinter, and pellets), which are of a similar quantity for all scenarios. However, it is worth noting that for Scenario 5, there is 2% increase over the base scenario, the highest increase of all. This amount is still considered minimal, and also the infrastructure of wind power electricity is not included. However, it is expected that the amount will be higher when infrastructure to produce electricity powered by wind is included. For example, wind turbines require rare earth elements like neodymium and dysprosium in permanent magnets (International Energy Agency, 2022).

Overall, it can be inferred that changing the carbon-based reductant into a more environmentally friendly alternative reductant has no significant impact on MRS. Given this stability in MRS values, meaningful improvements in this category will depend on measures such as improving iron ore grade, increasing scrap utilisation, and modifications to PCI feedstock alone.

5.1.6 Contribution Analysis of Environmental Impacts

A contribution analysis was conducted to identify the processes that have highest influence on the environmental impacts across the five scenarios. This step aligns with the interpretation outlined in ISO 14044 and also guided the selection of sensitivity parameters that are that are assessed in Chapter 6 (Section 6.2). The top three contributors for each impact category and each impact scenario are presented in Figure 30.

Global warming potential (GWP) was dominated mainly by emissions from the blast furnace operation, the production of coke, and the sintering of iron bearing materials. Although the relative proportions varied across scenarios, these three processes remained the dominant sources of climate impacts. Moreover, Senario 4 introduced an additional contribution from grey H_2 production, yet the blast furnace and coke supply continued to dominate the overall results.

Land use demonstrated a distinct pattern because it was influenced by the cultivation of biomass. Charcoal production accounts for 73 percent of total land use in Scenario 2, whereas switchgrass cultivation represented 70 percent in Scenario 3. Furthermore, for Scenarios without biomass as reductants like Scenario 1, 4, and 5, land occupation was governed by coke production and transport activities.

Fossil resource scarcity (FRS) was influenced mainly by coke production in every scenario contributing between 68 and 91 percents of total impacts. In addition, extraction of coal, sintering, and transport processes contributed to the remainder but the amount is relatively smaller. This indicates that reliance on fossil resources is closely aligned with the continued use of coke in blast furnace operation even when partial substitution with alternative reductants are considered.

Water consumption, followed a similar pattern like FRS. Coke production remained the largest contributor, followed by water consumption for blast furnace operation itself. Moreover, H_2 pathways revealed additional burdens. With grey H2 in Scenario 4 and green H_2 in Scenario 5 contributing for 18 and 14 percent respectively to the total impacts.

Mineral resource scarcity showed consistent trends, with iron sintering contributes approximately 58 percent, pellet production accounts for around 30 percent, and iron ore beneficiation contributes to the remaining 11 percent. These contributions were stable across all scenarios, reflecting the mineral intensive nature of producing iron bearing materials and indicate the choices of reductants have no impacts to this impact category.

The hotspot processes identified through this analysis shaped the design of sensitivity analysis in Chapter 6. Although these hotspots provide a clear basis for selecting the most influential parameters, it is important to recognise that the dominance of coke production, sintering, and blast furnace emissions largely reflects the barriers to fully decarbonise the blast furnace operation. Moreover, coke remains the main contributor across most impact categories because it continues to serve as the primary reductant in all scenarios, and this reliance continues due to process limitation that restrict the substitution potential of alternative reductants. In addition, the high land use associated with biomass and the higher water use linked to hydrogen indicates the trade offs that arise when new reductants are introduced. Furthermore, the stability of mineral resource scarcity across all scenarios shows that some impacts are not influenced by the reductant choices.

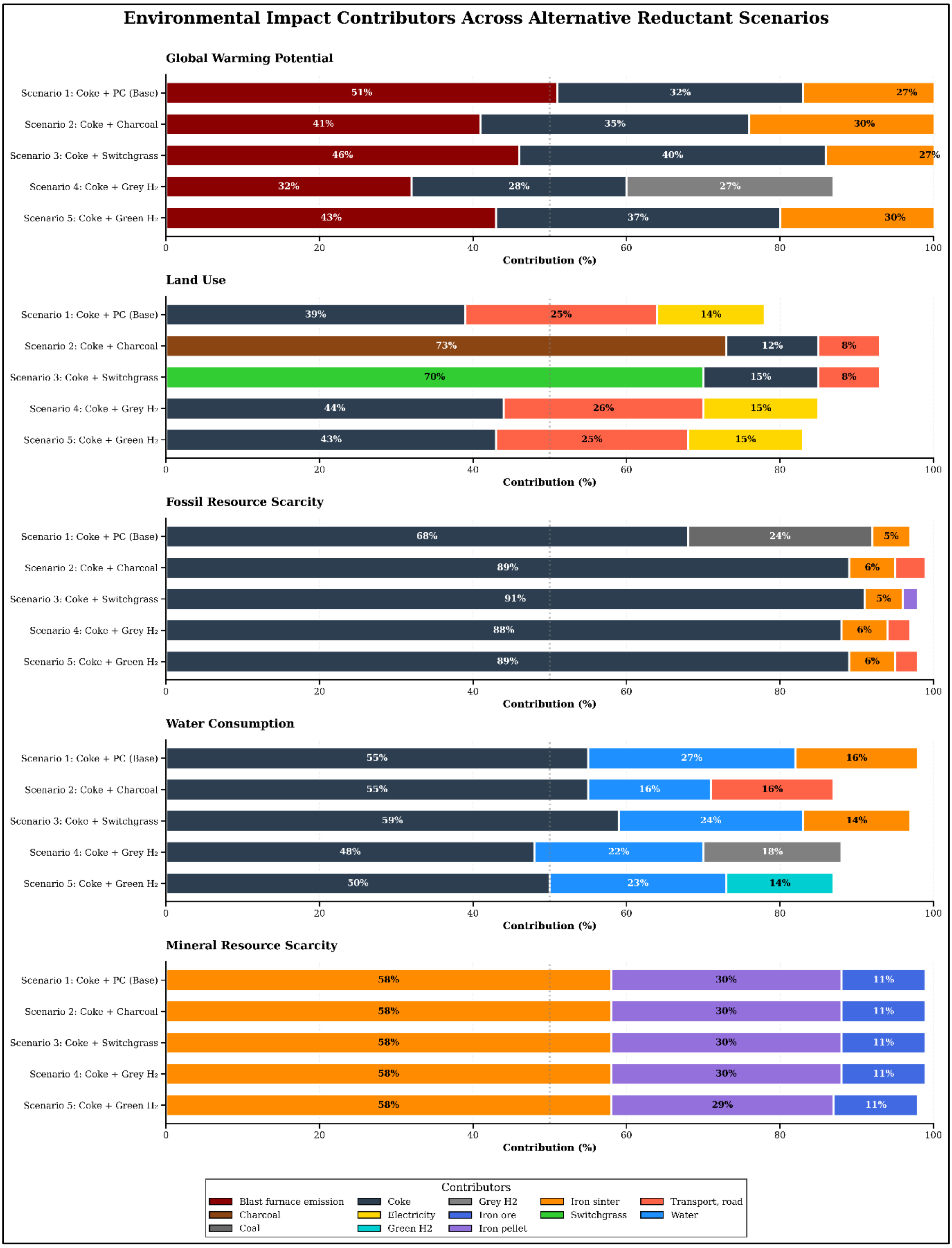

Figure 30: Environmental Impact Contributors for All Scenarios

5.1.7 Summary of LCA Assessment

Table 54 presents a comparative "traffic-light" assessment for all five scenarios evaluated, with five impact categories holistically considered. When compared with existing literature, this research is the first one to present a UK-contextualised LCA comparing five alternative blast furnace ironmaking pathways of alternative reductants such as charcoal, switchgrass, grey H_2, and green H_2, vs conventional blast furnace ironmaking.

Table 54: LCA Results for Environmental Impact Categories across Five Reductant Scenarios

Impact Category	Unit (per tonne of hot metal)	Scenario 1: Coke and Pulverised Coal (Baseline)	Scenario 2: Coke and Charcoal	Scenario 3: Coke and Switchgrass	Scenario 4: Coke and Grey H_2	Scenario 5: Coke and Green H_2
Global Warming Potential	tonne CO_2 equivalent	1.51	1.34 (▼11%)	1.47 (▼3%)	1.82 (▲ 21%)	1.36 (▼10%)
Land Use	m^2a crop equivalent	28	92.3 (▲ 230%)	91.1 (▲225%)	26.1 (▼7%)	1.36 (▼10%)
Fossil Resource Scarcity	kg oil equivalent	311	233 (▼25%)	281 (▼10%)	253 (▼19%)	250 (▼20%)
Water Consumption	m^3	3.34	3.33 (0 %)	3.81 (▲14%)	4.09 (▲22%)	3.90 (▲ 17%)
Mineral Resource Scarcity	kg copper equivalent	66.9	67 (▲0.1%)	67.1 (▲0.3%)	67 (▲0.1%)	68.2 (▲2%)

Table 55: Legend for colour codes used in LCA Results Summary

Colour	Meaning
(green)	**Improved** - lower environmental burden than baseline
(amber)	**Similar / negligible change** compared with baseline
(red)	**Worse** - higher environmental burden than baseline

Based on the findings, Scenario 2 (charcoal) and Scenario 5 (green H_2) offer the most favourable environmental performance. Nevertheless, each scenario carries distinct trade-offs that must be strategically addressed to ensure that the environmental benefits identified are achieved in practice.

Scenario 2 (charcoal) achieves the most significant absolute reductions in both GWP (-11%) and FRS (25%) compared to the base scenario. This result is consistent and aligns well with extensive literature showing that sustainably sourced biomass-derived reductants can effectively replace pulverised coal injection (PCI) and reduce fossil carbon emissions (Leão et al., 2023; Mousa et al., 2016; T. Norgate & Langberg, 2009; Suopajärvi et al., 2017). These improvements are primarily due to the biogenic nature of charcoal's carbon and the avoidance of methane emissions from coal mining (Abbasi et al., 2010; US EPA, 2024). However, charcoal production increases land occupation by more than threefold (92.4 m^2a crop eq/tHM) mainly due to the cultivation of eucalyptus feedstock, which requires a large plantation area (Zhang et al., 2021). This raises concerns over biodiversity loss, deforestation, and competition with agricultural production (Schulze et al., 2012; Food and Agriculture Organization of the United Nations, 2025)

The practical deployment of charcoal in the UK needs to follow the principles and recommendations outlined in the Biomass Strategy 2023 (Department for Energy Security & Net Zero, 2023a). The report states that biomass should only be used where it delivers the highest net-zero benefit to replace fossil fuels in ways that achieve substantial GHG emissions. Besides, charcoal must come from certified sustainable sources, and can be fully tracked and protected against deforestation or indirect land-use change. Moreover, blast furnace systems should be designed with carbon capture storage facilities to allow the efficient capture and permanent sequestration of CO_2 from the blast furnace top gas (Perpiñán et al., 2023). It is also worth noting that charcoal use should remain a transitional measure to avoid long-term dependence on biomass as the sector moves to cleaner technologies. Moreover, the deployment should follow phased, evidence-led steps starting with small-scale Bio-PCI trials and scale-up should only be done if the environmental, operational, and supply chain criteria are met to balance both process efficiency and environmental benefits. Lastly, continuous monitoring and transparent reporting need to be put in place to maintain compliance with environmental regulations. In the UK, sourcing charcoal sustainably can be demonstrated by ensuring compliance with the UK Timber Regulation (EUTR) to prevent illegally harvested timber or timber products on the market. At present, charcoal is excluded from the scope but is under consideration for inclusion (GOV.UK, 2025b). Besides, charcoal sourcing can be supported by independent, recognised certification schemes such as the Forest Stewardship Council (FSC), the Programme for the Endorsement of Forest Certification (PEFC), or the Sustainable Biomass Program (SBP). All the programmes provide sustainability assurance for woody-biomass supply chains (National Audit Office, 2024). In addition, the production of high-quality biocarbon can be further improved by upgrading raw biomass through torrefaction or pyrolysis as recommended by Suopajarvi et al. (2018) and Khasraw et al. (2024) (Suopajärvi et al., 2018; Khasraw et al., 2024). This is to ensure the production of biocarbon with higher fixed carbon content, lower volatile matter, and reduced moisture suitable for blast furnace ironmaking. Along with this, a gradual phased deployment in the UK blast furnace sector can be implemented, starting with partial PCI replacement at selected tuyeres to allow close monitoring of raceway temperature, hot metal quality, and slag chemistry before full-scale implementation.

The use of green H_2 to replace PCI (Scenario 5) delivers near-equivalent GWP reductions around 10% but without the land-use penalty, which is attributable to the compact footprint of onshore wind infrastructure to produce electricity (Maniscalco et al., 2024). The main drawbacks are a 17% increase in water consumption, which is primarily due to the electrolysis feed water requirement (Hren et al., 2023) and the thermodynamic constraints on H_2 injections that require additional O_2 enrichment and additional heating to maintain furnace stability (Yilmaz et al., 2017; Lan et al., 2022). For practical implementation in the UK, green H_2 supply must comply with the UK Low Carbon Hydrogen Standard (LCHS), which sets a life cycle GHG limit of 20 g CO_2 eq/MJ (LHV). Producers must also provide robust verification of renewable electricity inputs, such as a compliant Power Purchase Agreement (PPA), to meet LCHS requirements (Department for Energy Security & Net Zero, 2023a). Furthermore, actions need to be made to ensure electrolysers are installed at the same site as the steel plant and powered through PPA from onshore wind or wind-solar hybrid projects. This aims to reduce transmission losses, lower the risk of power curtailment, and support the necessary verification and standards under the LCHS.

In the UK, the transition to green H_2 requires strategic water resource management due to high water demand. National level analysis by the Department for Energy Security and Net Zero (DESNZ) outlined that H_2 production requires water for both electrolysis and cooling, with the differences based on technology and cooling system design. Water needed for electrolysis has a higher quality requirement and needs to be equivalent to ASTM Type II water. The water quality requirement for grey H_2 SMR is less stringent (UK Government, 2024b). The use of closed-loop cooling systems substantially reduces water consumption compared to once-through or evaporated types (Deloitte, 2024; Environment Agency, 2024). This guidance can be used during the design stage for sustainable green H_2 deployment for the steel industry. Moreover, freshwater can be produced by treating and reusing industrial or municipal wastewater. Adequate purified, reclaimed water can be used as viable feedwater for electrolysis, hence improving circularity and resilience. In addition, projections by Renewable UK indicate that the water requirements in the UK will increase fivefold by the year 2050 for H_2 production under current deployment trajectories. Therefore, this highlights the importance of including water availability assessment into regional planning and policy frameworks (Renewable UK, 2024). Sustainable green H_2 deployment can be attained by integrating into regional water planning, prioritised recycled or alternative water sources, mandating water audits and promoting water-efficient technologies (Lin et al., 2025).

In addition, staged injection trials can be conducted by starting with a few tuyeres and gradually increasing PCI replacement at the blast furnace. Both need to be accompanied by increased O_2 enrichment to counteract the endothermic cooling effects, as evidenced in the H_2Stahl project at Thyssenkrupp Steel's Duisburg plant (Yilmaz et al., 2017; Thyssenkrupp, 2022; BFI, 2025) and also in Nippon Steel's pilot trials in Japan (Nippon Steel, 2025).

In contrast, Scenario 4 (grey H_2) proves that not all H_2 pathways contribute to decarbonisation. The increase in GWP by 21% over the base scenario was partly due to high upstream emissions from steam methane reforming without carbon capture (International Energy Agency, 2021), and the water consumption is the highest among all scenarios (+22%) because of significant steam demand (Hren et al., 2023). Similarly, Scenario 3 (switchgrass) also yields only marginal improvements of around

3% GWP reduction and 10% FRS reduction, attributable to its low fixed carbon content and energy density, which require increased coke inputs. The findings corroborate the conclusions driven by Khasraw et al. (2024) and Ng et al (2010) that biomass upgrading is crucial before BF injection.

For all scenarios, MRS values remain comparable, indicating that the impact category is dominated by iron-bearing raw materials instead of choices of reductant. Thus, measures such as increasing the use of scrap steel, improving ore quality, and enhancing beneficiation efficiency can be implemented to address mineral depletion issues, rather than merely changing the PCI feedstock.

A parallel assessment using the Environmental Footprint (EF) method was conducted for the five impact categories. The overall results were consistent with those obtained using ReCiPe 2016 Midpoint (H), indicating that charcoal and green H_2 deliver the strongest overall environmental performance relative to the baseline. By contrast, grey H_2 consistently exhibited the worst performance under both methods. Furthermore, ReCiPe 2016 Midpoint (H) and EF showed similar trade-offs across impact categories for all scenarios. This consistency between the two methods supports the robustness of the findings and confirms that the study's conclusions are not dependent on the specific LCIA method applied. ReCiPe 2016 Midpoint (H) was retained as the primary method because it is more widely applied in the UK across both for academic and industrial contexts.

In this research, it is also worth noting that the analysis of the potential impacts of alternative reductants on slag quality and quantity, as well as on blast furnace top-gas quality and quantity, is excluded. However, changes are expected in practice. For example, the substitution of charcoal and switchgrass can increase the basicity of slag, which may affect its solidus and liquidus temperatures and influence downstream slag handling (Heikkilä et al., 2022). Similarly, the use of H_2 as a reductant can change the silicon reduction pathways in the cohesive zone and affect the silicon concentration in the hot metal (Nogami et al., 2012). In addition, as shown in Table 38, the quantity of blast furnace top gas decreases when charcoal, grey H_2, and green H_2 are used as alternative reductants. In the case-study UK steel plant, a major share of the blast furnace top gas is used for external applications such as on-site energy generation. Therefore, this reduction could have consequential operational, and energy supply impacts. For example, it has been reported that the decommissioning of blast furnace at one of UK steel plant, led to the need of about four natural gas fired boilers to meet on site energy demand due to the absence of blast furnace top gas (Holliman, 2025). Therefore, the use of alternative reductants needs to be carefully weighed and holistically assessed to avoid unintended consequences where reductions in top gas availability could lead to increased reliance on fossil-based fuels.

For both Scenario 2 (charcoal) and Scenario 5 (green H_2), successful implementation in the UK will require a unified monitoring, reporting and verification framework. This can entail a quarterly disclosure of cradle-to-gate GHG emissions, land use footprint, water use, and supply chain compliance for all reductant supply. Besides, embedding sustainability criteria into procurement contracts and site-level operating procedures can help ensure that the environmental benefits evidenced in this research are delivered in practice, whilst avoiding unintended consequences such as ecological degradation or operational instability.

Overall, it can be inferred that there is no single alternative reductant that can deliver uniform improvement across all impact categories evaluated in this research. However, sustainably sourced charcoal and green H_2 emerge as the most viable near-to-medium-term solutions for BF decarbonisation pathways in the UK. Integrations with targeted process adaptations, stringent supply chain governance, and phased operational integration can allow both pathways to potentially deliver significant climate benefits without shifting the burdens to other environmental impacts (e.g land use).

5.1.8 Economics Assessment

From the LCA assessment, Scenario 2 (coke and charcoal) and Scenario 5 (coke and green H_2) emerged as the most environmentally favourable alternatives to conventional blast furnace ironmaking in the UK. However, a preliminary economic scoping exercise is required to understand whether these environmental gains align with cost considerations. The total cost to produce 1 tonne of hot metal for Scenario 1 (base case), Scenario 2 and Scenario 5 is summarised as follows. The detailed calculation and assumptions used in this section are presented in Appendix C.

A preliminary economic scoping exercise was conducted for Scenario 2 (coke and charcoal) and Scenario 5 (coke and green H_2), the two most environmentally favoured alternative reductants. This assessment is limited to reductant purchase costs as a first-order approximation. Capital costs, operating costs variations, and co-product value changes are excluded from this assessment. Therefore, these results should be interpreted as indicative cost comparisons rather than comprehensive economic feasibility assessments.

In addition, the cost figures presented in Table 52 are subject to uncertainty and should therefore be interpreted with caution in the economic assessment. For green H_2, current UK production costs via electrolysis are estimated at around £3 per kg (WSS Energy Consulting, 2025). These costs depend on several factors, including electrolyser technology, renewable electricity source, and scale of operation. The green H_2 cost adopted in this research reflects market conditions in 2023 and should therefore be regarded as a near-term estimate rather than a long-term projection. Under optimistic scenarios, green H_2 is expected to become less expensive and more cost-competitive as renewable power capacity expands.

The total costs of reductants to produce 1 tonne of hot metal for Scenario 1 (Baseline), Scenario 2, and Scenario 5 are presented in Table 56. The full calculation is outlined in Appendix C.

Table 56: Total Reductant Cost for Production of 1 Ton of Hot Metal

Scenario	Scenario 1: Coke and PCI (Baseline)	Scenario 2: Coke and charcoal	Scenario 5: Coke and green H_2
Total Reductant Price (£/tHM)	112	146	168

These figures exclude transport and supply chain costs for simplification, which are important elements for all scenarios. Due to land availability constraints in the UK, large-scale domestic charcoal production is not viable and must be imported from Brazil or Eastern Europe, which increases overall costs. In contrast, green H_2 offers an opportunity for domestic production as part of emerging UK projects, including plans to develop the first large-scale green H_2 facility in South Wales, a project under the H_2 Energy Europe Plan (Trafigura, 2023). This localised advantage can improve the overall cost of green H_2 deployment.

Cost-Effective Analysis

The cost per tonne of CO_2 avoided was calculated for each alternative scenario to evaluate the economic efficiency of emissions reduction. This metric is derived by dividing the additional reductant cost by the GWP reduction achieved relative to the baseline as outlined in Section 5.1.1. The cost per tonne of CO_2 avoided provides a standardised basis for comparison with other industrial decarbonisation options and carbon-pricing mechanisms applied within the UK steel sector. The results are presented in Table 57.

Table 57: Cost-Effectiveness Analysis

Metric	Scenario 1: Coke and PCI (Baseline)	Scenario 2: Coke and charcoal	Scenario 5: Coke and green H_2
Environmental Performance			
GWP (tCO_2-eq/tHM)	1.51	1.34	1.36
GWP Reduction (tCO_2-eq/tHM)	–	0.17 (−11%)	0.15 (−10%)
Economic Performance			
Total Reductant Cost (£/tHM)	112	146 (+34)	168 (+56)
Cost per tCO_2 Avoided (£/tCO_2)	–	200	373

From Table 57, it can be observed that Scenario 2 (charcoal) exhibits a cost-effectiveness of £200 per tCO_2 avoided, while Scenario 5 (green H_2) costs £373 per tCO_2 avoided. In practical terms, this means that for every tonne of CO_2 emissions avoided, Scenario 2 (charcoal) costs an additional £200 compared to conventional practice, while Scenario 5 (green H_2) costs an additional £373 for the year 2023. These values represent the incremental increase in cost that steel producers need to pay when switching from conventional coke-based blast furnace operation to alternative reductants, purely from a reductant cost perspective. For context, the UK Emissions Trading Scheme (UK ETS) carbon price in 2023 was £83.03 (UK Government, 2024c). This carbon price represents the financial penalty that steel producers need to pay for each tonne of CO_2 they emit in accordance with a market-based cost for carbon emissions. Industrial carbon capture technology (CCS), which is widely considered for industrial decarbonisation costs, typically ranges from approximately £32 to £ 96 per

tCO_2 (at 2023 exchange rates) (International Energy Agency, 2021b). This benchmark is particularly relevant as CCS represents an established technology pathway to decarbonise heavy industry to reduce emissions, although it addresses emissions through a different approach than fuel substitution. CCS technology captures CO_2 after combustion, and this research explores ways to prevent its formation using alternative reductants.

As the cost per tCO_2 avoided for alternative reductants in Scenarios 2 and 5 exceeds the carbon price, they are not yet economically competitive on their own. This assessment indicates that both alternative scenarios require either higher carbon prices or cost reductions to achieve economic parity with conventional blast furnace operation on a reductant-cost basis alone. In the current market context (2023-2025), where carbon prices remain below £100 per tCO_2, steel producers face a substantial economic disincentive to voluntarily adopt these cleaner technologies without additional policy support or subsidies. This poses a challenge for the UK steel producers, who already operate on very tight margins, and in some cases, at a financial loss (Sky News, 2025). Nevertheless, the cost per tCO_2 avoided for charcoal (£200/tCO_2) is substantially lower than that for green H_2 (£373/tCO_2), making charcoal as a more economically accessible option in the near term.

CHAPTER 6

6.0 RESULTS AND DISCUSSION:
DATA QUALITY AND SENSITIVITY ANALYSIS

This chapter evaluates the robustness of the life cycle assessment by examining data quality and assessing the influence of key assumptions on the results. It presents the pedigree matrix scores for each scenario and identifies the main sources of uncertainty. The chapter then examines the effect of variations in coke sourcing, transport distances, biomass datasets, and iron-bearing materials on the environmental outcomes. It concludes by assessing the overall credibility of the comparative results and the extent to which the findings remain consistent under varying assumptions.

6.1 Data Quality

A structured data quality assessment was conducted using the Pedigree Matrix method to assess the reliability and robustness of Life Cycle Inventory (LCI) data across five reductant scenarios. This assessment is conducted against five criteria: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. Each scenario was scored accordingly based on relevance, transparency, and appropriateness of the data sources, with justifications based on literature, expert validation, and alignment with UK steelmaking practices. The following sections present a detailed rationale for each score.

6.1.1 Coke and pulverised coal (Baseline)

In Scenario 1, coke and pulverised coal are used as reductants in blast furnace ironmaking. The data quality for this scenario was evaluated based on the five Pedigree Matrix criteria, with the rationale for each score described as follows:

a) Reliability (Score: 2)

The majority of foreground data utilised in this scenario are sourced from Ng et al. (2010), a technical report produced by Canmet ENERGY, Canada's national energy R&D organisation under Natural Resources Canada. Although the report is not peer-reviewed, it is widely recognised for its methodological transparency and high-quality policy-relevant research. Additionally, the foreground data were validated by an expert with in-depth knowledge of the blast furnace operations at the case-study UK steel plant, who confirmed their representativeness for use in a PhD-level LCA. Furthermore, operational data such as the quantities of iron-bearing materials and the allocation of co-products were obtained directly from a representative of the case-study UK steel plant. Furthermore, cross verification was conducted using the Handbook of Ironmaking by Cameron et al. (2019), which confirmed consistency with global industrial benchmarks for the production of 1 tonne of hot metal. Since the dataset comprises a combination of measured values and partial assumptions, a score of 2 is assigned.

b) Completeness (Score: 1)

The dataset includes all crucial foreground flows needed for blast furnace modelling. This includes inputs such as iron ore, coke, coal, air, electricity, and outputs like blast furnace top gas, CO_2 and CO emissions, and slag. The inclusion of these flows is consistent with those reported in other peer-reviewed studies, such as Leao et al. (2023) and Burchart-Korol (2013), which verified the comprehensiveness of the dataset. A score of 1 is assigned.

c) Temporal Correlation (Score: 1)

Although the dataset from Ng et al. (2010) is over a decade old, its core parameters remain broadly representative of current industrial practice. The fundamental configuration and material flows of blast furnace operation have changed very little over this time. This temporal relevance was verified by an expert with detailed knowledge of the case-study UK steel plant's operations, and further supported by comparison with the global industry benchmark presented in the Blast Furnace Ironmaking book written by Cameron et al. (2019).

d) Geographical Correlation (Score: 2)

The foreground dataset originates from ArcelorMittal Dofasco, a Canadian steel plant that operates a blast furnace–basic-oxygen-furnace route, comparable in process principles to the case-study UK steel plant. Hence, it makes the data relevant for the study. Besides, to further improve the geographical relevance of the study, the co-products allocation (for blast furnace top gas and slag) for environmental burden, iron-bearing sources quantity, and key raw materials transportation distances were adjusted using UK-contextualised data. Consultation with an expert who has in-depth knowledge of the case-study UK steel plant confirmed that the data were transferable and representative of UK operating conditions.

e) Technological Correlation (Score: 2)

The technological processes described in Ng et al. (2010) are comparable to those at the case-study UK steel plant, where coke is used as the primary reductant and pulverised coal as the auxiliary reductant. Nevertheless, minor technological differences may exist because of regional operational practices and blast furnace-specific optimisation. However, these variations do not affect the comparability of LCI data. Hence, a moderate score of 2 is assigned.

Overall Assessment

Overall, the total pedigree matrix score for Scenario 1 is 8. This indicates high data quality with low to moderate uncertainty. This assessment indicates that this dataset is robust and appropriate to serve as the baseline scenario in the comparative LCA of blast furnace reductants.

Table 58: Pedigree Matrix Scores for Scenario 1 (Baseline)

Criterion	Score
Reliability	2
Completeness	1
Temporal Correlation	1
Geographical Correlation	2
Technological Correlation	2

6.1.2. Coke and charcoal

In Scenario 2, coke is used in combination with charcoal as a reductant in blast furnace ironmaking. The rationales behind the scores are described as follows.

a) Reliability (Score: 2)

The foreground data for this scenario are derived primarily from Ng et al. (2010), the same technical report used in Scenario 1. This report, developed by CanmetENERGY under Natural Resources Canada, is well-regarded for its transparent methodology and high-quality, policy-oriented research, despite not being peer-reviewed. This data was also reviewed in consultation with an expert who has detailed knowledge of the case-study UK steel plant's operations. The background data for charcoal production were sourced from Leão et al. (2023), a peer-reviewed study focusing on blast furnace ironmaking in Brazil. This research provides a detailed cradle-to-gate life cycle inventory for eucalyptus-based charcoal production in Brazil. Since the dataset comprises a combination of measured values and partial assumptions, a score of 2 is assigned.

b) Completeness (Score: 2)

The combined datasets comprehensively cover all relevant inputs and outputs for the coke and charcoal scenario. Foreground flows include iron-bearing inputs, reductants (coke and charcoal), electricity, and air, as well as outputs such as hot metal, blast furnace gas, CO_2, CO, particulates, and slag. Ng et al. (2010) provide a complete mass and energy balance for blast furnace operation. In parallel, Leão et al. (2023) detail the quantity of feedstock required and the associated energy and emissions for charcoal production. However, charcoal production is primarily in Brazil. Given these factors, a score of 2 was assigned.

c) Temporal Correlation (Score: 2)

Although the data from Ng et al. (2010) is a decade old, it remains temporally valid due to the stability of blast furnace process configuration and key performance parameters (e.g., coke rate, reductant injection, and emissions). The core parameters (coke rate, reductant injection, output emissions) have not significantly changed and remain consistent with those reported in the handbook of ironmaking that has been published in recent literature, such as Cameron et al. (2019). The quantity of charcoal to be used as auxiliary reductant outlined by Ng et al. (2010) is also within the range identified by several studies as benchmarked by Suopajarvi et al. (2018). Meanwhile, the charcoal dataset from Leao et al. (2023) is highly recent and reflects current carbonisation practices. Given the mixed ages of the sources, a score of 2 is assigned to reflect a moderate temporal correlation.

d) Geographical Correlation (Score: 3)

The foreground blast furnace model originates from a Canadian plant (ArcelorMittal Dofasco), similar to Scenario 1. UK-contextualised adjustments were made for transport distances, co-product allocation, energy mix, and water consumption to improve contextual relevance. Expert review further confirmed the applicability to the case-study UK steel plant.

However, the background dataset for charcoal is based on Brazilian eucalyptus charcoal, modelled using regional kiln technologies and Brazil’s electricity grid. In reality, this can be different because charcoal in the UK is imported from various countries such as Namibia, Paraguay, and South Africa (The Observatory of Economic Complexity, 2025b), where feedstocks, kiln types, and energy mixes may differ. Given these regional mismatches and the absence of UK-contextualised LCI data, a geographical correlation score of 3 is deemed appropriate.

e) Technological Correlation (Score: 2)

Charcoal injection in blast furnaces has been demonstrated at small to medium industrial scale in countries such as Brazil, Sweden, and Finland. The process principles are similar to those of pulverised coal injection and are technically feasible. However, no evidence of full-scale industrial implementation exists in the UK, and no academic literature confirms the use of charcoal in blast furnaces at the case-study UK steel plant or at other domestic facilities. Although the technological basis is valid, the absence of UK-contextualised demonstrations justifies a score of 2.

Overall Assessment

Overall, the total pedigree matrix score for Scenario 2 is 11, indicating moderate data quality. The blast furnace model is consistent and reliable, but the regional specificity and limited deployment of charcoal in UK practice introduce additional uncertainty. Hence, results from these scenarios need to be cautiously interpreted, especially when comparing with more mature industrial practices. The scores are summarised as follows.

Table 59: Pedigree Matrix Scores for Scenario 2

Criterion	Score
Reliability	2
Completeness	2
Temporal Correlation	2
Geographical Correlation	3
Technological Correlation	2

6.1.3. Coke and switchgrass

For Scenario 3, the scores were assigned for the use of coke and switchgrass as reductants. Each criterion is evaluated and assessed based on the nature of data sources and the relevance to the UK blast furnace. The rationale behind the scores for each criterion is described as follows.

a) Reliability (Score: 3)

The foreground data are sourced from Ng et al. (2010), consistent with Scenarios 1 and 2. Although not peer-reviewed, the report was prepared by CanmetENERGY under Natural Resources Canada and is regarded as technically robust and methodologically transparent. The data was also reviewed by an expert with in-depth knowledge of the blast furnace operations at the case-study UK steel plant.

However, the background data for switchgrass is not directly available in the Ecoinvent database. Instead, miscanthus, a perennial energy crop with similar cultivation practices, is used as a proxy. Although miscanthus is a perennial grass with comparable end-use potential, it differs from the other plants in terms of biomass yield, chemical composition, and ash content. The use of miscanthus as a proxy introduces a source mismatch and increases uncertainty in the background dataset, resulting in a lower score of 3.

b) Completeness (Score: 3)

The foreground dataset includes all critical process flows, such as coke, iron ore, electricity, air, and process outputs like hot metal, slag, and blast furnace gas. These inputs are consistent with the well-established mass and energy balance from Ng et al. (2010), as validated in previous scenarios. However, the background system is modelled using miscanthus data as a stand-in for switchgrass. While both species share similar agronomic practices and applications, essential distinctions exist in carbon content, moisture, and ash production, which affect combustion and emissions. Although the substitution approach is permitted under ISO 14044 (International Standard Organisation, 2022b) for addressing data gaps, it introduces uncertainty in completeness. Therefore, a moderate score of 3 is justified.

c) Temporal Correlation (Score: 3)

The core blast furnace data from Ng et al. (2010) remains widely relevant to the context study due to the stable nature of large-scale ironmaking operations, with the technological configurations still relevant to current industry practice. However, for switchgrass background data, miscanthus is used as a proxy due to data unavailability in Ecoinvent version 3.10. In this research, it was assumed that the switchgrass is sourced from the US, which is the leading supplier of switchgrass (IEA Bioenergy, 2011). Since switchgrass-specific datasets are not available in Ecoinvent, the current conditions are considered less specific temporally and may not accurately reflect the latest developments in US agricultural practices. Hence, a moderate score of 3 was assigned.

d) Geographical Correlation (Score: 3)

The foreground data are based on ArcelorMittal Dofasco in Canada, which utilises BF-BOF technology comparable to that of the case-study UK steel plant. UK-contextualised adjustments were made for energy mix, transportation distances, raw material sources, and co-product handling, consistent with previous scenarios. These were validated by expert consultation.

However, for switchgrass background data, miscanthus from Ecoinvent 3.10 is used as proxy data, and that miscanthus is assumed to be produced from the rest of the world. Meanwhile, the actual assumption for this scenario is that switchgrass is sourced from the US. Given the regional mismatch between assumed feedstock origin and actual proxy data, and the lack of UK-contextualised implementation or trials, a geographical correlation score of 3 is deemed appropriate.

e) Technological Correlation (Score: 3)

Unlike charcoal, which has been tested in industrial contexts, switchgrass has not yet been demonstrated as a reductant in any blast furnace operation. The concept remains theoretical, with no peer-reviewed studies or operational data confirming its application in ironmaking. Although the combustion characteristics of switchgrass are suitable in theory, its use in blast furnaces has not been validated even at the pilot scale. As such, the scenario represents a purely hypothetical pathway. A low technological correlation score of 3 is therefore assigned.

Overall Assessment

The total pedigree matrix score for Scenario 3 is 15. This indicates low overall quality with high uncertainty. This is primarily due to the reliance on proxy background data, the absence of temporal and regional specificity, and the lack of industrial implementation. However, this scenario may provide value as an exploratory or sensitivity modelling scenario. In addition, the results from this scenario need to be interpreted with caution, especially in terms of policy relevance.

Table 60: Pedigree Matrix Scores for Scenario 3

Criterion	Score
Reliability	3
Completeness	3
Temporal Correlation	3
Geographical Correlation	3

Technological Correlation	3

6.1.4: Coke and grey H_2

For Scenario 4, the use of coke and grey H_2 in blast furnace ironmaking was assessed. The data quality of this scenario is assessed against the Pedigree Matrix criteria, with scores and justifications outlined as follows.

a) Reliability (Score: 2)

The foreground dataset is sourced from a peer-reviewed study by Yilmaz et al. (2017). This research models partial H_2 injection into a blast furnace using a combination of process simulation tools. This research also involves validation of the model using actual operational data from a German steel plant, thereby strengthening the reliability of the dataset. The background data for grey H_2 is derived from Hren et al. (2023). This entails production of grey H_2 using the steam methane reforming (SMR) route, which includes direct process emissions, upstream emissions and the amount of electricity needed. Both datasets are peer-reviewed literature, well-documented and are deemed credible for this research. Despite the credibility of both sources, the absence of UK-contextualised hydrogen production data introduces minor uncertainty. Since the dataset comprises a combination of measured values and partial assumptions, a score of 2 is assigned.

b) Completeness (Score: 2)

The foreground dataset encompasses all significant inputs and outputs required for comparative LCA, including the quantity of coke, hydrogen inputs, iron-bearing raw materials, electricity, air, and outputs such as hot metal and process emissions. The background dataset from Hren et al. (2023) accounts for SMR-based H_2 production, associated CO_2 emissions, and upstream natural gas supply. To ensure consistency with other scenarios, infrastructure and equipment are excluded. Although comprehensive, the lack of UK-contextualised production data introduces some uncertainty, resulting in a score of 2.

c) Temporal Correlation (Score: 2)

Yilmaz et al.'s (2017) study represents technological and modelling assumptions from 2017, which is six years before the year of reference for this research, 2023. However, the fundamental principles of H_2 injection into blast furnaces remain unchanged, and the modelling approach is still relevant. In addition, the background data from Hren et al. (2023) is highly recent, reflecting up-to-date data for grey H_2 production. Hence, the overall score of 2 is justified based on the relevance of the combined system.

d) Geographical Correlation (Score: 2)

The foreground blast furnace model is calibrated based on a German steel plant and not directly based on UK operations. However, given that both countries operate within a European industrial context, it was assumed that the technological configuration and model are reasonably transferable. In this research, it is essential to note that the electricity mix and water used in the background for both hot metal and grey H2 production are adjusted to be UK-specific. Given all these assumptions, a score of 2 is assigned.

e) Technological Correlation (Score: 2)

The scenario reflects the use of coke as the primary reductant and grey H2 as the auxiliary reductant in a blast furnace. This concept is technologically feasible and has been validated at pilot scale in several initiatives involving projects like Thyssenkrupp Steel in Germany and Nippon Steel in Japan. These initiatives prove the feasibility of H_2 injection into a blast furnace without major redesign. Meanwhile, SMR is a mature industrial process and has been widely used in the chemical and refining sectors. However, grey H_2 is not yet used at scale in the UK steel sector. Given these factors, a score of 2 is assigned for technological correlation.

Overall Assessment

The total pedigree matrix score for Scenario 4 is 10. This indicates moderate data quality with acceptable levels of uncertainty. The use of peer-reviewed and calibrated modelling approaches improves the data robustness. Besides, the integration of UK-contextualised energy data and import data strengthens geographical representativeness. Nevertheless, the absence of direct UK measurement and the limited deployment of H_2 injection technology highlight the need for cautious interpretation.

Table 61: Pedigree Matrix Scores for Scenario 4

Criterion	Score
Reliability	2
Completeness	2
Temporal Correlation	2

Geographical Correlation	2
Technological Correlation	2

6.1.5: Coke and green H_2

For Scenario 5, the use of coke and green H_2 in blast furnace ironmaking was assessed. The rationale behind scores for each criterion was discussed as follows.

a) Reliability (Score: 2)

The foreground dataset is sourced from Yilmaz et al. (2017), a peer-reviewed study that models H_2 injection into the blast furnace. The model was calibrated with operational data from a German steel plant. The background dataset for green H_2 is derived from Hren et al. (2023), which provides a cradle-to-gate LCI for H_2 produced via water electrolysis powered by renewable energy, specifically wind power. For this research, the electricity supply was adjusted to reflect the UK grid mix for renewable electricity. Both studies are methodologically rigorous and credible, but the lack of UK-contextualised operational datasets introduces minor uncertainty. Since the dataset comprises a combination of measured values and partial assumptions, a score of 2 is assigned.

b) Completeness (Score: 2)

The datasets collectively include all significant foreground flows, such as coke, green hydrogen, iron-bearing materials, electricity, and air, as well as process outputs including hot metal, slag, and blast furnace emissions. The hydrogen background dataset from Hren et al. (2023) fully covers electrolysis operation, water use, electricity demand, and direct emissions. Infrastructure and equipment requirements were excluded to be consistent with the approach in other scenarios. Although comprehensive, the absence of site-specific UK data reduces completeness slightly, justifying a score of 2.

c) Temporal Correlation (Score: 2)

Yilmaz et al.'s (2017) study represents technological and modelling assumptions for the year 2017. This is six years before the year of reference for this research, 2023. However, it is deemed that the underlying concepts remain the same for the reference year. In addition, the background data from Hren et al. (2023) is recent, reflecting up-to-date data for green H_2 production. Hence, the overall score of 2 is justified based on the relevance of the combined system.

d) Geographical Correlation (Score: 2)

The foreground blast furnace model is calibrated based on a German steel plant and not directly based on UK operations. However, given that both countries operate within a European industrial context, it was assumed that the technological configuration and model are reasonably transferable. In this research, it is important to note that the electricity mix and water used in the background for both hot metal and green H_2 production are adjusted to be UK-specific. Given all these assumptions, a score of 2 is assigned.

e) Technological Correlation (Score: 3)

Hydrogen injection into blast furnaces has been validated at pilot scale in several initiatives, including projects by Thyssenkrupp Steel (Germany) and Nippon Steel (Japan). However, these demonstrations primarily involved grey hydrogen or industrial hydrogen blends, rather than green hydrogen derived from renewable electrolysis. Hence, while the mechanism of tuyere injection is technically proven, the large-scale industrial use of green hydrogen in blast furnaces has not yet been tested or deployed. Challenges remain regarding supply variability, scalability, and cost. This lack of demonstration in real-world steelmaking, especially in the UK, justifies a lower technological correlation score of 3.

Overall Assessment

The total pedigree matrix score for Scenario 5 is 11. This indicates moderate data quality with acceptable levels of uncertainty. The methodological robustness of peer-reviewed datasets and the use of UK-contextualised adjustments improve reliability and geographical relevance. However, the absence of industrial trials with green hydrogen in blast furnace operations introduces uncertainty around technological maturity. While the scenario represents a promising and environmentally favourable pathway, it remains a forward-looking, pre-commercial option. Results from this scenario should therefore be interpreted with caution in policy and industrial contexts.

Table 62: Pedigree Matrix Scores for Scenario 5

Criterion	Score
Reliability	2
Completeness	2
Temporal Correlation	2
Geographical Correlation	2
Technological Correlation	3

6.1.6 Summary of Data Quality

Table 63 summarises the pedigree matrix scores evaluated for this research across five scenarios. The data quality of datasets across five scenarios was assessed using the pedigree matrix method, with scores from 1 to 5 assigned for five quality indicators, such as reliability, completeness, temporal correlation, geographical correlation, and technological correlation (Weidema et al., 2013). A lower score indicates higher data quality. Although the pedigree matrix is widely utilised in LCA, neither the original framework nor ISO 14044 provides any official guidelines for interpreting aggregated scores (Weidema et al., 2013; International Standard Organisation, 2022b). However, several studies have adopted the alternative approach of summing or averaging the five indicator scores to support data screening and prioritisation of improvement effort (Baek et al., 2017; Edelen et al., 2018; Balcioglu et al., 2025). Following this established practice and acknowledging that the mean score of 3 or total score of 15 across five indicators typically reflects medium representativeness, this research applies a cut-off value of 15 as an author-defined threshold for inclusion in the LCA study. In essence, datasets with a total score of 15 and below are considered acceptable for comparative analysis in this research.

Table 63: Summary of Pedigree Matrix Scores across Five Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Coke and pulverised coal (base scenario)	**Coke and charcoal**	**Coke and switchgrass**	**Coke and grey H_2**	**Coke and green H_2**
Reliability	2	2	3	2	2
Completeness	1	2	3	2	2
Temporal correlation	1	2	3	2	2
Geographical correlation	2	3	3	2	2
Technological correlation	2	2	3	2	3
Total Score	8	11	15	10	11

Scenario 1 (coke and pulverised coal) achieved the lowest total score of 8. This indicates high-quality and reliable datasets and therefore confirms its suitability as a baseline scenario for comparative LCA.

Furthermore, Scenario 4 (coke and grey H_2) scored 10, while Scenario 2 (coke and charcoal) and Scenario 5 (coke and green H_2) both scored 11. All of these three scenarios indicate moderate data quality. For Scenario 2 (coke and charcoal), the main weakness is the geographical correlation, scoring 3, because the dataset is based on Brazilian production. In contrast, charcoal is primarily produced in Namibia, Paraguay, and South Africa. For Scenario 4 (coke and grey 2), the consistent moderate score of 2 across all criteria reflects the reliance on German blast furnace data and the lack of UK-contextualised datasets. For Scenario 5 (coke and green H_2), score 2 was assigned for reliability, completeness, and temporal correlation. However, a score of 3 is assigned for technological correlation due to the absence of industrial-scale trials of renewable H_2 injection into blast furnaces. Moreover, Scenario 3 (coke and switchgrass) achieved the highest score at 15, making it the least reliable among all scenarios. All criteria score 3, reflecting the reliance on miscanthus as a proxy dataset for switchgrass, limited temporal and geographical specificity, and the complete absence of industrial validation. Hence, this scenario is best regarded as exploratory and limited to sensitivity testing rather than informing policy or industrial practice.

In summary, the results show that data robustness decreases as technologies move further from established practice. The order of reliability is Scenario 1 (8)> Scenario 4 (10)> Scenario 2 and 5 (11) > Scenario 3 (15). These findings highlight the need for regionally specific inventories for charcoal and H_2 to improve data robustness. Furthermore, these outcomes also highlight the need for pilot-scale H2 injection trials in the UK to enhance technological correlation. For exploratory options such as Scenario 3 (coke and switchgrass), new datasets are required before this scenario can be applied beyond sensitivity analysis. This assessment demonstrates that while strong and reliable datasets support conventional reductants (coke and PCI), the robustness of data on alternative reductants depends on improved geographical representativeness, technological validation, and dataset development to provide evidence that is both credible and actionable for guiding the transition of the UK steel sector to net zero.

Despite the variations observed in data quality levels across the five scenarios, all datasets achieved total scores of 15 and below. Therefore, the data used in this study can be considered as robust for the comparative LCA presented. Nevertheless, further improvement in geographical representativeness, technological representativeness, and the availability of UK-contextualised pilot scale data can help strengthen future assessment and improve confidence in the results.

6.2 Sensitivity Analysis

Sensitivity analysis was conducted to evaluate how changes in key input parameters influence the environmental performance across all five reductant scenarios. This analysis focused on key parameters derived from the identification of hotspots from the baseline LCA. These key parameters include iron-bearing sources, coke production location, transportation distance, and background datasets for charcoal. The assessment was performed across five impact categories, such as global warming potential (GWP), land use, water consumption, fossil resource scarcity (FRS), and mineral resource scarcity (MRS). The results of each impact category are presented as follows, supported by an interpretation of the magnitude and direction of changes.

6.2.1 Global Warming Potential (GWP)

The sensitivity analysis identified several parameters with a significant influence on GWP, which are described as follows.

a) Sensitivity Factor: Use of 100% Pellet as iron-bearing source (All Scenarios)

The GWP impact of changing the iron-bearing sources was assessed for all five scenarios. It was observed that the substitution of ore/sinter with 100% iron pellets consistently reduced GWP by approximately 19-22%. This reduction is attributable to the higher iron content and lower energy demand of pellets during production, which in turn decreases upstream emissions compared to sinter. Based on a study of iron processing in China, pelletizing is shown to require less energy and produce fewer GHG emissions than sintering, thus reinforcing its environmental advantage (Lv et al., 2019). Moreover, the benefits of higher use of iron pellets to reduce emissions are also supported by several studies (Mourao et al., 2020; Chen et al., 2025).

Table 64: Sensitivity Analysis Results for Impact of Using 100% Pellets on GWP (All Scenarios)

Input Variation	Use of 100% iron pellets		
Scenarios	Baseline Assessment Results	Sensitivity Analysis Results	Percentage of changes
	kg CO_2 eq	kg CO_2 eq	%
Scenario 1: Coke and PCI	1510	1220	-19
Scenario 2: Coke and charcoal	1340	1050	-22
Scenario 3: Coke and switchgrass	1470	1180	-20
Scenario 4:Coke and grey H_2	1820	1530	-16
Scenario 5:Coke and green H_2	1360	1070	-21

b) Sensitivity Factor: Closest Import Markets to the UK (All Scenarios)

The GWP impact of changing the transportation distances was assessed for all five scenarios. It was observed that variation of transportation distance also had a significant impact on GWP. Sourcing key raw materials from the closest import markets lowered GWP by up to 11% compared to the baseline. The decrease in GWP is attributable to the lower GHG emissions generated through shorter distances. These findings highlight the significant role of transportation distance in influencing carbon emissions, thereby revealing the potential of supply chain optimisation as a decarbonisation strategy. Besides, focus can be made on improving transportation efficiency through several means, including the use of fuel-efficient vehicles, consolidation of shipments, and the adoption of alternative transportation modes with lower emissions (e.g., trains to replace trucks). In addition, optimising transportation distances can also lead to cost savings through lower fuel consumption, decreased maintenance costs, and improved operational efficiency. Furthermore, the optimised transportation distance can benefit the local communities, which helps to reduce traffic congestion, improve air quality, and reduce disruption to ecosystems related to the transportation corridors.

Table 65: Sensitivity Analysis Results for Impact of Transportation Distance on GWP (All Scenarios)

Input Variation	Transportation Distance		
Scenarios	Baseline Assessment Results	Sensitivity Analysis Results	Percentage of changes
	kg CO_2 eq	kg CO_2 eq	%
Scenario 1: Coke and PCI	1510	1360	-10
Scenario 2: Coke and charcoal	1340	1190	-11
Scenario 3: Coke and switchgrass	1470	1340	-9
Scenario 4:Coke and grey H_2	1820	1680	-8
Scenario 5:Coke and green H_2	1360	1220	-10

c) Sensitivity Factor: Coke Production Sourcing region (All Scenarios)

The GWP impact of changing the sourcing region of coke was assessed for all five scenarios. It was observed that the sourcing region exerted a notable impact on GWP outcomes. In the baseline model, the “Rest of the World” (RoW) dataset was used to represent the diversity of coal imports in the UK. However, substituting this with country-specific datasets for the United States and Germany reduced GWP by up to 16% and 19%, respectively. The carbon intensity of coke production in the US (0.0181 kg CO_2 eq/MJ) and Germany (0.0203 kg CO_2 eq/MJ) was lower than the aggregated ROW dataset (0.0393 kg CO_2 eq/MJ). This discrepancy indicates methodological differences in dataset construction. The RoW dataset entails production data from multiple countries, including Australia, China, Indonesia, India, Russia, and South Africa. Many of these countries rely on older and less efficient coke-making technologies, have lower environmental regulations, and lack an advanced emission control system. In addition, the amount of methane (CH_4) emitted during coal mining is influenced by several factors, which include coal rank, coal seam depth, and mining method (Irving et al., 2002). Given the variations of these parameters from various countries, the impacts will also be aggregated by taking into account both low and high values. As a result, the use of the RoW dataset average tends to result in higher reported emissions compared with country-specific datasets representing more efficient producers. For other input variations, only minimal changes were observed.

Table 66: Sensitivity Analysis Results for Impact of Coke Sourcing Region on GWP (All Scenarios)

Input Variation	Coke Sourcing Region					
Scenarios	Baseline Assessment Results, Coke Production "Rest of the World"	Sensitivity Analysis Results for Coke Production in the US	Percentage of changes		Sensitivity Analysis Results for Coke Production in Germany	Percentage of changes
	kg CO_2 eq	kg CO_2 eq	%		kg CO_2 eq	%
Scenario 1: Coke and PCI	1510	1320	-13		1270	-16
Scenario 2: Coke and charcoal	1340	1160	-13		1110	-17

Scenario 3: Coke and switchgrass	1470	1240	-16		1190	-19
Scenario 4: Coke and grey H_2	1820	1620	-11		1570	-14
Scenario 5: Coke and green H_2	1360	1160	-15		1110	-18

Finally, across all five reductant scenarios, charcoal (Scenario 2) and green H_2 (Scenario 5) consistently achieved lower GWP values than the other scenarios.

6.2.2 Land Use

a) Sensitivity Factor: Charcoal Dataset Source (Only Scenario 2)

For land use, the sensitivity analysis primarily focused on Scenario 2. This is because land use calculated for Scenario 2 is the highest among all five scenarios, with charcoal as the primary contributor, accounting for around 73.2%. This marks charcoal as a critical environmental hotspot, and it is crucial to verify if charcoal-related datasets influence the overall land use profile. For baseline assessment, the dataset for charcoal production in Scenario 2 is sourced from peer-reviewed literature, Leao et al. (2023). This charcoal dataset was generated by Sablowski (2008) based on six charcoal producers of distinct sizes in Minas Gerais, a state that accounts for 76% of pig iron production in Brazil. This dataset relies exclusively on eucalyptus to produce charcoal. Eucalyptus plantations typically have a short rotation period and hence reflect high efficiency of land use. Besides, the charcoal produced in Brazil is on an industrial scale, which is typically produced using masonry kilns (Miranda Santos et al., 2017).

In contrast, the charcoal dataset from Ecoinvent considers several hardwood species like birch, beech, eucalyptus, oak, pine and spruce (EcoQuery, 2025). These variations of species have a longer rotation cycle and reduced productivity. In addition, charcoal production from Ecoinvent utilises small-scale production with a lower yield:

0.33 tonnes of wood needed to produce 1 tonne of charcoal, compared to the dataset from Leao et al. (2023), which has a higher yield: 0.27 tonne of eucalyptus to produce 1 tonne of charcoal. This means that a higher amount of wood is needed for the Ecoinvent dataset. Hence, the results indicate more extensive land occupation. These findings highlight that the selection of charcoal datasets has a significant impact on land use outcomes. Despite both datasets modelling charcoal production, the assumed feedstock species, technology, and yield value have significant impacts on the land use outcomes. This illustrates the significance of dataset transparency, species specificity, and geographical relevance when assessing biomass-based reductants in LCA studies.

Table 67: Sensitivity Analysis Results for Impact of Charcoal Dataset Source on Land Use (Scenario 2)

Input Variation	Charcoal Dataset Sources (Literature vs Ecoinvent)		
Scenarios	Baseline Assessment Results	Sensitivity Analysis Results	Percentage of changes
	m^2a crop eq	m^2a crop eq	%
Scenario 2: Coke and charcoal	92.3	284	+208

These results emphasise the need for scrutiny of LCI sources, especially when biomass plays a substantial role in reducing emissions. Using non-representative datasets can lead to flawed conclusions about the environmental trade-offs and misrepresent land use burdens. Therefore, it is crucial to use representative datasets to ensure the sustainability performance of bio-based alternatives is adequately assessed.

6.2.3 Water Consumption

Water consumption demonstrated moderate sensitivity to variation of input parameters. Across all input variations, it was observed that changing coke sourcing to country-specific regions, such as the US and Germany, can reduce water consumption for all five scenarios by up to 47% and 23%, respectively. This trend is attributable to improved overall efficiencies when coke is sourced in one region, as opposed to aggregated data that needs to take into account variations in efficiencies, as discussed in the GWP section.

Table 68: Sensitivity Analysis Results for Impact of Coke Sourcing Region on Water Consumption (All Scenarios)

Input Variation	Coke Sourcing Region					
Scenarios	Baseline Assessment Results, Coke Production "Rest of the World"	Sensitivity Analysis Results for Coke Production in the US	Percentage of changes		Sensitivity Analysis Results for Coke Production in Germany	Percentage of changes
	m^3	m^3	%		m^3	%
Scenario1: Coke and PCI	3.3	2.16	-35.3		2.56	-23
Scenario 2: Coke and charcoal	3.3	2.18	-35.1		2.56	-23
Scenario 3: Coke and switchgrass	3.8	2.38	-43.3		2.86	-25
Scenario 4: Coke and grey H_2	4.1	2.85	-47.2		3.27	-20

Scenario 5: Coke and green H_2	3.9	2.66	-44.6		3.07	-21

Another notable observation was that the replacement of iron-bearing sources with 100% pellets increased water demand for all scenarios by up to 11%. This trend is attributable to properties of pellets that require more water to achieve suitable granulation and pellet formation compared to sinter feeds (Oliveira et al., 2019; Souza Pinto et al., 2021). For other input variations, only minimal changes were observed.

Table 69: Sensitivity Analysis Results for Impact of Using 100% Pellets on Water Consumption (All Scenarios).

Input Variation	Use of 100% iron pellets		
Scenarios	Baseline Assessment Result	Sensitivity Analysis Result	Percentage of change
	M3	M3	%
Scenario1: Coke and PCI	3.3	3.71	11
Scenario 2: Coke and charcoal	3.3	3.71	11
Scenario 3: Coke and switchgrass	3.8	4.18	10
Scenario 4:Coke and grey H_2	4.1	4.47	9
Scenario 5:Coke and green H_2	3.9	4.27	9

6.2.4 Fossil Resource Scarcity (FRS)

FRS showed limited variations across all sensitivity scenarios. The most significant factor influencing FRS is the type of reductants used, which has been covered in the core of this research. As demonstrated in the LCA findings, the use of alternative reductants that primarily reduce coke consumption will result in lower FRS. There are no variations of the type of reductant explored in this sensitivity analysis, as it requires changes in both mass and energy balances to ensure it still meets the 1 tonne of hot metal requirement. Moreover, it can also be observed that changing transportation distances and geographic origin of coke production have also had a minimal influence on fossil resource outcomes. Although these factors may introduce slight differences in upstream emissions, they did not materially affect the overall resource demand. Hence, it can be inferred that FRS emerges as a robust indicator to differentiate between fossil-based and renewable reductants, with consistent results among different sensitivity scenarios. The results of FRS are summarised in Table 70.

Table 70: Sensitivity Analysis Results for Impact of Coke Sourcing Region, Pellet Use, and Transportation Distance on Fossil Resource Scarcity (All Scenarios)

Sensitivity Scenarios	Baseline Results	Coke Production in the US	Coke Production in Germany	100% Iron Pellet	50% sinter, 50% pellet	Shortest Transportation Distance	Longest Transportation Distance
Unit	Kg oil eq						
Scenario 1: Coke and PCI	311	323	320	313	313	307	313
Scenario 2: Coke and charcoal	233	246	243	235	236	230	236
Scenario 3: Coke and switchgrass	281	296	293	283	284	278	283
Scenario 4:Coke and grey H_2	253	267	263	255	256	250	256
Scenario 5:Coke and green H_2	250	263	260	252	253	247	253

6.2.5 Mineral Resource Scarcity (MRS)

MRS showed limited variations across all sensitivity scenarios for all five scenarios assessed. However, the use of 100% iron pellets demonstrated an exception, with the MRS value increasing by up to 14% compared to the baseline results for all five scenarios. This is attributable to properties of iron pellets that require higher-quality iron ore compared to sinter. Pellet production requires beneficiated iron ore concentrates, typically with a minimum of 67% Fe content to limit ore impurities and to ensure efficient equipment operation. In contrast, iron sinter production can be produced using a wide range of lower-grade ores and by-products (Devlin et al., 2023). In conventional ironmaking, blast furnaces generally do not use 100% pellets but rely on a mixture of sinter and lump ore due to a combination of technical and economic reasons (Cameron et al., 2019). Pellets are more expensive than sinter due to these higher iron ore requirements, and the permeability of the blast furnace can be low at high temperatures, hence there is an increased risk of clogging (Geerdes et al., 2015). The results of MRS are summarised in Table 71.

Table 71: Sensitivity Analysis Results for Impact of Coke Sourcing Region, Pellet Use, and Transportation Distance on Mineral Resource Scarcity (All Scenarios)

Sensitivity Scenarios	Baseline Results	Coke Production in the US	Coke Production in Germany	100% Iron Pellet	50% sinter, 50% pellet	Shortest Transportation Distance	Longest Transportation Distance
Unit	Kg Cu eq						
Scenario 1: Coke and PCI	66.9	67	67	76.5	70.5	66.4	67.3
Scenario 2: Coke and charcoal	67	67	67	76.6	70.6	66.5	67.4
Scenario 3: Coke and switchgrass	67.1	67.1	67.1	76.7	70.6	66.6	67.5
Scenario 4:Coke and grey H_2	67	67.1	67.1	76.6	70.6	66.6	67.4
Scenario 5:Coke and green H_2	68.2	68.2	68.2	77.8	71.7	67.7	68.6

6.2.5 Combined Best-Case Sensitivity Analysis

In this assessment, the three assumptions that produced the most favourable results in the earlier one-at-a-time sensitivity analysis were applied simultaneously i) 100% pellet use, ii) Sourcing key raw materials from the shortest transportation distance, iii) modelling coke processing in Germany. The objective of this combined analysis was to evaluate the cumulative influence of these assumptions on the environmental performance of each scenarios.
Overall, the combined best-case sensitivity case significantly reduce the GWP impacts across all scenarios with reductions ranging from 37% to 52% compared to the main case. The highest reductions were observed for the charcoal and green H2 scenario. Improvement was seen for grey H2 scenario but it remained the highest emitting case. Furthermore, it was evidenced that land use changed more modestly, with reductions ranging from 6% to 20%, indicating that this category was less sensitive to the combined assumption than GWP.

In contrast, FRS increased slightly across all scenarios by 3% to 4%, while MRS increased consistently by 13 to 14%. This showed that although combined assumptions improved several impact categories, they also introduced trade-offs in resource related indicators. The slight increase on FRS is potentially due to the use of 100% pellets that increased processing requirements. Furthermore, the increase of MRS was associated with requirement of high quality ore to produce pellets.

In summary, these findings indicate that the cumulative applications of the most favorable can improve results for GWP, land use, and water consumption, but does not eliminate the wider trade-offs between impact categories. From this analysis, it can also be deduced that the relative interpretation of the scenarios remains consistent with the main case results. This signifies that the comparative conclusions of the research are robust even under the combined best study. Table 72 illustrates the results of the combined best-case sensitivity analysis for all five scenarios across five selected impact categories.

Table 72: Comparison of main-case and combined best-case sensitivity results

Impact category	Unit	Result type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
			Coke + pulverised coal (Base case)	Coke + charcoal	Coke + switchgrass	Coke + grey H_2	Coke + green H_2
Global Warming Potential	tonne CO_2 eq	Main case	1,510	1,340	1,470	1,820	1,360
		Combined best-case sensitivity	839	669	766	1,150	687
		Change (%)	-44%	-50%	-48%	-37%	-49%
Land use	m²a crop eq	Main case	28.0	92.3	91.1	26.1	26.8
		Combined best-case sensitivity	22.8	87.2	85.5	20.8	21.5
		Change (%)	-19%	-6%	-6%	-20%	-20%
Fossil resource scarcity	kg oil eq	Main case	311.0	233.0	281.0	253.0	250.0
		Combined best-case sensitivity	319.0	241.0	291.0	262.0	259.0
		Change (%)	+3%	+3%	+4%	+4%	+4%
Water use	m³	Main case	3.34	3.33	3.81	4.09	3.90
		Combined best-case sensitivity	2.70	2.71	3.01	3.42	3.22
		Change (%)	-19%	-19%	-21%	-16%	-17%
Mineral resource scarcity	kg Cu eq	Main case	66.9	67.0	67.1	67.0	68.2
		Combined best-case sensitivity	76.0	76.0	76.0	76.0	77.0
		Change (%)	+14%	+14%	+14%	+14%	+13%

6.2.6 Summary of Sensitivity Analysis

The sensitivity analysis verifies the robustness of the LCA results and identifies key parameters that significantly affect the environmental outcomes. Across all five reductant scenarios, GWP was most sensitive to the changes of iron-bearing source, coke production region, and transport distance. The replacement of a mixture of iron sources (lump ore, sinter, pellets) with 100% pellets consistently reduced GWP by up to 22%, indicating the higher iron content and lower production energy of pellets. However, this benefit came at the expense of increased water consumption and scarcity of mineral resources, indicating trade-offs across impact categories.

Furthermore, the coke sourcing location substantially influenced both GWP and water use, with country datasets such as the US and Germany exhibiting lower impacts than the Rest of World average, attributed to superior process efficiencies and stricter environmental controls. Moreover, transportation distance also demonstrated a measurable influence on GWP (up to 11% reduction), highlighting the importance of optimising supply chains for decarbonisation. For land use, it can be observed that the results were highly sensitive to the choice of the charcoal dataset. The shift from a high-yield, eucalyptus-based system dataset from literature to a lower-yield, various hardwood species, small-scale model (Ecoinvent) produces a land occupation that is a threefold increase over the baseline result. This highlights the crucial role of species selection, yield, scale of technology, and regional relevance in biomass assessment for determining the environmental impacts.

By contrast, FRS and MRS exhibited limited sensitivity to input variations, except for an MRS increase for the scenario considering the use of 100% iron pellets. This is attributed to the higher-grade iron ore required to make pellets. These findings demonstrate the importance of careful dataset selection and modelling assumptions, particularly for bio-based inputs, and emphasise that supply chain parameters and material sourcing have significant impacts on environmental impacts.

When the three most favorable assumptions were applied simultaneously in the combined best-case sensitivity analysis, GWP was further reduced across all scenarios by 37% to 52% relative to the main case, with the highest reductions observed for the charcoal and green H_2 scenarios. Land use also decreased, although more modestly, by 6% to 20% confirming this category was less sensitive than GWP to the combined assumptions. In comparison, FRS increased slightly by 3% to 4%, while MRS increased consistently by 13% to 14%, indicating that although the combined assumptions improved climate related performance, they also introduced trade-offs in resource-related categories. These findings demonstrate the importance of careful dataset selection and modeling assumptions, and emphasise that supply chain parameters and materials sourcing have significant impacts on environmental impacts.

It is worth highlighting that the ranking of reductant options remains the same and therefore reinforces the conclusion that charcoal and green H_2 routes provide clear environmental benefit compared to conventional reductants. However, the analysis highlights essential trade-offs that need to be taken into account when scaling up for deployment.

Overall, the sensitivity analysis results strengthen the credibility of the LCA findings and provide evidence-based guidance for future improvement to decarbonise blast furnace ironmaking operations.

CHAPTER 7

7.0 CONCLUSIONS AND FUTURE WORK

This chapter synthesises the main findings of the research by addressing the research questions that guided the study. It summarises the environmental and economic insights gained from assessing alternative reductants and reflects on their implications for blast furnace ironmaking in the UK. The chapter outlines the key limitations that influence the scope and interpretation of the results, and it concludes by identifying the areas where further work is required to support industrial applications.

7.1 Conclusions

This conclusion section summarises the findings of this research by addressing the three research questions that guided the study. Research Question 1 served as a scoping exercise to identify which alternative reductant were sufficiently relevant, technically plausible, and supported by available literature to justify the detailed comparative assessment for UK blast furnace ironmaking. Research Question 2 examined the environmental performance of charcoal, switchgrass, grey hydrogen, and green hydrogen relative to a conventional coke and PCI baseline. Research Question 3 evaluated the economic feasibility of the most environmentally favourable reductants. Research Question 4 explored practical options for deploying the favoured reductants in blast furnace operations. The findings integrate environmental, economic and practical considerations into a coherent interpretation that informs industrial decision-making and future decarbonisation strategy in the UK.

The research also fills a critical evidence gap for the UK, where no previous cradle-to-gate assessment has evaluated the solid and gaseous reductant pathways within a single integrated framework. Five scenarios were examined, including the conventional coke and PCI baseline. The results confirm that reductant pathways deliver different advantages and trade-offs, and therefore no single scenario is universally favourable across all environmental impact categories.

As a scoping exercise (RQ1), the research first reviewed and screened potential alternative reductants for UK blast furnace ironmaking using multi-criteria assessment. This stage was intended to establish which alternative reductant was sufficiently relevant and plausible to justify detailed comparative analysis. The scoping results showed that charcoal and subcoal emerged as the strongest solid alternatives across the assessed scenarios. However, when wider UK considerations such as scalability, product consistency, supply chain readiness, and policy alignment were taken into account, charcoal was selected as the preferred solid reductant for subsequent cradle-to-gate LCA.

From the environmental perspective (RQ2), charcoal provides the largest reduction in GWP (-11 percent) and FRS (-25 percent) but increases land occupation by threefold. Green hydrogen achieves a comparable climate benefit (-10 percent) without land use pressure but increases water demand (+17 percent). Grey hydrogen performs least favourably, increasing GWP and water use due to methane-intensive upstream gas processing, while switchgrass only offers marginal improvements because of its low energy density. These findings show that environmental performance is shaped not only by reductant characteristics but also by supply chain assumptions and regional constraints. The application of the pedigree matrix strengthened the credibility of these findings, as all scenarios achieved total scores of 15 or lower.

A sensitivity analysis further demonstrated that environmental outcomes are strongly influenced by upstream configurations. Changing the coke region of coke production reduced GWP by up to 19 percent and water demand by 47 percent, while charcoal results were highly sensitive to hardwood feedstock characteristics and kiln efficiency. These findings indicate that optimising existing blast furnace operations and coke supply chains represents an immediate decarbonisation opportunity.

From an economic perspective (RQ3), conventional blast furnace operation remains the lowest cost option. Charcoal introduces higher costs due to limited domestic land availability, and the resulting need for imported feedstock, while green hydrogen is significantly more expensive under current UK market conditions. Although charcoal yielded the lowest cost per tonne of CO_2 avoided compared with green hydrogen, neither reductant is yet cost-competitive with the coke and PCI baseline. Green hydrogen becomes more viable in the medium to long term as costs decline, infrastructure expands, and UK hydrogen policy continues to evolve. These results highlight that environmental performance alone cannot determine reductant feasibility without considering economic competitiveness and supply chain readiness.

Based on these environmental and economic findings, Research Question 4 is addressed through a practical implementation pathway. Before considering the phased introduction of alternative reductants, it is crucial to strengthen the existing blast furnace system, as coke remains the dominant reductant across all scenarios and continues to account for the highest share of environmental impacts. Therefore, immediate improvements to existing blast furnace operation and the optimising supply chain should form the foundation of the blast furnace decarbonisation pathway. These improvements may include optimising coke quality, reducing transport distances, strengthening procurement from lower-emission coking coal sources and coordinating with suppliers to enhance environmental standards. These actions can deliver meaningful reductions regardless of which alternative reductant pathway is adopted.

After establishing these foundational improvements, a phased implementation strategy can be considered. In the short term, plant operators should begin with controlled charcoal injection trials at selected tuyeres, since charcoal offers immediate climate benefits and requires minimal infrastructure modification. At the same time, steel producers should establish sustainable biomass supply chains through recognised certification schemes such as the Forest Stewardship Council, Programme for the Endorsement of Forest Certification, and Sustainable Biomass Program (National Audit Office, 2024). In the medium term, the steel industry should prepare for green hydrogen integration by co-locating electrolysers with steelworks, securing renewable electricity through compliant Power Purchase Agreements and working with water utilities to develop reclaimed water systems (Department for Energy Security & Net Zero, 2023a). Throughout these stages, blast furnace operators should monitor potential impacts on raceway conditions, slag chemistry and hot metal quality.

In addition, a unified monitoring, reporting and verification framework will be essential to ensure that the expected environmental performance is achieved in practice as guided by the Steel Standards Principles (Steel Standards Principles, 2025). Policymakers should set consistent national requirements, and steel producers should embed site-level monitoring for cradle-to-gate emissions, water use, land footprint, and supply chain compliance. Independent verification can also improve transparency and reinforce regulatory alignment.

Overall, the findings indicate that decarbonising UK blast furnace ironmaking requires a phased hybrid strategy that builds on immediate improvements to current operations while preparing for the adoption of alternative reductants. In the short term, sustainably certified charcoal can offer an immediate opportunity to reduce emissions. In the medium term, green hydrogen presents a viable option as supply chains develop and production costs decline. In the longer term, deeper decarbonisation may be achieved through bioenergy with carbon capture and storage (BECCS) and hydrogen-enriched pathways, provided that land, water, and infrastructure challenges are addressed. Therefore, this research shows that meaningful decarbonisation needs to balance environmental performance, economic feasibility, and operational practicality, while considering regional supply chain and policy conditions.

In summary, these findings provide clear answers to the four research questions. For RQ1, the scoping exercise established that charcoal was the most appropriate solid alternative reductant to take forward for detailed assessment.For RQ2, charcoal and green hydrogen offer the strongest environmental benefits but introduce significant trade-offs that affect overall feasibility. For RQ3, neither the charcoal nor the green hydrogen pathways are cost-competitive with the baseline case, although both show promise under future UK policy and market conditions. For RQ4, successful deployment requires first strengthening existing blast furnace operation and raw materials supply chains, followed by a phased approach in which sustainably certified charcoal is introduced in the short term, green hydrogen becomes a medium term option as infrastructure and markets develop, and BECCS and hydrogen enriched pathways are considered as longer term opportunities. These deployment strategies require coordinated actions from plant operators, industry decision-makers, water utilities, and policymakers. These combined insights demonstrate that blast furnace decarbonisation in the UK must be pursued through an integrated, sequenced, and region-specific strategy that recognises environmental, economic and practical realities.

7.2 Research Limitations

Although this research provides a robust comparative assessment of alternative reductants in UK blast furnace ironmaking, several limitations need to be clearly acknowledged. These limitations arise from the scope of the modelling framework, data availability constraints, and the operational complexity of large-scale blast furnace operations. It is essential to identify these constraints to ensure that the findings are interpreted appropriately. Besides, recognising the limitations of this research is important to conduct further refinement to strengthen the evidence for decarbonising blast furnace ironmaking as outlined in the future work recommendations in Section 7.3.

7.2.1 Steady-State Modelling Assumption

A fundamental limitation of this research is the steady-state assumption that is used throughout the blast furnace modelling assessment. In reality, blast furnace operation is dynamic, characterised by continuous fluctuations in raceway temperature, burden descending rate, gas distribution patterns, and the chemical compositions of feed materials (Geerdes et al., 2015; Cameron et al., 2019). The model developed in this research assumes stable operating conditions and uniform reductant injection rates, thereby simplifying the comparative assessment. However, this approach does not fully capture the transient behaviour and operational variability that happens during actual blast furnace operation. For example, burden permeability due to fines generation and tuyere injection rate adjustment in response to furnace thermal state can all influence process stability and environmental performance. Therefore, while the steady-state approach is methodologically appropriate for comparative LCA studies and widely accepted in the literature, the results should be interpreted as representative of ideal operating conditions rather than real-time performance under dynamic industrial operation .Addressing this limitation would require pilot scale experimental validation as discussed in Section 7.3.2.

7.2.2 Single-Plant Representation and Generalisability

Furthermore, the environmental assessment is based mainly on operational data and process conditions from a single UK integrated steel plant. Although this case-study approach allows site-specific insights and ensures direct relevance to the UK steel industry context, it limits the generalisability of the absolute impact values to other steel plants in the UK and globally. This is because different blast furnaces operate under different technical configurations, including differences in furnace volume, burden preparation method, tuyere design, and refractory materials (Geerdes et al., 2015; Cameron et al., 2019). The implications of single-plant representation and opportunities for broader validation are discussed in Sections 7.3.1, 7.3.2, and 7.3.7.

7.2.3 Regional Variability and Contextual Factors

In addition, regional factors such as the availability and quality of raw materials, energy infrastructure, electricity grid carbon intensity, and regulatory frameworks vary significantly across different geographical locations. Hence, although the environmental trends, trade-offs between impact categories, and relative performance rankings identified in this research are broadly applicable and can provide insights on strategies, the absolute values of environmental impacts should not be extrapolated directly to other operational scenarios without site-specific adjustments and recalibration of key input parameters. The transferability of findings to international contexts is addressed in Section 7.3.7.

7.2.4 Methodological Assumptions

A further limitation is associated with methodological assumptions particularly with the use of system expansion for co-product credits. Although aligned with ISO 14044, alternative allocation methods such as mass-based or economic allocation may produce different outcomes in the comparative results. Biogenic carbon is also modelled using ReCiPe Midpoint (H) method, which credits carbon uptake does not accost for temporal dynamics such as forest regrowth rates or potential carbon debt. Future work should test the sensitivity of the results to allocation choices and biogenic carbon modelling approaches to improve robustness as outlined in Section 7.3.3.

7.2.5 Data Quality and Availability

Data quality and availability of operational parameters are further identified as limitations of this research. Most operational data in this research were obtained from published literature and Ecoinvent database rather than direct measurements from the case-study UK steel plant. Only the proportions of iron-bearing materials and co-products allocation were obtained directly from the steel producer, while critical parameters like coke rate and top gas composition were based on secondary sources. Eventhough the data quality evaluation was conducted as outlined in Section 6.1 and comprehensive sensitivity analysis was performed to test the robustness of results, the reliance on literature-based and database parameters introduced geographical and technological correlation uncertainties. This data gap limits the precision of absolute impact values and highlight the need for primary data collection for UK steel producers as prioritised in Section 7.3.1 and 7.3.2.

7.2.6 Temporal Scope and Dynamic Evolution

Another key limitation is the temporal scope of the assessment. The life cycle inventory data and operational parameters used in this study represent a snapshot of supply chain conditions, technological configurations, and energy systems as they existed in 2023. However, the steel industry and associated upstream and downstream value supply chains are subject to rapid technological developments, evolving policy frameworks, and shifting market dynamics that can fundamentally change the environmental profile over time. For example, ongoing advances in biomass pyrolysis technology and optimisation of supply chain logistics can substantially reduce both the economic and environmental footprint of sustainably sourced charcoal in future scenarios. Besides, emerging policy instruments such as carbon border adjustment mechanisms, updated trajectories of emissions trading scheme prices, and evolving sustainable certification requirements are not fully captured in the assessment framework. Therefore, the results presented should be periodically re-evaluated to account for future viability of alternative reductant pathways through dynamic LCA approaches as discussed in Section 7.3.3.

7.2.7 Exclusion of Hot Metal Quality and Slag Chemistry

Moreover, the detailed hot metal quality and slag chemistry are excluded from the scope of the research. The impacts of alternative reductants to hot metal quality are not assessed. In addition, although the quantity of slag produced were modelled based on assumptions, the study did not quantitatively assess how alternative reductants influence critical metallurgical parameters such as slag basicity ratios, meting behaviour, viscosity, and downstream reusability potential. For example, charcoal injection can introduce additional ash that can alter the basicity ratios, and affect the slag functionality (Suopajärvi et al., 2013; Khasraw et al., 2024). The need for metallurgical assessment is addressed in Sections 7.3.4 and 7.3.5.

7.2.8 Omission of Social Life Cycle Assessment

Finally, this research did not include social life-cycle assessment dimensions, which are increasingly recognised as an essential element of LCA assessment. The shift away from conventional blast furnace ironmaking towards alternative reductant pathways may have significant social implications, including workforce employment impacts, requirements for worker retraining and skill development in regions dependent on traditional steel industry employment. For example, transition towards green hydrogen or sustainably certified biomass-based reductants may require substantial investment in workforce training programmes to develop new technical competencies. Besides, it will enforce changes in regional biomass supply and create adjustments to local economic structures that have historically depended on coal mining and coke production. The integration of social sustainability considerations is discussed in Section 7.3.8.

In summary, the findings and conclusions of this research should be interpreted carefully within the context outlined by the limitations and boundary conditions. Nevertheless, the methodological framework developed and utilised in this research provides a rigorous and transparent foundation for comparative environmental assessment and has been strengthened through data quality evaluation and sensitivity analysis with acknowledgement of assumptions and limitations.

7.3 Future Work

As outlined in Section 7.2, several limitations have been identified in this research. This identification provides a clear direction for future studies to improve data robustness, integrate metallurgical performance, capture wider system effects, and strengthen policy relevance. Furthermore, addressing these limitations highlighted in this section is crucial to ensure a more comprehensive assessment and insights for decarbonising primary steelmaking that can be transferred globally.

7.3.1 Improving Data Quality through Primary Sourcing

A key limitation of this study, as assessed in Section 6.1 Data Quality, is the limited availability of operational data for the blast furnace ironmaking process from the steel plant. Most operational parameters were sourced from the literature and the Ecoinvent database, except for the proportions of iron-bearing materials and the co-product allocation, which were provided by the case-study UK steel plant. Although this research is supplemented by data quality and sensitivity analyses to verify the robustness of the data, future work should prioritise sourcing site-specific data directly from UK steel producers, including coke rate, injection ratio, top gas composition, and slag chemistry. These data will significantly enhance the robustness of life cycle inventories, improve allocation procedures, and ensure that LCA results accurately represent actual industrial performance.

In addition, more UK-contextualised data are required for alternative reductants. Although most of the biomass used in the UK is imported, modelling UK-grown feedstocks is vital for policy and resilience purposes. Domestic cultivation scenarios align with the UK Biomass Strategy (2023) and allow assessment of long-term supply chain security.

7.3.2 Pilot-scale Blast Furnace Trials in the UK

The absence of a small-scale blast furnace in the UK limits opportunities for experimental validation of modelling results. Future work should assess the feasibility of establishing a pilot-scale blast furnace (e.g., 100-200 kTHM/year) or utilising existing steel research facilities like Advanced Steel Research Centre at University of Warwick (The University of Warwick, 2025) for testing various reductants under controlled conditions. These facilities can generate high-quality operational data, enhance collaboration between industry and academia, and accelerate the development of low-carbon ironmaking technologies. Besides, it would also provide critical insights into slag handling, tuyere design, and gas recycling that cannot be fully modelled at present

7.3.3 Refinement of LCA Methodology

Several limitations were identified in this research. Future work should test the sensitivity of results to key methodological assumptions. First, allocation choices (e.g mass allocation, economic allocation) may influence environmental outcomes. A structured sensitivity test would help assess the robustness of comparative conclusions. Second, the treatment of biogenic carbon using ReCiPe Midpoint (H) method does not capture temporal dynamics such as regrowth periods or potential carbon debt. Future work needs to evaluate alternative biogenic carbon accounting approaches. Finally, the steady state attributional LCA applied does not reflect indirect system changes. Future work need to explore consequential or dynamic LCA methods to better understand long-term impacts under evolving UK energy and biomass supply conditions.

7.3.4 Effects on Hot Metal and Slag Quality

The analysis in this research focused on the quantity of reductant without considering the detailed effect on hot metal or slag quality. Future studies should evaluate how the injection of charcoal, hydrogen, and biomass influences key properties, such as silicon, sulphur, and phosphorus content in hot metal, as well as the basicity and reusability of slag. For example, replacing coke with charcoal can increase alkali levels in the slag through its ash content, thereby changing its basicity (CaO/SiO_2 and MgO/Al_2O_3 ratios). This in turns shifts the solidus and liquidus temperatures. These changes are vital because basicity control desulphurization and refractory wear, while the solidus-liquidus range dictates slag melting, viscosity, and effective separation from metal (Heikkilä et al., 2022). In contrast, use of H_2 as an alternative reductant may alter silicon reduction in the blast furnace, thus affecting hot metal content and quality (Nogami et al., 2012). Therefore, conducting this assessment would help link environmental benefits with metallurgical performance to ensure that the decarbonisation does not compromise product quality.

7.3.5 Impacts on Blast Furnace and Top Gas Energy Recovery

Alternative reductants will alter the composition and calorific value of blast furnace top gas, which is currently used for energy recovery. This research revealed that the use of alternative reductants generally reduces the calorific value available for energy recovery, but an in-depth evaluation was not conducted. Future work should quantify how substitution affects energy recovery potential, integration of top gas recycling, or waste heat recovery systems. For example, H_2-rich top gas may reduce calorific value, limit its reuse in power generation, but can allow cleaner combustion. By considering this, a more holistic assessment of energy efficiency under different reductant scenarios can be achieved.

7.3.6 Economic and Policy Enablers for UK Adoption

Although the environmental performance of alternative reductants has been demonstrated, their higher costs pose a constraint to their adoption. In this research, only a simplified economic assessment was conducted, and a more detailed, in-depth assessment is recommended for the future. Future work should assess the role of UK policy support, such as subsidies and carbon pricing, in making charcoal, H_2, and other sustainable biomass competitive with coke and PCI. For example, modelling scenarios at different UK Emission Trading Scheme (UK ETS) carbon prices would help establish the threshold at which alternative reductant injection becomes cost-effective. Additionally, the impacts of UK policy support will enable the establishment of practical subsidy levels necessary for the adoption of biomass and H_2.

7.3.7 Expanding to a Global Context

While this research focuses on the UK context, the steel industry is global in scale. Therefore, results may differ in other regions with different energy systems, resource availability, supply chains, and policy frameworks. Future work can apply a similar analysis to major steel-producing regions, such as China, India, Brazil, and the EU. For example, Sweden’s access to high-grade iron ore and large-scale renewable electricity can enable early adoption of H_2-based reductants. Meanwhile, Australia’s dependence on long-distance export supply chains and the availability of natural gas may lead to different decarbonisation pathways. Comparative assessments would highlight where alternative reductants provide the most significant benefits, ensuring that the results and recommendations are transferable beyond the UK.

7.3.8 Social LCA

Social LCA needs to be integrated into future research to assess workforce employment impacts, skill development requirements, and community economic resilience associated with the transition from conventional blast furnace operation to alternative reductant pathways. For example, the shift towards green hydrogen or certified biomass-based systems may create new employment opportunities in renewable energy sectors whilst simultaneously creating a need to manage the transition for workers currently employed in coal mining and coke production. Assessment is needed to ensure decarbonisation strategies deliver positive social outcomes whilst minimising significant impacts on affected communities.

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APPENDICES

Appendix A: System Expansion Data

A.1 Co-Product Quantities and Credits

This section summarises the quantities of blast furnace top gas and slag recovered for external use across all five reductant scenarios. The energy credits for blast furnace gas (BFG) recover are calculated based on heating value of 3.4 MJ/Nm³ (International Flame Research Institution, 2003). It is assumed that 1 MJ of BFG displaces 1 MJ of natural gas in external energy applications. Additionally, a one-to-one mass substitution is assumed for replacing clinker with ground granulated blast furnace slag (GGBS) in cement production. The summary of the calculation is presented in Table A-1.

Table A-1: Co-Product Quantities and Energy Credits Applied in System Expansion

	Blast Furnace Top Gas Displacement Calculation				Slag Displacement Calculation		
Scenario	**Top Gas Generated**	**Top Gas Used for Other Purposes**	**Top Gas Energy**	**Equivalent Natural Gas Energy**	**Slag Produced**	**Slag Used for Clinker Substitution**	**Clinker Displaced**
	Nm³/ tHM	**Nm³ / tHM**	**MJ / tHM**	**MJ per t HM**	**kg / tHM**	**kg / tHM**	**kg / tHM**
Case 1: Coke and PCI	1 660	1 560	5 305	5 305	250	245	245
Case 2 : Coke and Charcoal	1 654	1 555	5 286	5 286	250	245	245
Case 3 : Coke and Switchgrass	1 724	1 621	5 510	5 510	250	245	245
Case 4 : Coke and Grey H_2	1 462	1 374	4 673	4 673	250	245	245
Case 5 : Coke and Green H_2	1 462	1 374	4 673	4 673	250	245	245

Notes:
** 96% of blast furnace gas is used for energy generation.*
** 98% of slag is used for clinker substitution.*
** All values are expressed per functional unit of 1 tonne hot metal (tHM).*

Appendix B. Scenario-Specific Life-Cycle Inventory Data

Appendix B presents the life-cycle inventory data for each of the five blast furnace reductant scenarios. Each scenario includes:

- **Foreground Inventory**: Direct inputs, outputs, and emissions for 1 tonne of hot metal.
- **Background Inventory**: Ecoinvent v3.10 APOS datasets for upstream processes.
- **Reductant Production Inventory**: For charcoal, grey hydrogen, or green hydrogen, where applicable.
- **UK-contextualised Adjustments**: Revisions to distances, imports, and utility factors.

B.1 Scenario 2: Coke and Charcoal

B.1.1 Foreground Inventory

Table B-1 presents the foreground inventory for the production of one tonne of hot metal in Scenario 2. It includes all major material and energy inputs, the transport of raw materials from the exporting countries to the port of an integrated UK steel plant, and the outputs such as slag, top-gas and direct air emissions.

Table B-1: Foreground Inventory Data for Scenario 2 – Coke and Charcoal

Categories	Data	Value	Unit	Source	Remarks
Inputs	Iron lump ore	196	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron pellet	393	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron sinter	921	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Coke	364	kg	Ng et al., 2010	Use conversion 28.6 MJ/kg in SimaPro
	Charcoal	140	kg	Ng et al., 2010	
	Dolomite	19	kg	Ng et al., 2010	
	Limestone	19	kg	Ng et al., 2010	
	Air	1413	kg	Ng et al., 2010	Assume air density is 1.293 kg/m3

	Water	906.3	kg	Leao et al., 2023	
	Electricity	111.4	kW	Leao et al., 2023	
	Transport (road)	3096	t.km	Manual calculation	Google Maps was used to estimate the road distance to transport raw materials from the importers to the UK steel plant.
	Transport (sea)	32134	t.km	Manual calculation	The Sea Distance Calculator estimated the distance by sea to transport raw materials from the importers to the UK steel plant.
Output (Reference Product)	Pig Iron (Functional Unit)	1000	kg	NA	
Output (By/co-products)	Slag	250	kg		
	Top Gas	1654	Nm3	Ng et al., 2010	
Emissions to air	CO_2 (Fossil)	557.1	kg	Ng et al., 2010	
	CO_2 (Biogenic)	209	kg	Ng et al., 2010	
	CO (Fossil)	362.3	kg	Ng et al., 2010	
	CO (Biogenic)	136	kg	Ng et al., 2010	
	H_2	3.6	kg	Ng et al., 2010	
	N_2	1035.8	kg	Ng et al., 2010	

B.1.2 Background inventory datasets

The modelling of Scenario 2 also relied on background processes from the Ecoinvent 3.10 APOS database. These dataset represents intermediate flows and emissions associated with upstream supply chains. The background datasets are summarised in Table B-2.

Table B-2: Background Inventory Datasets for Scenario 2

	Item	**Intermediate and Elementary Flows in Ecoinvent version 3.10**

Inputs	Lump ore	Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | APOS, U
	Pellet	Iron pellet {RoW}| iron pellet production | APOS, U
	Sinter	Iron sinter {RoW}| iron sinter production | APOS, U
	Coke	Coke {RoW}| coke production | APOS, U
	Charcoal	Refer to Table B-1
	Dolomite	Dolomite {RoW}| market for dolomite | APOS, U
	Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U
	Air	Air
	Water	Water, decarbonised {GB}| market for water, decarbonised | APOS, U
	Electricity	Electricity, medium voltage {GB}| market for electricity, medium voltage | APOS, U
	Road Transport	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U
	Sea Transport	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land transformation	Carbon dioxide, land transformation
	CO_2 fossil	Carbon dioxide, fossil
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	CO fossil	Carbon monoxide, fossil
	H_2O	Water
	H_2	Hydrogen
	N_2	Nitrogen
	O_2	Oxygen
	Particulates	Particulate

B.1.3 Charcoal production inventory

Charcoal production is a critical parameter in this scenario. Table B-3 presents the detailed foreground inventory and Table B-4 presents the background datasets for producing one tonne of charcoal via eucalyptus as reported by Leao et al. (2023). This inventory was used to model the upstream burden of charcoal supplied to the blast furnace.

Table B-3: Foreground Inventory of 1.0 t of Charcoal Production from Eucalyptus Biomass (Leão et al., 2023).

	Item	Value	Unit
Inputs	Wood (eucalyptus)	2715	kg
	Electricity	11	kWh

	Pyroligneous liquor (heating utility)	200	kg
Reference Product	Charcoal (Reference Product)	1000	kg
	By-/co-product		
By-/co-product	Pyroligneous liquor	1149	kg
	Utility (closed-loop)	200	kg
	Utility (open-loop)	949	kg
Emissions to the air	CO_2 (Biogenic)	214	kg
	CO_2 (Land transformation)	161	kg
	CO (Biogenic)	120	kg
	CO (Land transformation)	90	kg
	H_2O	361	kg
	H_2	30	kg
	Hydrocarbons	30	kg
	NOx	1	kg
	O_2	1	kg

Table B-4: Background Inventory Datasets for Charcoal Production

	Item	Intermediate and Elementary Flows in Ecoinvent version 3.10
Inputs	Charcoal	Cleft timber, measured as dry mass {BR-MG}| hardwood forestry, eucalyptus ssp., planted forest management | APOS, U
	Transport (road)	Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U
	Electricity	Electricity, medium voltage {BR}| market group for electricity, medium voltage | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land transformation	Carbon dioxide, land transformation
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	H_2O	Water
	H_2	Hydrogen
	HC	Hydrocarbons, unspecified
	N_2O	Nitrogen oxides
	O_2	Oxygen

B.1.4 UK-contextualised adjustments and assumptions

- The sourcing of primary raw materials (iron ore, coking coal, and charcoal) has been updated to reflect imports of raw materials to the UK based on data from the UK Trade Association for 2024, necessitating revisions to the distances travelled by road and sea. The delivery location is at the port of an integrated steel plant in the UK. The details of raw materials imported and % of raw materials imported to the UK are shown in Table B-5:

Table B-5: Raw-material Importers and Percentage Share of UK Imports for Scenario 2

Raw Materials	Exporters Countries and Percentage of Import	References
Iron-bearing materials	Norway (48%) Canada (27%) Netherlands (26)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)
Charcoal	Namibia (40%) Paraguay (33%) South Africa (28%	(The Observatory of Economic Complexity, 2025b)

Note: Percentages may not sum to exactly 100% due to rounding.

- Electricity and water sources have been adjusted to align with specific UK conditions customised in SimaPro software.
- Road transportation for moving raw materials from producers to the ports in the exporting countries is assumed to be via truck instead of rail to ensure consistency in the assessment for comparative purposes. This is due to a lack of data regarding rail distances and efficiencies.
- The distances from raw material producers to the ports in the exporting countries are estimated using Google Maps.
- The sea travel distances from the exporting countries to Port Wales in the UK are calculated with the Sea Rate Distance calculator.
- A round-trip journey was considered for road and sea transportation.

The technological equivalence, raw-material quality and quantity, energy consumption, and process efficiency follow the original parameters described by Ng et al. (2010) and were assumed similar to those of the UK blast furnace operation.

B.2 Scenario 3- Coke and switchgrass

This scenario represents a blast furnace ironmaking pathway in which switchgrass replaces pulverised coal injection as the auxiliary reductant, while coke remains as the main reductant. The quantity and proportion of iron bearing materials and fluxes are maintained the same as in Scenario 1. The corresponding cradle to gate inventory data are presented as follows.

B.2.1 Foreground inventory

Table B-6 presents the foreground inventory for the production of one tonne of hot metal in Scenario 3. It includes all major material and energy inputs, the transport of raw materials from the exporting countries to the port of an integrated UK steel plant, and the outputs such as slag, top-gas and direct air emissions.

Table B-6: Foreground Inventory Data for Scenario 3– Coke and Switchgrass

Categories	Data	Value	Unit	Source	Remarks	Description
Inputs	Iron lump ore	196	kg	Ng et al., 2010 Tata Steel UK., 2024		NA
	Iron pellet	393	kg	Ng et al., 2010 Tata Steel UK., 2024		
	Iron sinter	921	kg	Ng et al., 2010 Tata Steel UK., 2024		
	Coke	449	kg	Ng et al., 2010	Use conversion 28.6 MJ/kg in SimaPro	
	Switchgrass	140	kg	Ng et al., 2010		
	Dolomite	30	kg	Ng et al., 2010		
	Limestone	30	kg	Ng et al., 2010		
	Air	1413	kg	Ng et al., 2010	Assume air density is 1.293 kg/m3	
	Water	906.3	kg	Leao et al., 2023		
	Electricity	111.4	kW	Leao et al., 2023		
	Transport (road)	3070	t.km	Manual calculation	Google Maps was used to estimate the road distance to transport raw materials from the importers to the UK steel plant.	

	Transport (sea)	28479	t.km	Manual calculation	The Sea Distance Calculator estimated the distance by sea to transport raw materials from the importers to the UK steel plant.	
Output (Reference Product)	Pig Iron (Functional Unit)	1000	kg	NA		NA
Output (By/co-products)	Slag	250	kg			
	Top Gas	1724	Nm3	Ng et al., 2010		
Emissions to the air	CO_2 (Fossil)	682.5	kg	Ng et al., 2010		
	CO_2 (Biogenic)	112.9	kg	Ng et al., 2010		
	CO (Fossil)	454.8	kg	Ng et al., 2010		
	CO (Biogenic)	75.3	kg	Ng et al., 2010		
	H_2	6.4	kg	Ng et al., 2010		
	N_2	1036.6	kg	Ng et al., 2010		

B.2.2 Background inventory datasets

The modelling of Scenario 3 also relied on background processes from the Ecoinvent 3.10 APOS database. These dataset represents intermediate flows and emissions associated with upstream supply chains. The background datasets are summarised in Table B-7.

Table B-7: Background Inventory Datasets for Scenario 3

	Item	Intermediate and Elementary Flows in Ecoinvent version 3.10
Inputs	Lump ore	Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | APOS, U
	Pellet	Iron pellet {RoW}| iron pellet production | APOS, U

	Sinter	Iron sinter {RoW}| iron sinter production | APOS, U
	Coke	Coke {RoW}| coke production | APOS, U
	Switchgrass	Miscanthus, chopped {RoW}| miscanthus production | APOS, U
	Dolomite	Dolomite {RoW}| market for dolomite | APOS, U
	Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U
	Air	Air
	Water	Water, decarbonised {GB}| market for water, decarbonised | APOS, U
	Electricity	Electricity, medium voltage {GB}| market for electricity, medium voltage | APOS, U
	Road Transport	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U
	Sea Transport	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land transformation	Carbon dioxide, land transformation
	CO_2 fossil	Carbon dioxide, fossil
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	CO fossil	Carbon monoxide, fossil
	H_2O	Water
	H_2	Hydrogen
	N_2	Nitrogen
	O_2	Oxygen

	Particulates	Particulate

B.2.3 UK-contextualised adjustments and assumptions.

The original parameters were changed to reflect UK-contextualised conditions, as needed. The parameters that have been revised to be UK-contextualised for Scenario 3 are summarised as follows.

- The sourcing of primary raw materials (iron ore, coking coal, and switchgrass) has been updated to reflect imports of raw materials to the UK based on data from the UK Trade Association for 2024, necessitating revisions to the distances travelled by road and sea. The delivery point is the port facility of an integrated steel plant in the UK. The details of raw materials imported and % of raw materials imported to the UK are shown in Table B-8:

Table B-8: Raw-material Importers and Percentage Share of Imports to the UK for Scenario 3

Raw Materials	Exporting Countries and the Percentage of Imports	References
Iron-bearing materials	Norway (48%) Canada (27%) Netherlands (26)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)
Switchgrass	USA (100%)	(IEA Bioenergy, 2011)

Note: Percentages may not sum to exactly 100% due to rounding.

- Electricity and water sources have been adjusted to align with specific UK conditions customised in SimaPro software.
- Road transportation for moving raw materials from producers to the ports in the exporting countries is assumed to be via truck instead of rail to ensure consistency in the assessment for comparative purposes. This is due to a lack of data regarding rail distances and efficiencies.

- The distances from raw material producers to the ports in the exporting countries are estimated using Google Maps.
- The sea travel distances from the exporting countries to Port Wales in the UK are calculated with the Sea Rate Distance calculator.
- A round-trip journey was considered for road and sea transportation.

Other parameters, such as the technological equivalence of the blast furnace process, the quality and composition of the iron-bearing aterials, the energy efficiency and the process yields, were assumed to remain similar to those described by Ng et al. (2010). Moreover, the environmental performance in terms of air emissions, water use, waste generation and resource consumption was also assumed to be comparable between the Canadian reference plant and the UK context.

B.3 Scenario 4: Coke and Grey Hydrogen

This scenario represents a blast furnace ironmaking pathway in which grey H_2 replaces pulverised coal injection as the auxiliary reductant, while coke remains as the main reductant. The quantity and proportion of iron bearing materials and fluxes are maintained the same as in Scenario 1. The corresponding cradle to gate inventory data for Scenario 4 are presented as follows.

B.3.1 Foreground inventory

Table B-9 presents the foreground inventory for the production of one tonne of hot metal in Scenario 4. It includes all major material and energy inputs, the transport of raw materials from the exporting countries to the port of an integrated UK steel plant, and the outputs such as slag, top-gas and direct air emissions

Table B-9: Foreground inventory data for Scenario 4 – Coke and Grey H_2

Categories	Data	Value	Unit	Source	Remarks
Inputs	Iron lump ore	196	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron pellet	393	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron sinter	921	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Coke	389.8	kg	Ng et al., 2010	Use conversion 28.6 MJ/kg in SimaPro

	Hydrogen	27.5	kg	Yilmaz et al., 2017	
	Dolomite	35	kg	Ng et al., 2010	
	Limestone	35	kg	Ng et al., 2010	
	Air	1159	kg	Yilmaz et al., 2017	Assume air density is 1.293 kg/m3
	Water	906.3	kg	Leao et al., 2023	
	Electricity	111.4	kW	Leao et al., 2023	
	Transport (road)	14	t.km	Manual calculation	Google Maps was used to estimate the road distance to transport raw materials from the importers to the UK steel plant.
	Transport (sea)	2928	t.km	Manual calculation	The Sea Distance Calculator estimated the distance by sea to transport raw materials from the importers to the UK steel plant.
	Transport (pipeline)	14	t.km	Manual calculation	
Output (Reference Product)	Pig Iron (Functional Unit)	1000	kg	NA	
Output (By/co-products)	Slag	250	kg		
	Top Gas	1446	Nm3	Yilmaz et al., 2017	

Emissions to the air	CO_2 (Fossil)	578.8	kg	Yilmaz et al., 2017	
	CO (Fossil)	319.7	kg	Yilmaz et al., 2017	
	H_2	16.6	kg	Yilmaz et al., 2017	
	N_2	911.7	kg	Yilmaz et al., 2017	

B.3.2 Background inventory datasets

The modelling of Scenario 4 also relied on background processes from the Ecoinvent 3.10 APOS database. These dataset represents intermediate flows and emissions associated with upstream supply chains. The background datasets are summarised in Table B-10

Table B-10: Background Inventory Datasets for Scenario 4

	Item	**Intermediate and Elementary Flows in Ecoinvent version 3.10**
Inputs	Lump ore	Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | APOS, U
	Pellet	Iron pellet {RoW}| iron pellet production | APOS, U
	Sinter	Iron sinter {RoW}| iron sinter production | APOS, U
	Coke	Coke {RoW}| coke production | APOS, U
	Hydrogen	See Table B-11
	Dolomite	Dolomite {RoW}| market for dolomite | APOS, U
	Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U
	Air	Air
	Water	Water, decarbonised {GB}| market for water, decarbonised | APOS, U
	Electricity	Electricity, medium voltage {GB}| market for electricity, medium voltage | APOS, U
	Road Transport	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U

	Sea Transport	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land transformation	Carbon dioxide, land transformation
	CO_2 fossil	Carbon dioxide, fossil
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	CO fossil	Carbon monoxide, fossil
	H_2O	Water
	H_2	Hydrogen
	N_2	Nitrogen
	O_2	Oxygen
	Particulates	Particulate

B.3.3 Grey H_2 production inventory

Grey H_2 production is a critical parameter in this scenario. Table B-11 presents the detailed foreground inventory for producing one tonne of hydrogen via steam methane reforming as reported by Hren et al. (2023). This inventory was used to model the upstream burden of grey H_2 supplied to the blast furnace.

Table B-11: Foreground Inventory of 1.0 t of Grey H_2 Produced via Steam Methane Reforming (Hren et al., 2023)

	Item	Value	Unit
Inputs	Natural Gas	4744.92	M^3
	Steam	10	Tonne
	Electricity	1137	MJ
	Water	18.85	Tonne
Outputs	H_2	1	Tonne
	CO_2	10.62	Tonne
	CH_4	0.06	Tonne
	Solid Waste	0.202	Tonne

B.3.4 UK-contextualised adjustments and assumptions

The original parameters were changed to reflect UK-contextualised conditions, as needed. The parameters that have been revised to be UK-contextualised for Scenario 4 are summarised as follows

- The sourcing of primary raw materials (iron ore, coking coal, and hydrogen) has been updated to reflect imports of raw materials to the UK based on data from the UK Trade Association for 2024, necessitating revisions to the distances travelled by road and sea. The delivery point is the port facility of an integrated steel plant in the UK. The details of raw materials imported and % of raw materials imported to the UK for Scenario 4 are presented in Table B-12:

Table B-12: Raw-material Importers and Percentage Share of Imports to the UK for Scenario 4

Raw Materials	Exporting Countries and the Percentage of Import	References
Iron-bearing materials	Norway (48%) Canada (27%) Netherlands (26)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)
Grey H_2	UK (100%	(BOC Limited, 2025)

Note: Percentages may not sum to exactly 100% due to rounding.

- Electricity and water sources have been adjusted to align with specific UK conditions customised in SimaPro software.
- Road transportation for moving raw materials from producers to the ports in the exporting countries is assumed to be via truck instead of rail to ensure consistency in the assessment for comparative purposes. This is due to a lack of data regarding rail distances and efficiencies.
- The distances from raw material producers to the ports in the exporting countries are estimated using Google Maps.
- The sea travel distances from the exporting countries to Port Wales in the UK are calculated with the Sea Rate Distance calculator.

- A round-trip journey was considered for road and sea transportation.

While the previous parameters were revised to adapt to UK ironmaking, the following parameters and conditions remain the same, as described below.

- **Technological Equivalence**: The blast furnace technology, process specifications, and operating practices in German, as reported by Yilmaz et al. (2017), are broadly consistent with those in the UK. This similarity applies to furnace size, efficiency levels, process parameters, and overall production methods.
- **Raw Material Quality and Quantity**: The quality, quantity, physical composition, and chemical composition of iron-bearing materials (e.g., ore, pellet, and sinter), are the same in Germany and the UK.
- **Energy Consumption**: Energy consumption and efficiency used are the same. This includes fuel usage (coke, coal, natural gas) and auxiliary energy sources (electricity, hot blast air).
- **Process Efficiency**: Process efficiency, yield rate, losses, and waste generation are assumed to be similar in the UK.
- **Environmental Performance**: Air emissions, water usage, waste generation, and resource consumption.

B.4. Scenario 5: Coke and Green Hydrogen

This scenario represents a blast furnace ironmaking pathway in which green H_2 replaces pulverised coal injection as the auxiliary reductant, while coke remains as the main reductant. The quantity and proportion of iron bearing materials and fluxes are maintained the same as in Scenario 1. The corresponding cradle to gate inventory data for Scenario 5 are presented as follows.

B.4.1 Foreground inventory

Table B-13 presents the foreground inventory for the production of one tonne of hot metal in Scenario 5. It includes all major material and energy inputs, the transport of raw materials from H_2 production plant to the port of an integrated UK steel plant, and the outputs such as slag, top-gas and direct air emissions.

Table B-13: Foreground inventory data for Scenario 5 – Coke and Green H_2

Categories	Data	Value	Unit	Source	Remarks
Inputs	Iron lump ore	196	kg	Ng et al., 2010 Tata Steel UK., 2024	

	Iron pellet	393	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Iron sinter	921	kg	Ng et al., 2010 Tata Steel UK., 2024	
	Coke	389.8	kg	Ng et al., 2010	Use conversion 28.6 MJ/kg in SimaPro
	Hydrogen	27.5	kg	Yilmaz et al., 2017	
	Dolomite	35	kg	Ng et al., 2010	
	Limestone	35	kg	Ng et al., 2010	
	Air	1159	kg	Yilmaz et al., 2017	Assume air density is 1.293 kg/m3
	Water	906.3	kg	Leao et al., 2023	
	Electricity	111.4	kW	Leao et al., 2023	
	Transport (road)	0	t.km	Manual calculation	Google Maps was used to estimate the road distance to transport raw materials from the importers to the UK steel plant.
	Transport (sea)	2928	t.km	Manual calculation	The Sea Distance Calculator estimated the distance by sea to transport raw materials from the importers to the UK steel plant.

	Transport (pipeline)	3	t.km	Manual calculation	
Output (Reference Product)	Pig Iron (Functional Unit)	1000	kg	NA	
Output (By/co-products)	Slag	250	kg		
	Top Gas	1446	Nm3	Yilmaz et al., 2017	
Emissions to the air	CO_2 (Fossil)	578.8	kg	Yilmaz et al., 2017	
	CO (Fossil)	319.7	kg	Yilmaz et al., 2017	
	H_2	16.6	kg	Yilmaz et al., 2017	
	N_2	911.7	kg	Yilmaz et al., 2017	

B.4.2 Background inventory datasets

The modelling of Scenario 5 also relied on background processes from the Ecoinvent 3.10 APOS database. These dataset represents intermediate flows and emissions associated with upstream supply chains. The background datasets are summarised in Table B-14.

Table B-14: Background Inventory Datasets for Scenario 5

	Item	**Intermediate and Elementary Flows in Ecoinvent version 3.10**
Inputs	Lump ore	Iron ore, crude ore, 63% Fe {IN}| iron ore mine operation, 63% Fe | APOS, U
	Pellet	Iron pellet {RoW}| iron pellet production | APOS, U
	Sinter	Iron sinter {RoW}| iron sinter production | APOS, U

	Coke	Coke {RoW}| coke production | APOS, U
	Hydrogen	Refer to Table B-15
	Dolomite	Dolomite {RoW}| market for dolomite | APOS, U
	Limestone	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U
	Air	Air
	Water	Water, decarbonised {GB}| market for water, decarbonised | APOS, U
	Electricity	Electricity, medium voltage {GB}| market for electricity, medium voltage | APOS, U
	Road Transport	Transport, freight, lorry 16–32 metric ton, euro5 {RoW}| market for transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U
	Sea Transport	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | APOS, U
Outputs	CO_2 biogenic	Carbon dioxide, biogenic
	CO_2 land transformation	Carbon dioxide, land transformation
	CO_2 fossil	Carbon dioxide, fossil
	CO biogenic	Carbon monoxide, biogenic
	CO land transformation	Carbon monoxide, land transformation
	CO fossil	Carbon monoxide, fossil
	H_2O	Water
	H_2	Hydrogen
	N_2	Nitrogen
	O_2	Oxygen
	Particulates	Particulate

B.4.3 Green H_2 production inventory

Green H_2 production is a critical parameter in this scenario. Table B-15 presents the detailed foreground inventory for producing one tonne of hydrogen via electrolysis powered by wind electricity as reported by Hren et al. (2023). This inventory was used to model the upstream burden of green H_2 supplied to the blast furnace.

Table B-15: Foreground Inventory of 1.0 t of Green H_2 Produced via Electrolysis powered by Wind Energy (Hren et al., 2023).

	Item	Value	Unit
Inputs	Potassium Hydroxide (KOH)	0.0019	tonne
	N_2	0.00029	tonne
	Electricity	180	GJ
	Deionised water	10	tonne
	Steam	0.11	tonne
Outputs	H_2	1	tonne
	O_2	32	tonne

B.4.4 UK-contextualised adjustments and assumptions

The original parameters were changed to reflect UK-contextualised conditions, as needed. The parameters that have been revised to be UK-contextualised for Scenario 5 are summarised as follows

- The sourcing of primary raw materials (iron ore, coking coal, and green hydrogen) has been updated to reflect imports of raw materials to the UK based on data from the UK Trade Association for 2024, necessitating revisions to the distances travelled by road and sea. The delivery point is the port facility of an integrated steel plant in the UK. The details of raw materials imported and % of raw materials imported to the UK for Scenario 4 are presented in Table B-16:

Table B-16: Raw-material Importers and Percentage Share of Imports to the UK for Scenario 5

Raw Materials	**Exporters Countries, and Percentage of Imports**	**References**
Iron-bearing materials	Norway (48%) Canada (27%) Netherlands (26)	(The Observatory of Economic Complexity, 2025a)
Coking Coal	USA (59%) Canada (16%) Australia (25%)	(UK Government, 2024a)

Green H_2	UK (100%)	(RWE, 2025)

Note: Percentages may not sum to exactly 100% due to rounding.

Other operating parameters such as technological configuration, process efficiencies, yields and environmental profiles remain similar to those assumed in the preceding scenarios.

Appendix C: Economic Assessment Calculation

This appendix presents the economic calculations used to evaluate the cost-effectiveness of alternative reductant scenarios for blast furnace ironmaking. The assessment focuses on Scenario 1 (baseline), Scenario 2 (coke and charcoal), and Scenario 5 (coke and green H_2), as these represent the baseline and the two most environmentally favourable alternatives identified through the life-cycle assessment.

C.1 Reductant Requirements

The reductant requirements for producing 1 tonne of hot metal (tHM) in each scenario are summarised in Table C-1. These values represent the mass of coke and auxiliary reductants required per functional unit.

Table C-1: Reductant Requirements for Production of 1 Tonne of Hot Metal

Scenario	Amount of coke (kg per tHM)	Amount of coke (tonne per tHM)	Amount of auxiliary reductant (kg per tHM)	Amount of auxiliary reductant (tonne per tHM)
Scenario 1 (Coke and pulverised coal)	370	0.37	140	0.14
Scenario 2 (Coke and charcoal)	364	0.364	140	0.14
Scenario 5 (Coke and green hydrogen)	389.8	0.3898	27.5	0.0275

C.2 Reductant Price Data

The economic assessment is based on 2023 market prices for each reductant type. These prices represent the cost of the reductants and exclude transportation costs from origin, storage costs, and other auxiliary costs. The reductant prices used in this assessment are presented in Table C-2.

Table C-2: Fuel Prices of Reductants Used for Economic Assessment (2023 Data)

Reductant Type	Reductant Price (£/tonne)	References
Coking Coal and Coke	220	(Focus Economics, 2025)
Charcoal	472	(IndexBox Inc, 2020)
Green H_2	3000	(WSS Energy Consulting, 2025)

Notes:

- For simplicity, coke and pulverised coal are assumed to have the same price, although coke is typically more expensive due to the additional coking process required. This conservative assumption understates the potential cost advantage of alternative reductants.
- The charcoal price represents imported charcoal from eucalyptus biomass, which is the basis for the life cycle inventory used in Scenario 2.
- The green H_2 price is based on hydrogen produced via wind-powered electrolysis, consistent with the LCA modelling assumptions in Scenario 5.
- All prices are in 2023 British pounds sterling.

C.3 Total Reductant Cost Calculation

The total cost of reductants to produce one tonne of hot metal is calculated using Equation C-1:

Total Reductant Price (£/tHM) = $(m_{coke} \times P_{coke}) + (m_{aux} \times P_{aux})$ [C-1]

Where:

m_{coke} = mass of coke (tonne)

P_{coke} = coke price (£/tHM)

m_{aux} = mass of auxiliary reductant (tonne)

P_{aux} = auxiliary reductant price (£/tHM)

Table C-3: Total Reductant Cost for Production of 1 Tonne of Hot Metal

Scenario	Amount of coke (tonne per tHM)	**Reductant Price (£/tonne)**	Amount of auxiliary reductant (tonne per tHM)	**Reductant Price (£/tonne)**	**Total Reductant Price (£/tHM)**
Scenario 1 (Coke and pulverised coal)	0.37	220	0.14	220	112
Scenario 2 (Coke and charcoal)	0.364	220	0.14	472	146

Scenario 5 (Coke and green hydrogen)	0.3898	220	0.0275	3000	168

Sample Calculation for Scenario 2:

Total Reductant Price = (0.364 × 220) + (0.140 × 472)

= 80.08 + 66.08

= 146.16 ≈ £146/tHM

Notes:

- These figures exclude transport costs, storage costs, supply chain costs, and capital expenditure required for process modifications. The values represent reductant costs only and provide a simplified comparison for preliminary economic screening.

C.4 Cost-Effectiveness Calculation

The cost-effectiveness of each alternative scenario is expressed as the cost per tonne of CO_2 avoided. This metric allows comparison with carbon pricing mechanisms and other decarbonisation technologies. The cost per tonne of CO_2 avoided is calculated using Equation C-2 as follows.

$$\text{Cost per tCO}_2\text{ avoided} = (C_{alt} - C_{base}) / (E_{base} - E_{alt}) \quad [C\text{-}2]$$

Where:

C_{alt} = total reductant cost for alternative scenario (£/tHM)
C_{base} = total reductant cost for baseline scenario (£/tHM)
E_{base} = greenhouse gas emissions for baseline scenario (kg CO_2-eq per tHM)
E_{alt} = greenhouse gas emissions for alternative scenario (kg CO_2-eq per tHM)

The greenhouse gas emissions data used in this calculation are derived from the life cycle assessment results presented in Chapter 4. The cost-effectiveness analysis results are presented in Table C-4.

The economic assessment presented in this appendix is subject to several limitations and simplifying assumptions:

- **Price Volatility:** Commodity prices, particularly for fossil fuels and renewable energy, are subject to significant market volatility. The 2023 prices used may not reflect future market conditions.
- **Economies of Scale:** Prices for green H_2 and charcoal may decrease significantly with increased production scale and technological maturation.

- **Carbon Price Trajectory:** The analysis assumes static carbon prices for comparison purposes. However, UK ETS prices are projected to increase substantially , which will improve the relative economics of low-carbon alternatives.
- **Excluded Costs:** Transportation, storage, capital expenditure, and operational modifications are excluded from this simplified assessment.
- **Regional Variation:** Reductant prices vary significantly by region. The prices used reflect UK market conditions and may not be applicable to other geographical contexts.
- **Policy Incentives:** Government subsidies, tax credits, or other policy support mechanisms that could improve the economics of low-carbon reductants are not included in this baseline assessment.