HM Government

Unlocking Resource Efficiency

Phase 1 Steel Report

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Organisation	Type of Organisation
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Brunel University London	Research
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Institution of Structural Engineers	Trade Association
Liberty Steel UK	Manufacturer
Sheffield Forge Masters	Manufacturer
Sims Metal	Manufacturer
Tata Steel	Manufacturer
The Materials Processing Institute	Research
University of Cambridge	Research
University of Warwick – Advanced Steel Research Centre	Research

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Introduction

The Department for Energy Security and Net Zero commissioned a research project to explore the potential benefits from increasing resource efficiency in the UK. This research has been done in collaboration with the Department for Environment, Food & Rural Affairs. This report outlines the findings of this research for the steel sector.

For the purposes of this report, resource efficiency is defined as any action that achieves a lower level of resource use for a given level of final consumption. This can occur at any stage of the supply chain including production, consumption, and end-of-life. While material substitution may not always meet the definition of resource efficiency set out above, it is in scope of this research where it reduces whole life carbon.

This research was conducted in the first half of 2023, and reports were written in August 2023. As such, this report does not reflect sector developments beyond that point. The Department for Energy Security and Net Zero has consulted with technical experts as part of research activities for this report. The following report is our understanding of the available evidence and is accurate to the best of our knowledge; however, if any factual errors are encountered, please contact us at Resource_efficiency@energysecurity.gov.uk.

This report and the research that underpins it was produced before the Port Talbot green transition announcement[1] and as such this report does not reference this announcement. This announcement will be contextually important to measures that relate to electric arc furnaces (EAFs) and should be considered when interpreting the results for these measures.

Methodology

This aim of this research was to achieve four key objectives:

- Identify a comprehensive list of resource efficiency measures for each sector;
- Identify current and anticipated drivers and barriers which are affecting improvements in the identified resource efficiency measures in each sector, and their relative importance;
- Build consensus estimates for the current “level of efficiency” and maximum “level of efficiency” in 2035, for each of the identified resource efficiency measures in each sector; and
- Identify the extent to which industry is currently improving resource efficiency and build consensus estimates for the likely “levels of efficiency” in 2035 given current private sector incentives and the existing policy mix (a “business-as-usual” scenario), for each of the identified resource efficiency measures in each sector.

To achieve these research objectives a mixed-methods methodology was developed. A literature review was conducted for each sector to synthesise evidence from the existing literature relevant to these objectives. The findings from this literature review were presented and tested in facilitated workshops with industry and academic experts. The aim of the

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[1] Gov.uk (2023), *Welsh steel’s future secured as UK Government and Tata Steel announce Port Talbot green transition proposal.* Available at link

workshops was to test the findings of the literature and fill any outstanding evidence gaps. This project did not aim to identify policy recommendations but rather understand the potential for resource efficiency in the UK.

This project has attempted to identify three level of efficiency estimates for each resource efficiency measure:

1. The **current level of efficiency** which is the best estimate for the current level of efficiency of the measure i.e. what is happening in the UK now (in 2023);
2. The **maximum level of efficiency** which is the maximum level of efficiency that is technically possible by 2035 in the UK, without factoring in barriers that could be overcome by 2035 i.e. what is the maximum level that could be achieved; and
3. The **business-as-usual (BAU) scenario** which is the level of efficiency that would be expected in the UK by 2035 with the current policy mix and private sector incentives i.e. what would happen if there were no substantial changes in the policy or private sector environment.

These levels of efficiencies have been identified to understand the potential for resource efficiency and do not represent government targets.

To estimate these levels of efficiency an indicator has been developed for each of the identified measures. These indicators have been chosen based on how well they capture the impact of the relevant measure, and how much data there is available on this basis (both in the literature review and from expert stakeholders).

Note, the purpose of the indicators in this research is to estimate current, maximum and BAU level of efficiency on a consistent basis. They are not intended be used as metrics to monitor the progress of these resource efficiency measures over time, or to be used as metrics for resource efficiency policies.

A high-level overview of the research stages is presented below. A more detailed version of this methodology is presented in the Technical Summary which accompanies this publication.

Literature Review

The literature sources were identified through an online search, and through known sources from Defra, the Department for Energy Security and Net Zero, the research team, and expert stakeholders.

Once literature sources had been identified they were reviewed by the research team and given an Indicative Applicability Score (IAS) ranging from 1 to 5 which indicated the applicability of the sources to the research objectives of this study. This score was based on five key criteria: geography, date of publication, sector applicability, methodologies used and level of peer review.

After the five criteria of the IAS had been evaluated, the overall IAS score was calculated, ranging from 1 to 5, according to the number of criteria scoring ‘high’ and ‘low.’

Table 1: Methodology for the calculation of the IAS

Number of 'high' criteria	Number of 'low' criteria	IAS
<=2	3 or more	1
<= 1	2	2
>= 2	2	3
<= 2	1	3
>= 3	1	4
<= 1	None	3
2	None	4
>= 3	None	5

A detailed overview of the parameters used to assess high / medium / low scores for each of the five criteria feeding into the IAS calculation can be found in Appendix A.

The research team drafted literature summaries for each sector which synthesised the best available evidence from the literature for each of the four research objectives. When drafting these summaries, literature sources with a higher IAS score were weighted more than those with lower IAS score.

Facilitated workshops

The findings from these literature summaries were then presented at two half-day facilitated workshops per sector. The workshops were attended by a range of sector experts from both academia and industry (covering different aspects of the value chain). The purpose of these workshops was to test the findings of the literature review against stakeholder expertise, and to fill any evidence gaps from the literature.

The stakeholders contributed through sticky notes in a shared virtual Mural board, by participating in the verbal discussions and by voting on pre-defined ranges on the levels of efficiency and the top drivers & barriers.

Finally, the findings of the literature review and the stakeholder engagement were combined to reach final conclusions against each research objective. For the estimates on the level of efficiency for each measure (objectives 3 and 4), a five-tier evidence RAG rating was assigned to indicate the level of evidence supporting the proposed figures. Only where the datapoints were supported by literature sources with high IAS and a high degree of consensus amongst experts in the workshops, were the datapoints considered to have a "green" evidence RAG rating. The definitions are as follows:

- **Red:** Limited evidence available from literature review or stakeholders

- **Red-amber:** Some evidence available from literature review but it is not relevant/out of date, limited evidence from stakeholders, stakeholders are not experts on this measure
- **Amber:** High quality evidence from either literature or stakeholders
- **Amber-green:** High quality evidence from literature or stakeholders, evidence from stakeholders is supported by some information in the literature (or vice versa)
- **Green:** High quality evidence from literature supported by stakeholder expertise.

It should be noted that the business-as-usual (BAU) level of efficiency was only informed by the stakeholder engagement, so the maximum evidence RAG rating for the BAU is amber.

Sector Introduction

The UK steel sector is large and economically significant. It employs 39,000 people in 1,135 businesses[2] and has an economic output of £2.4bn, making up 0.1% of the UK economy and 1.2% of manufacturing output.[3] Steel is a widely used material across the economy and is fundamental to the construction, automotive, defence and energy sectors.

There are two ways of making steel. Traditionally, mined iron ore is heated using coal and fossil fuels in a blast furnace, and then reacted with oxygen in a basic oxygen furnace (BF-BOF). Coke derived from coal is used as a reductant in the BF-BOF steel making process. An alternative process involves primarily melting of recycled scrap steel in an electric arc furnace (EAF). In the UK in 2021 7.2MT total of steel was produced with1.3MTpa from EAF and 5.9Mt from BF-BOF.

The purest form of steel has traditionally been from blast furnaces using virgin, uncontaminated ore. However, recent advances in EAF technology allows equivalent performance if feedstocks are tightly controlled for composition. EAFs typically reprocess scrap steel, from all sources, and the UK's imports of scrap are from known and established sources and so allow domestic (UK) EAFS to produce steel of reliable quality for construction and other mass markets.

Resource efficiency is a critical pathway that the steel sector can use to reduce its environmental impact, reducing raw material consumption, energy use, greenhouse gas emissions and waste generation. Using resources more efficiently can also result in cost savings through a reduction in raw material use, and a switch to potentially cheaper alternative materials.

Sector Scope

Resource efficiency measures in the steel sector focus on optimising the use of steel throughout the entire lifecycle. This covers:

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[2] Keep, M.; Jozepa, I.; Ward, M.; (2023). Contribution of the steel industry to the UK economy. House of Commons Library Debate Pack.

[3] Keep, M.; Jozepa, I.; Ward, M.; (2023). Contribution of the steel industry to the UK economy. House of Commons Library Debate Pack.

- **Steelmaking – raw materials** – replacing fossil fuels used as reductants (coal, coke and natural gas) with non-fossil (e.g. biomass, plastics and rubber, green hydrogen).
- **Steelmaking – production** – primarily related to greater use of EAF (and therefore a greater use of scrap steel), but also relating to the reuse of steel-making byproducts.
- **Use of steel - products** – Light-weighting and lifespan extension of steel-based products.
- **Use of steel - end-of-life processes** – reusing, repairing, remanufacturing and recycling steel-based products.

The scope of this report covers resource efficiency measures for the steel sector as described above. To avoid duplication and double counting with other studies the following topics are out of scope of this study:

- Fuel switching: Fuel switching e.g. to hydrogen (H2DRI) is out of scope of this study. Fuel switching and energy efficiency are out of scope as these relate to carbon efficiencies and not steel resource efficiencies.
- Energy efficiency: This is not considered within this study as it is considered in other studies outside of this project.
- Steel used in other sectors: This includes steel used in the production of vehicles and in construction as these are considered separately in separate reports within this project.

Literature review approach

The literature review identified 138 sources discussing steel design, manufacturing, use and end-of-life. These were identified using a range of search strings relating to resource efficiency, the circular economy and the steel sector. The search strings are listed in Appendix B. Further sources were identified from sector experts via the workshops and the pre-workshop survey. The full list of sources used are listed in Appendix C.

These 138 sources comprised of:

- 61 academic papers;
- 36 industry reports;
- 7 policy documents;
- 4 technical studies; and
- 30 website articles.

The sources were considered of generally high applicability and credibility when assessed against the data assessment framework, which recognises the relevance of the sources and the strength of their methodology. The sources had an average IAS of 4.3, with 106 of the sources scoring 4 or above.

More detail on the purpose and approach for these literature reviews can be found in the Technical Summary annex.

Workshop approach

Two workshops on resource efficiency in the steel sector were held, involving 16 participants from across the steel industry including: five representatives from steel manufacturing organisations (including BF-BOF and EAF steelmakers), two representatives from steel scrap recyclers; seven steel industry researchers and academics; and two participants from other steel-related associations.

The participants represented well the manufacturing, research and development, and end-of-life aspects of steel production and use. Stakeholders were knowledgeable on Measures 1 to 6, although aspects of BF-BOF production had limited discussion from representatives of such plants.

Workshop sessions also had limited attendance from end-of-life steel experts, who could share views on the matters of steel reuse, repair, remanufacture and recycling (Measure 8). Useful discussion occurred on the potential resource efficiency achieved through these methods, however there was limited knowledge of the quantitative aspects of the levels of efficiency. Additionally, participants had limited knowledge of light-weighting of steel-based consumer products (Measure 7). Further representation of and insight on the uses of steel through the value chain would have been beneficial, however, these measures were also covered for specific steel-containing products in the vehicles and construction sectors research (with electricals also covered in Phase 2 of the research).

More detail on the purpose and design of these workshops can be found in the accompanying Technical Summary.

List of resource efficiency measures

The literature review and workshops identified eight steel resource efficiency measures. These were considered under four categories – design, manufacturing, use, and end-of-life. Resource efficiency measures in the construction and vehicles sectors, which are both major steel consumers, are covered in sector reports for the vehicle and construction sectors.

The first category (design) focuses on resource efficiency via substitution of the primary materials used in steel and ironmaking, which can be realised through the following proposed set of three measures:

- Substitution of fossil-carbon reductants with waste-based alternatives
- Substitution of fossil-carbon reductants with hydrogen direct reduced iron in EAFs
- Transition from ore-based to scrap-based steel production

The second category (manufacturing) covers three measures:

- Transition from basic oxygen furnace to electric arc furnace steelmaking
- Recovery and utilisation of process off-gases
- Recovery and use of steelmaking by-product materials

The third category (use) covered one key measure concerning the use of steel in consumer products:

- Light-weighting and use of higher grades of steel in consumer products

Finally, in the fourth category (end-of-life), one measure was proposed covering more circular use of end-of-life steel products and components:

- Increased reuse, repair, remanufacture and recycling of steel-based products

Further details of the resource efficiency measures are provided in Table 2.

Table 2: List of resource efficiency measures for the steel sector

#	Lifecycle stage	Strategy	Measure name	Measure indicator
1	Design	Primary material substitution	Substitution of fossil-carbon reductants with waste-based alternatives	% reductant (in weight) replaced by plastic or rubber waste alternatives
2	Design	Primary material substitution	Substitution of fossil-carbon reductants through use of hydrogen to produce direct reduced iron in EAFs	% of UK crude steel produced using hydrogen-DRI-EAF
3	Design	Use of secondary raw materials	Transition from ore-based to scrap-based steel production	% of scrap per tonne of crude steel for BF-BOF and EAF in UK steel production
4	Manufacture	Shift to electric arc furnace	Transition from basic oxygen furnace to electric arc furnace steelmaking	% of UK crude steel produced using EAF
5	Manufacture	Process efficiencies	Recovery and utilisation of process off-gases	% reduction in carbon inputs
6	Manufacture	Process efficiencies	Recovery and use of steelmaking by-product materials	% of steelmaking by-products recovered and used
7	Design	Light-weighting	Light-weighting and use of higher grades of steel in consumer products	% reduction in weight of consumer product
8	Use / EoL	Life extension / reuse / remanufacture / recycling	Increased reuse, repair, remanufacture and recycling of steel-based products	% of reused product % of repaired product % of remanufactured product % of recycled product

Additional measures of ongoing and recent interest to the steel sector were also researched (water and wastewater efficiency; carbon capture and storage) but were deemed out of scope as they did not meet the definition of resource efficiency for this research (see list in Appendix D). Measures relating to the use of steel in vehicles or construction are covered in the sector reports for these sectors.

Drivers and Barriers

Drivers and barriers were categorised using two separate systems:

1. The PESTLE framework which is focused on the types of changes: political, economic, social, technological, legal and environmental;

2. The COM-B framework which is focused on behaviour change:
   - **Capability**: can this behaviour be accomplished in practice?
     - Physical Capability – e.g., measure may not be compatible for certain processes
     - Psychological Capability – e.g., lack of knowledge
   - **Opportunity**: is there sufficient opportunity for the behaviour to occur?
     - Physical Opportunity: e.g., bad timing, lack of capital
     - Social Opportunity: e.g., not the norm amongst the competition
   - **Motivation**: is there sufficient motivation for the behaviour to occur?
     - Reflective motivation: e.g., inability to understand the costs and benefits,
     - Automatic motivation: e.g., lack of interest from customers, greater priorities

1. Measure 1 – Substitution of fossil-carbon reductants with waste-based alternatives

1.1 Steel resource efficiency measure

1.1.1 Description

Partial substitution of fossil-carbon reducing agents with waste-based alternatives, namely rubber tyres and plastics, in steelmaking.

Fossil-carbon reductants used in steelmaking can be substituted with waste-based materials derived from sources such as used tyres or waste plastics. These materials are the subject of research on mitigation of greenhouse gas emissions which also provides evidence of the effects of their use as alternative reductants.[4] Blends involving common plastics, such as HDPE, PET, and PP, have been successfully applied and proven to be beneficial at industrial EAF scale outside the UK.[5] According to the literature review, the injection of plastic wastes in BF-BOFs has not been recently explored as extensively in the UK, whereas it is a common practice in some integrated steel plants in Germany, Austria and Japan.[6]

This measure is most likely in EAF steelmaking, and this is the main focus as there is negligible experience of its use in UK BF-BOF plants.

1.1.2 Measure indicator

The indicator selected for Measure 1 was the **% of fossil fuel reductant (in weight) that can be replaced by plastic or rubber waste alternatives**. The initial indicator was “tonnes of fossil resource replaced with waste-based alternative” but it was agreed that a percentage is a more convenient expression for the indicator.

1.1.3 Examples in practice

Use of tyres in EAFs

Waste rubber tyres can partially replace coke in the EAF steelmaking route. The addition of tyres as a coal substitute in EAFs requires precision in their placement within the scrap basket to ensure that the tyres will not result in a temperature increase in the off-gas dedusting system. This is due to the highly volatile content of materials like tyres and polymers. The tyres should be specifically placed in the middle of the basket to prevent direct contact with the ‘hot heel’ component of the EAF and to decrease the burn-off through direct contact with the

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[4] Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions

[5] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

[6] Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions

furnace atmosphere. Research focusing on the efficiency of a rubber-coke blend substitution demonstrated that carbon additions can be reduced by 12%.[7]

Use of waste plastics in EAFs

Waste plastics, including HDPE, PP, and PET, can partially replace coke in EAF steel production. Polymer-coke blends such as HDPE-coke and PET-coke have proven to offer beneficial reaction rates, increased slag volumes, and improved chemical reduction of slag in comparison to pure coke inputs. A study that tested the efficiency of the HDPE-coke blend in EAF steelmaking showed a decrease in specific energy consumption (-3%) in comparison to coke injection and a potential for reduction of carbon resources by about 15%.[8]

1.2 Available sources

1.2.1 Literature Review

Most of the literature regarding the use of waste plastics as reductants in blast furnaces is contemporaneous with the rise in society's use of plastics and the results remain applicable to a BF technology that was already mature. The most notable research was undertaken by Ariyama et al. (1997)[9], Lindenberg et al. (1996)[10], Janz and Weiss (1996)[11], Heo and Baek (2002)[12], Jeschar and Dombrowski (1996)[13]. The majority of more current research addresses use of waste-based reducing agents in EAFs which is the main focus of Measure 1.

No literature sources were identified with a focus on the UK. However, an explanation for this was given by stakeholders during the workshops, who highlighted that the UK has strict emission limits for the persistent organic pollutants (POPs) which are emitted from some potential feedstocks during steel production. This is expanded upon in the Drivers & Barriers section below. It is also likely that this led to the lack of available literature on the potential levels of efficiency for this measure in the UK.

1.2.2 Workshops

Interaction between stakeholders during the discussion of this measure was limited because few had extensive knowledge of waste substitutions in steel production. However, it was apparent that this measure is not currently implemented on a large scale in the UK.

The level of engagement in both workshops was as follows:

- **Workshop 1** – Five stakeholders across industry and academia were active on the mural board and no stakeholders actively contributed to verbal discussion.

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[7] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

[8] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

[9] Ariyama et al. (1997). Development of shaft-type scrap melting process characterized by massive coal and plastics injection.

[10] Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions.

[11] Janz, J. and Weiss, W. (1996). Injection of waste plastics into the blast furnace of Stahlwerke Bremen.

[12] Heo and Baek (2002). The effect of injection of waste plastics on the blast furnace operation.

[13] Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions.

- **Workshop 2** – Five stakeholders across industry and academia were active on the mural board and one stakeholder actively contributed to verbal discussion.

1.3 Drivers & Barriers

The drivers and barriers associated with Measure 1 are listed in Table 3 and Table 4 respectively, including their PESTLE and COM-B categorisation. The most significant drivers and barriers for Measure 1 were decided by stakeholders through voting during workshops and these are displayed in bold.

1.3.1 Drivers

The drivers that would enhance the implementation of waste-based substitutions in steelmaking are limited at present, with two being identified in total.

Table 3: Drivers for steel Measure 1

Driver	PESTLE	COM-B
Operational flexibility through wider choice of feedstocks	Technological	Capability – physical
Lack of biomass feedstock availability.	Economic	Motivation – reflective

Literature on the measure identifies operational flexibility improvements from the wide choice in waste-based feedstocks (mainly used tyres and plastics).[14] Substitution of fossil-carbon by waste products is already proven on an industrial scale in plants such as cement kilns[15], and this experience may indicate a corresponding level of ambition is possible in steelmaking.

1.3.2 Barriers

Table 4: Barriers for steel Measure 1

Barriers	PESTLE	COM-B
Emission limits for contaminants such as dioxin and furan.	**Technological**	**Capability - physical**
Requirements for precision in charging (loading) process for end-of-life tyres in EAFs.	Technological	Capability - physical
Supply limitations caused by low availability and price of waste feedstock.	Technological Economic	Capability - physical

During workshop sessions, stakeholders expressed concerns with regards to the use of waste-based feedstocks in the UK as a substitute for fossil-carbon reductants. The better use of waste in other sectors outside the steel industry was raised (reflecting a waste hierarchy) while

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[14] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

[15] Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions.

their use in BF-BOFs and EAFs is limited globally at present. Steel manufacturers highlighted that this option is not currently being implemented at scale in the UK, but some trials have been completed.

There are two main technical challenges when using plastics or end-of-life tyres in EAFs:

- Levels of contaminants, primarily persistent organic pollutants (POPs) such as dioxins and furans, for which there are strict emission limits in the UK. It is seen as a complicated option, both in terms of cost and chemistry, and carbon impact savings are thought to be small. One steel manufacturer elaborated on this challenge, stating that an EAF plant must include abatement technology for POPs in order to be able to accept such waste-based reductants. Such solutions may involve high-temperature incineration for the waste plastics. However, abatement technology for these applications has not been the subject of investment and biomass is seen as a preferred reductant compared to waste-based alternatives.
- Requirements for high precision in the loading ('charging') of end-of-life tyres into the EAFs before smelting.[16]

Finally, stakeholders added that this route requires high volumes of plastic of the right type and size, which is unlikely to be available at a viable cost to make a meaningful difference to carbon emissions in the steel sector, a key benefit associated with the saving in reductant. This perspective may also influence a low level of research and development for this measure.

1.4 Levels of efficiency

Table 5: Levels of efficiency for steel Measure 1

Indicator: % of fossil fuel reductant (in weight) replaced by plastic or rubber waste alternatives			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0%	0 – 5%	0 – 1%
Evidence RAG	Amber	Red	Amber

1.4.1 Current level of efficiency

The current level of efficiency was agreed by stakeholders to be 0%, with no dissenting votes. One stakeholder noted that there have been UK trials, but no quantitative data was identified by the research.

An amber RAG rating of evidence is assigned to this range due to the lack of confirming literature and the low engagement from stakeholders (although with consensus).

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[16] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

1.4.2 Maximum level of efficiency in 2035

Literature on this measure was minimal. One Australian study indicated a 12% to 15% reduction in carbon additions through HDPE and rubber substitutions[17] in EAFs but the results may not be applicable to the UK due to a different pollution control regime (particularly for POPs and chlorine).

Stakeholders expressed disagreement with the potential presented for such a high level of uptake and thus maximum resource efficiency by 2035 in the UK due to the significant challenges of pollution control, which apply to both the EAF and BF-BOF steelmaking processes.

A range of 0% to 5% for maximum technical level of efficiency was voted for by most stakeholders, suggesting that waste alternatives are unlikely to be used extensively in the steel sector for fossil-reductant substitutions.

A red RAG rating of evidence is assigned to this range due to the conflicting views of the literature source and the stakeholders, as well as the overall low level of stakeholder engagement.

1.4.3 Business-as-usual in 2035

As a result of the barriers identified for this measure, the business-as-usual level of efficiency achieved in 2035 is estimated to be in the range of 0% to 1%. This range received the most votes in the second workshop, although there was one vote for the range 4% to 5%. This vote was associated specifically with EAFs, as one stakeholder stated that the smaller absolute quantity of carbon required in this route may allow for higher levels of substitution, but this also depends on the implementation of abatement technologies in the EAFs.

Due to the consensus that significant changes will be required for the currently unabated plants to accept waste feedstocks, the range 0% to 1% is selected with an amber RAG level of evidence from literature review and stakeholder engagement.

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[17] Thomas Echterhof (2015). Review on the Use of Alternative Carbon Sources in EAF Steelmaking.

2. Measure 2 – Substitution of fossil-carbon reductants through use of hydrogen to produce direct reduced iron in EAFs

2.1 Steel resource efficiency measure

2.1.1 Description

This measure relates to the use of hydrogen as a substitute reducing agent rather than as a substitute fuel. Use of hydrogen as a substitute fuel is out of the scope of this study.

Chemical reduction of iron ore is a critical process in steel production and involves the conversion of iron oxide (ore) to metallic iron which can then be used in steelmaking. The reduction is conventionally undertaken with using fossil-carbon (coal, coke, or natural gas) but this leads to significant carbon emissions, with the steel sector accounting for up to 11% of the global total. To achieve higher resource efficiency and decrease emissions, alternative reductants such as green hydrogen[18] can be used.

Iron ore may be chemically reduced by separating iron from oxygen in an alternative industrial process than through smelting in a blast furnace. The process called direct reduction of iron (DRI) typically takes place in a shaft furnace producing ‘sponge iron’ where the falling ore is met by rising gases or in an inclined rotary furnace using coal. Sponge iron can then be melted directly in an EAF to produce steel.[19] [20] [21] When the gas used is green hydrogen generated from renewable electricity, the overall process leads to significant carbon savings.

Literature sources identify a change in CO_2 emissions achieved by this measure of 90%[22] compared to BF-BOF emissions as well as quoted productivity increases of 85%.[23] The total costs of production, and hence productivity, are highly dependent on the price of electricity and the quantities of scrap used.[24]

The transition to greater use of hydrogen-DRI (H2-DRI) within steelmaking requires significant investment but brings change in types of material use, from fossil-carbon to renewables, as well as a shift to sustainable and low carbon steel production. The UK already has the

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[18] Green hydrogen is defined as hydrogen produced using the water electrolysis process with electricity generated by renewable energy.

[19] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry

[20] Viisainen, B. V., & Rowden, H. (2022). Building the future A faster route to clean steel.

[21] Patisson, F. and Mirgaux, O. (2020). Hydrogen Ironmaking: How It Works.

[22] Patisson, F. and Mirgaux, O. (2020). Hydrogen Ironmaking: How It Works.

[23] Viisainen, B. V., & Rowden, H. (2022). Building the future A faster route to clean steel.

[24] Vogl, V.; Åhman, M.; Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking

necessary expertise and pilot facilities to realise decarbonisation through this measure, but commercialisation depends on investment conditions.[25]

2.1.2 Measure indicator

The original indicator (% of CO_2 reduction in EAF steelmaking) was changed to the actual indicator used **"% of UK crude steel produced using hydrogen-generated DRI via the EAF route**" to avoid the influence of levels of decarbonisation of the electricity grid. It is important to reiterate that the role of hydrogen in this case is that of a reducing agent, and not as a fuel which is out of scope for this study.

2.1.3 Examples in practice

This technology is still in the early stages of development and as such, large scale, commercial examples of H2-DRI steelmaking are not yet available.

2.2 Available sources

2.2.1 Literature Review

The potential for clean hydrogen to contribute to decarbonising steelmaking is well-understood and has been widely explored in recent years as part of research and policymaking. The measure has a range of effects with numerous barriers and drivers.

Eight key literature sources with high IAS scores (of 5) were identified to be directly relevant to the UK and EU situation and were prioritised. These were mainly academic reports focusing on different perspectives of the steel sector covering: industry and market challenges to UK future capacities and capabilities[26]; policy and financial barriers to decarbonisation[27, 28];technological innovation options for decarbonisation[29]; clean steel production opportunities and challenges[30]; hydrogen ironmaking[31, 32]. The UK Hydrogen Strategy was the fundamental document used to inform the context for hydrogen policy in the UK[33].

All references indicated that the direct reduction of iron in EAFs using hydrogen and the phasing-out of fossil-carbon reducing agents is an efficient decarbonisation option for the steel sector. The quantitative data in these sources aligned with the opinion of stakeholders who also provided additional evidence during the workshops.

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[25] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry
[26] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry
[27] Richardson-Barlow, C., Pimm, A. J., Taylor, P. G., & Gale, W. F. (2022). Policy and pricing barriers to steel industry decarbonisation: A UK case study
[28] Energy Monitor (2021). With the right policies, the UK could lead on green steel production.
[29] Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A. (2020). Technology innovation system analysis of decarbonisation options in the EU steel industry
[30] Viisainen, B. V., & Rowden, H. (2022). Building the future A faster route to clean steel.
[31] Patisson, F. and Mirgaux, O. (2020). Hydrogen Ironmaking: How It Works.
[32] Vogl, V.; Åhman, M.; Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking
[33] UK Government (2021). UK Hydrogen Strategy.

2.2.2 Workshops

Measure 2 was one of the most-discussed measures. Workshop participants, including steel manufacturers and research and development experts with in-depth understanding of the steel sector and the benefits and challenges of hydrogen usage, discussed potential feasibility in the UK by 2035.

Overall, there was agreement regarding the levels of efficiency, with multiple barriers noted, particularly regarding scalability and the need for a stable and affordable supply of renewable energy required for hydrogen production. Stakeholders largely focused on these challenges, as they broadly agreed that the measure itself poses a significant opportunity for the UK steel sector. These are further discussed in the following section.

The level of engagement in both workshops was as follows:

- **Workshop 1** – Five stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Six stakeholders across industry and academia were active on the mural board and three stakeholders actively contributed to verbal discussion.

2.3 Drivers & Barriers

The drivers and barriers associated with Measure 2 were identified through a combination of literature review and stakeholder feedback during the workshops. The drivers and barriers are listed in Table 6 and Table 7 respectively, including their PESTLE and COM-B categorisation. The most significant drivers and barriers for Measure 2 were decided by stakeholders through voting during workshops, and these are displayed in bold.

2.3.1 Drivers

The drivers for this measure depend on the progress of global decarbonisation policies and programmes. At a national level, the UK Hydrogen Strategy recognises hydrogen would be instrumental in the decarbonisation of primary steelmaking and would generate green jobs.[34] The drivers are listed in Table 6 with the increased availability of renewable energy assuming to lead to increased volumes of green hydrogen.

Table 6: Drivers for steel Measure 2

Driver	PESTLE	COM-B
Increasing availability of renewable energy sources for steel making.	**Economic**	**Opportunity – social**
Increasing H2-DRI applications in EAF steelmaking in the EU.	Social	Opportunity - social

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[34] UK Government (2021). UK Hydrogen Strategy.

[35] In this case, green hydrogen refers to “fossil-free steelmaking” based on hydrogen direct reduction of iron (H2-DRI) in electric arc furnaces (EAFs).

Driver	PESTLE	COM-B
Expected demand and price increase for high-quality scrap.	Economic	Motivation – reflective
The need to decarbonise primary steelmaking and retain primary steelmaking capability.	Environmental	Motivation – reflective

Using less ore aligns with an overall objective of minimising resource use but there is a continued global need for ore because demand exceeds supply of scrap. Measure 2 implicitly locates DRI production within the UK, but DRI and scrap may be produced and traded internationally, and the proportions used of each can be variable as they are close substitutes, and consumption will depend on short term market prices in the UK.

The driver voted as most significant for Measure 2 was the growing share of renewable energy sources which may make renewables-based steelmaking technologies economically feasible. Stakeholders noted that in terms of quantity, UK production of offshore wind energy would meet demand for green hydrogen while the precedents established in the Nordic counties may influence the level of UK ambition.

Stakeholders noted that by 2035, due to increasing use of EAF, the price of high-quality steel scrap and use of green hydrogen[35] DRI as an alternative will rise.

The quality of scrap is a key driver for DRI. The UK has poorly characterised scrap which results in a low-quality stream, requiring more DRI to dilute impurities. Because DRI is a quantitative substitute for scrap, it will have a similar globally traded price, though with a premium for the inherent quality of ore. Where DRI substitutes for fossil-processed ore, there is a resource efficiency saving from the reduced fossil-inputs from blast furnace production no longer required, and corresponding savings in emissions. Where DRI substitutes for scrap, there is a resource efficiency loss, as the preferred scrap is not being used. However, this loss is offset if DRI was required anyway to meet global demand, and DRI use in the UK leads to better and earlier installation of DRI production processes and a reduction in the use of current fossil-derived ore.

2.3.2 Barriers

Literature sources highlight an array of technological, legal and economic barriers and voting on the most significant barriers in the workshop was spread across almost all barriers in Table 7.

Table 7: Barriers for steel Measure 2

Barrier	PESTLE	COM-B
UK has sufficient scrap supply for EAFs, without need of DRI.	Technological	Capability – physical
Limited availability of green hydrogen and demand increasing from other sectors.	Economic	Opportunity – social

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[35] In this case, green hydrogen refers to “fossil-free steelmaking” based on hydrogen direct reduction of iron (H2-DRI) in electric arc furnaces (EAFs).

Barrier	PESTLE	COM-B
Lack of cost-efficient technologies for hydrogen at the industrial scale.	Technological Economic	Capability – physical
Regulatory framework for hydrogen and other new clean technologies and infrastructure still in development.	Legal	Opportunity – social
Low levels of investment.	Economic	Opportunity – social
Current ore quality is inadequate for use in a hydrogen-DRI-EAF scenario.	Technological	Capability – physical
Insufficient access to stable and reasonably priced renewable power supplies.	Economic	Opportunity – social
High energy costs to produce hydrogen.	Economic	Opportunity – social

The barrier voted as most significant was the expected availability of substitutes, namely scrap, meaning H2-DRI is not required at least in the near term. Steel manufacturers expect to have enough scrap to operate UK EAFs without DRI up until 2035 and there was general agreement amongst stakeholders that DRI will not be required in large quantities for steelmaking.

Another key barrier is the immaturity of hydrogen technology which leads to lack of cost-efficient technologies at industrial scale for the production and distribution of green hydrogen.[36] Contributing factors are low investment levels in technologies applicable to the steel industry[37], compounded by the technical infrastructure being only at a pilot phase and industries which are cautious to invest in new markets as these may see significant regulatory developments, particularly in the early phase, for example as a result of pilot studies.[38]

Stakeholders specifically noted that:

- The quality of ore in the UK is inadequate for H2-DRI-EAF applications compared to Scandinavian countries which are deploying this measure.
- Green hydrogen will see growth in demand from other sectors such as power and transport.[39]

Both literature and workshop outputs show consensus that further policy development[40], financial incentives on research and development, and supply chain engagement[41] would contribute to mitigating the issues identified.

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[36] Vogl, V.; Åhman, M.; Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking

[37] Vogl, V.; Åhman, M.; Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking

[38] Vogl, V.; Åhman, M.; Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking

[39] Patisson, F. and Mirgaux, O. (2020). Hydrogen Ironmaking: How It Works.

[40] Richardson-Barlow, C., Pimm, A. J., Taylor, P. G., & Gale, W. F. (2022). Policy and pricing barriers to steel industry decarbonisation: A UK case study

[41] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry

2.4 Levels of efficiency

Table 8: Levels of efficiency for steel Measure 2

Indicator: % of UK crude steel produced using hydrogen-generated DRI via the EAF route			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0%	15 – 30%	0 – 15%
Evidence RAG	Amber	Red	Red

2.4.1 Current level of efficiency

Quantitative levels of efficiency were not explicitly stated in literature but the consensus in the workshops was that H2-DRI is not currently used for EAF steelmaking and therefore the current level of efficiency is 0%.

Due to the lack of literature sources, an amber RAG rating for evidence is assigned to the current level of efficiency noting the consensus and high engagement of the expert stakeholders.

2.4.2 Maximum level of efficiency in 2035

The maximum level of efficiency provided is based on workshop outputs because the outlook for H2-DRI production in the UK by 2035 is a scenario that has not been explored in literature and does not have quantitative estimates. The UK Hydrogen Strategy, does, however foresee that hydrogen will play a significant role in supporting sectors such as steel, to anchor the UK supply chains by facilitating their decarbonisation and development of a low-carbon proposition that will ultimately be exportable.[42]

Most stakeholders considered that a maximum of approximately 15% to 29% of UK crude steel could be produced using H2-DRI in EAFs in 2035. This would replace some of the 80% of UK-made steel currently manufactured in blast furnaces[43]. One diverging vote estimated a maximum level of efficiency between 30% and 44%. Some participants suggested EAFs would use large quantities of scrap in the future while others referred to growth in H2-DRI use while noting its dependency on economic and political factors.

The level of evidence for the estimated maximum level of efficiency is demonstrated with a red RAG rating due to the lack of literature sources, the lack of agreement from stakeholders and dependency on economic and political factors.

2.4.3 Business-as-usual in 2035

Stakeholders stated business-as-usual levels of efficiency would not be high as H2-DRI use was likely to be minimal without government intervention, due to the high costs involved in transitioning to this technology.

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[42] UK Government (2021). UK Hydrogen Strategy.
[43] Energy Monitor (2021). With the right policies, the UK could lead on green steel production.

Most voting was for an estimated 0% to 14% level of efficiency in 2035 with one diverging vote for the range of 15% to 29%.

One participant noted that large quantities of scrap were likely to be processed by EAFs in the business-as-usual scenario while enhanced H2-DRI use would require financial intervention. However, while recognising this requirement, it was generally agreed that substantial volumes of steel could be produced using H2-DRI particularly if low-carbon electricity from UK offshore wind was used. During discussion, it was also noted by one participant that a 90% maximum crude steel production via this route is unlikely under business-as-usual as EAFs will still be using significant quantities of steel scrap. However, it was generally agreed that substantial volumes of steel could be produced using H2-DRI were there to be government economic incentives. The UK also has access to low-carbon electricity through offshore wind power generation which complement use of H2-DRI for green steel production.

The evidence RAG rating for the estimated business-as-usual level of efficiency is red due to the lack of literature sources and dependency on economic and political factors.

3. Measure 3 – Transition from ore-based to scrap-based steel production

3.1 Steel resource efficiency measure

3.1.1 Description

This measure aims to substitute of iron ore with scrap steel in steel production.

Producing steel with scrap decreases demand for virgin iron resources and associated processing and emissions. The use of scrap also decreases the demand for coal to make coke and the associated energy demands for producing coke from coal.[44] Higher scrap use can be achieved by substituting iron ore in BF-BOF production, although BF-BOF can only use roughly 25% scrap.[45] Alternatively, EAF capacity can be increased to increase scrap usage.

There are currently 11.3Mtpa of scrap steel arisings per year in the UK of which 2.6Mtpa are used as feedstock for steel production. The UK is a net scrap exporter – 8.7Mtpa is exported and less than 0.4Mtpa imported.[46]

3.1.2 Measure indicator

The indicator used for Measure 3 was **"% of scrap per tonne of crude steel for BF-BOF and EAF in UK steel production**" (excluding alloying elements).

Note that EAFs can already use up to 100% scrap and the indicator chosen would report a lower efficiency value if EAF capacity and total scrap use increased but there was also new use of additional non-scrap ferrous feedstocks such as H2-DRI sponge iron. An alternative indicator – of scrap tonnage – was discussed in the workshops but rejected because it does not represent resource efficiency gains from increasing scrap usage in BF-BOF nor provides the same comparison with the maximum scrap usage in EAF.

3.1.3 Examples in practice

Scrap is already widely recycled for steelmaking in the UK, with 2.6Mt of scrap used as a feedstock per year.[47] Scrap steel is used in both BF-BOF and EAF steelmaking.

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[44] Coke is produced by heating coal in the absence of oxygen to evaporate the volatile components in the coal. The gas produced through coke manufacturer is called coke oven gas and is a mixture of different chemicals.

[45] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[46] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[47] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

3.2 Available sources

3.2.1 Literature Review

The benefits of increasing scrap use in steelmaking are raised in four key general papers on resource efficiency in steelmaking[48, 49, 50] though some of the benefits are not applicable in the UK.[51] More general information on the UK steel sector and scrap use is covered in supporting industry reports[52, 53, 54, 55] and academic papers.[46] These sources cover the levels of scrap use in UK BF-BOF steelmaking but the same information for EAF steelmaking was only available from stakeholders.

The literature sources identified in the literature review were all produced within the last 10 years and included industry reports specifically related to the UK steel sector. As a result, the majority of the sources had an IAS of 5.

3.2.2 Workshops

The invitees to the workshops included a balance of industry experts and academics with participation from the EAF and scrap sectors but a lower level of participation from the UK BF-BOF sector.

There was general consensus on the volumes of scrap volumes used for UK steelmaking and on the current and potential levels of efficiency in scrap use in both EAF and BF-BOF, with stakeholders confirming evidence from the literature review. The substantial discussion on drivers and barriers for scrap use, particularly in relation to contamination levels and characterisation of UK scrap. For example, whilst copper contamination of more than 0.1% is generally problematic, constructional steel such as rebar can tolerate copper levels of up to 0.4%. Automotive steel on the other hand is generally only up to 0.05% copper.

The level of engagement in both workshops was as follows:

- **Workshop 1** – 13 stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Seven stakeholders across industry and academia were active on the mural board and three stakeholders actively contributed to verbal discussion.

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[48] WSP and Parsons Brinckerhoff (2015). Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Iron and Steel

[49] International Energy Agency (IEA) (2020) Iron and Steel Technology roadmap: Towards more sustainable steelmaking

[50] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry: Technical Appendices

[51] Gonzalez, H.A., Paoli, L., Cullen, J. (2018). How resource-efficient is the global steel industry?

[52] Make UK UK Steel (2022). Key Statistics Guide April 2022.

[53] World Steel (2020). World Steel in Figures 2020

[54] UK Steel (2019). UK Steel Key Statistics Guide 2019

[55] World Steel (2021). Scrap use in the steel industry. Fact Sheet 2021.

3.3 Drivers & Barriers

3.3.1 Drivers

Drivers and barriers for increased use of scrap can both be grouped into two main categories: those related to a transition to EAF steelmaking where scrap use can be higher than in BF-BOF steelmaking, and those related to characterisation of UK scrap so that it can be used appropriately. In total, five drivers were identified and discussed in the workshops (see Table 9).

Table 9: Drivers for steel Measure 3

Driver	PESTLE	COM-B
Transition to EAF.	**Technological**	**Capability – physical**
Adding scrap to the blast furnace stage of BF-BOF steelmaking.	Technological	Capability – physical
The generally high quality of UK scrap.	Technological	Opportunity – physical
Valorisation of by-products such as zinc dust.	Economic	Opportunity – physical
Potential of Asian markets to supply greater scrap yields in the future.	Economic	Opportunity – physical

In terms of volumes, the domestic UK scrap market could meet significant growth in EAF capacity without requiring H2-DRI or additional imports. However, scrap composition is also important in particular applications to maintain levels of alloying elements and avoid impurities, particularly copper.

Participants in the first workshop commented on the high quality and value of the 11.3Mtpa scrap arising in the UK with, for example, 2Mtpa from the automotive industry[56] where copper concentrations are as low as 0.05%. However, in practice, scrap compositions may be unknown or not appropriate to the grades of steel being produced[57] and so lead to use of alternative feedstocks. A large-scale transition to EAF could increase demand for well-characterised scrap, raising prices and incentivising investment in scrap sorting infrastructure, which needs to be of certain scale to be cost-effective (See further detail in Barriers).

Participants confirmed that scrap could be reprocessed in the blast furnace stage of BF-BOF steelmaking with corresponding savings in ore, coke and associated emissions produced by a particular plant. One source estimates 150kg of scrap can be used to produce each tonne of hot metal in the blast furnace stage.[58]

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[56] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[57] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[58] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

The use of scrap leads to by-products such as zinc dusts which have potential commercial value, and this was also identified as a driver.

3.3.2 Barriers

The levels of contamination and of the characterisation of the UK scrap supply underlie barriers as they do drivers. Eight barriers were identified prior to the workshops, as well as the "lack of support of and investment into the UK scrap steel market" which was initially framed as a driver (see Table 10). The use of scrap depends on availability. The specific barriers in the table are set within a general context where the UK has access to international markets with availability at particular price point dependent on global supply. In addition, the combination of barriers may contribute to a general perception of low UK scrap quality.

Table 10: Barriers for steel Measure 3

Barrier	PESTLE	COM-B
Lack of support of and investment into the UK scrap steel market.	**Economic**	**Opportunity – physical**
Technical limits meaning traditional blast furnaces can only use 25% scrap material.	**Technological**	**Capability – physical**
Certain contaminants are costly to remove and volumes may not justify investment.	**Technological**	**Capability – physical**
Downcycling of high-grade scrap needs to be avoided.	**Technological**	**Opportunity – physical**
Increased costs of sorting and managing scrap.	**Economic**	**Capability – physical**
Information on scrap steel characteristics is lacking.	Technological	Capability – psychological
Global limits on scrap availability not able to meet steel demand	Technological	Capability – physical
Scrap sorting services need improvement to provide the right scrap to the right producers.	Economic	Capability – physical
Price of high-quality scrap	Economic	Capability – physical
Increasing the use of scrap in UK steel production will not significantly increase global resource efficiency or improve global emissions	Political	Motivation – Reflective
Perception that steel produced using scrap is of worse quality	Political	Capability – psychological

The highest voted barrier was "lack of support of and investment into the UK scrap steel market" and reflects the similar driver above for providing well-characterised supply in sufficient quantity, noting the UK is a scrap exporter with sources including high quality, low contaminant volumes from the automotive industry.[59]

The limited information on scrap composition was identified in the literature review and also highlighted during workshops as causing inefficiencies for subsequent use (as reprocessed steel). The current organisation and infrastructure of scrap suppliers and steel manufacturers may not lead to appropriate feedstock quality for producers. This can lead to potential 'downcycling', with the example of high-quality scrap from the automotive industry being mixed with lower quality scrap leading to a reduction both in the number of times it can be recycled and in the range of potential applications.

A key literature source identified that improvements to scrap sorting could improve the characterisation of the UK scrap supply and improve the business alignment between manufacturers and scrap suppliers.[60] The UK scrap sorting standards currently focus on size and source of scrap, but the inclusion of chemical composition information would enable manufacturers to find more appropriate scrap. Additionally, improvements to the scrap sorting technology would improve quality control of scrap which currently relies heavily on visual inspection of scrap and occasional X-ray fluorescence analysis.[61]

As well as improving sorting standards and technologies, stakeholders commented that investment into scrap sorting and management infrastructure is required. Participants suggested that potentially huge amount of investment is required to improve the supply of quality scrap in the UK. As well as the financial barriers associated with developing shredding and sorting sites, participants raised difficulties with obtaining permits as well as finding suitable locations for the sites. Ideally, these facilities need to be both near locations where scrap arises (primarily population centres) and near to industrial areas with steel mills.

Stakeholders representing the scrap sector commented that financial incentives for improvements in sorting infrastructure are low and there is a low premium for high grade scrap. Participants did note that price trends are increasing and transition to EAF would lead to increased demand for higher grade scrap and so enable investment benefitting from economies of scale.

For BF-BOF production, only small increases are possible from current to maximum levels of efficiency due to practical and thermodynamic limits and this was identified as a barrier.

It was noted that scrap is part of an international market and increased UK domestic use may just lead to reduced use of scrap elsewhere with no overall global improvements in resource efficiency, barring the costs of transporting scrap. If only the UK is a concern, then increased domestic use is nevertheless a valid measure regardless of global patterns of use.

3.4 Levels of efficiency

Table 11: Levels of efficiency for steel Measure 3

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[59] Compañero, R.J., Feldmann, A. & Tilliander, A. (2021). Circular Steel: How Information and Actor Incentives Impact the Recyclability of Scrap

[60] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[61] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

Indicator: % of scrap per tonne of crude steel for BF-BOF and EAF in the UK steel production			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	BF-BOF: 20% EAF: 100%	BF-BOF: 25% EAF: 100%	BF-BOF: 20% EAF: 100%
Evidence RAG	Green	Amber-Green	Amber-Green

3.4.1 Current level of efficiency

The current levels of efficiency of roughly 20% scrap use in UK BF-BOF production were obtained from two literature sources, each with an IAS of 5[62, 63], and were confirmed by voting of participants in the first workshop. BF-BOF production accounts for 5.9Mtpa of steel out of the 2021 total of 7.2Mtpa [64].

The sources in the literature review suggested but did not explicitly state that UK EAFs used 100% scrap[65, 66] but this was explicitly confirmed by stakeholders (percentage excluding alloys). The combination of quality evidence from the literature review and confirmation by the stakeholders including EAF steel manufacturers means the evidence level is assessed as RAG rating green.

3.4.2 Maximum level of efficiency in 2035

BF-BOF Process

For BF-BOF steelmaking the maximum technical level of efficiency for scrap usage was indicated as 25% in literature sources[67, 68] and is specifically referenced in relation to the UK.[69] When this value of 25% was presented to the stakeholders during workshop 1, the voting was generally split between “level of efficiency is about right” and “level of efficiency should be higher”. In discussion, some participants also estimated 25% but others suggested a higher level of 30% with reference to experience on modern BF-BOF production sites. One stakeholder also suggested a maximum level of efficiency of 30-40% could be achieved with investment. A level of 25% reflected a majority view from both participants and the literature, while a level of 30% would require new modern, advanced BF-BOF sites, which according to stakeholder feedback, are unlikely to be constructed in the UK by 2035.

EAF Process

For EAF steelmaking, the current level of efficiency, as agreed by stakeholders, is already at the maximum technical level of efficiency which is 100% (all facilities use scrap). Aside from

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[62] Sandbag Climate Campaign ASBL (2022). Starting from scrap. The key role of circular steel in meeting climate goals

[63] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[64] Make UK UK Steel (2022). Key Statistics Guide April 2022.

[65] Sandbag Climate Campaign ASBL (2022). Starting from scrap. The key role of circular steel in meeting climate goals

[66] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[67] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[68] World Steel (2021). Scrap use in the steel industry. Fact Sheet 2021.

[69] UK Parliament (2022). Green steel post note

the other barriers, a further constraint on the number of new facilities due to scrap availability is not expected given the access the UK has to significant scrap markets and full use of scrap would continue (100%). This would however require the barriers associated with the UK scrap market identified to be overcome. The combination of quality evidence from the literature review and confirmation by the stakeholders means this has an evidence level of “green”. However, there was some variation in the participants voting for BF-BOF with some participants indicating the maximum level of efficiency could be higher than 20% As a result the overall evidence RAG rating for this is amber-green.

3.4.3 Business-as-usual in 2035

Discussion of the business-as-usual scenario covered the topics of the transition to EAF, characterisation of UK scrap and the maximum technical efficiencies for scrap in BF-BOF and EAF. Concerns were raised that while EAF can technically use 100% scrap as feedstock, the need for a particular chemical composition in the final product may mean that scrap may constitute as little as 50% of the feedstock and require supplementary inputs from DRI or pig iron and other iron sources. In the UK, EAF production is focused on rebar and other uses that can accommodate higher levels of contamination and can so use 100% scrap as feedstock.

Voting on the business-as-usual scenario was based on the assumptions of no interventions to change the characterisation levels in the UK scrap supply chain and no large scale-transition to EAF production (giving uncertainty surrounding this area). As a result, the voting on the BAU scenario generally matched the current levels of scrap use for EAF and BF-BOF with one vote for BF-BOF BAU efficiency of over 30%.

As with the voting, the evidence level for this follows the maximum efficiency evidence level with a high level of evidence for EAF, but some variation in participant voting on BF-BOF. As a result, the overall evidence RAG rating is amber-green.

4. Measure 4 – Transition from basic oxygen furnace to electric arc furnace steelmaking

4.1 Steel resource efficiency measure

4.1.1 Description

There are two primary methods of steel production: BF-BOF and EAF. This measure aims to transition a greater proportion of UK steelmaking from BF-BOF to EAF.

As EAFs can use a greater proportion of scrap steel as feedstock than BF-BOF, a shift to greater use of EAF steelmaking would decrease demands for raw materials and increase steel resource efficiency, subject to global scrap availability. After scrap, electrical energy is the other major input and for sustainability is required to be ‘green electricity’, such as produced by wind and solar farms and hydro-electric facilities.

Production using EAF is already well established at several facilities in the UK which have an aggregate output of 1.3Mtpa (18%) of the national total of 7.2Mtpa in 2021.[70] However, this is below the UK EAF capacity of 2.5Mtpa, suggesting there is spare capacity for increased scrap use.[71]

Despite the resource efficiency benefits resulting from greater scrap use, as well as the greenhouse gas emission reductions, there are significant practical, financial and logistical barriers to implementing a large-scale transition to EAF production.

4.1.2 Measure indicator

An indicator of “**% of UK crude steel produced using EAF**” was chosen for this measure. “Crude steel” was specified to differentiate it from final steel products. A percentage figure for the proportion of steel produced via EAF was chosen instead of a tonnage indicator to avoid dependency on temporal fluctuations in statistics on total UK steel production and to focus on transition from BF-BOF to EAF and not solely on increasing EAF capacity.

4.1.3 Examples in practice

Alongside BF-BOF, EAF steelmaking is one of the two main steelmaking pathways. EAF steelmaking is used across the world and has been employed in the UK for over 100 years.

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[70] Make UK UK Steel (2022). Key Statistics Guide April 2022.

[71] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

4.2 Available sources

4.2.1 Literature Review

As one of the major steelmaking methods, EAF steelmaking was discussed to some extent in the majority of the papers identified in the literature review, including five key papers relating to the UK specifically.[72, 73, 74, 75, 76] Others covered the benefits of using scrap[77, 78, 79, 80] and the contribution of this to reducing greenhouse gases.[81, 82] The number of papers provides an appreciable body of evidence and the majority have IAS scores of 4 or 5. This provided a solid evidence base for the workshop discussion on the levels of efficiency and the barriers and drivers.

4.2.2 Workshops

This measure has appreciable interdependencies with other measures and is likely to affect all aspects of the UK steel sector. As such it was the most extensively discussed measure at the workshops. Along with the many contributions made by academic and industry experts, an EAF steel manufacturer was able to give specific insight regarding the industry in the UK.

Participants generally agreed on the advantages of transition to EAF although some suggested EAF transition should be the first step in a larger transition to green hydrogen steelmaking. The discussion mainly focused on the drivers and barriers to a large-scale transition to EAF including feasibility and timeframes.

The level of engagement in both workshops was as follows:

- **Workshop 1** – 13 stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.
- **Workshop 2** – 8 stakeholders across industry and academia were active on the mural board and three stakeholders actively contributed to verbal discussion.

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[72] Green Steel for Europe. (2021) Technology Assessment and Roadmapping

[73] Colla, V., Branca, T. A. (2020) "Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"

[74] Peters, K.; Malfa, E.; Colla, V.; Brimacombe, L. (2015). Resource efficiency in the Strategic Research Agenda of the European Steel Technology Platform

[75] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

[76] Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A. (2020). Technology innovation system analysis of decarbonisation options in the EU steel industry

[77] Gonzalez, H.A., Paoli, L., Cullen, J. (2018). How resource-efficient is the global steel industry?

[78] Bhaskar, A., Assadi, M., & Somehsaraei, H. N (2021). Can methane pyrolysis based hydrogen production lead to the decarbonisation of iron and steel industry?

[79] Johansson, M.T. & Söderström, M. (2011). Options for the Swedish steel industry – Energy efficiency measures and fuel conversion.

[80] Van der Stel, J. et al (2013). Top gas recycling blast furnace developments for 'green' and sustainable ironmaking

[81] Dondi G, Mazzotta F, Lantieri C, Cuppi F, Vignali V, Sangiovanni C. (2021). Use of Steel Slag as an Alternative to Aggregate and Filler in Road Pavements.

[82] Colla, V., Branca, T. A. (2020) "Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"

4.3 Drivers & Barriers

4.3.1 Drivers

Five key drivers were presented for voting (see Table 12). The highest voted driver for this measure was “increasing pressure to reduce carbon emissions”. This related to both political pressure introduced through government policy as well as consumer pressure from steel users that are increasingly demanding low carbon materials. Key literature sources cite the lower emissions from EAF as underpinning a pathway to the decarbonisation of the UK steel sector.[83, 84, 85]

Table 12: Drivers for steel Measure 4

Driver	PESTLE	COM-B
Increasing pressure to reduce emissions	**Political** **Social**	**Motivation – Reflective**
Improvements to the contamination levels and monitoring of scrap quality	Technological	Capability – physical
By-product valorisation	Economic	Capability – physical
Rising price of carbon	Economic	Opportunity – physical
Investment in hydrogen DRI technology	Technological	Opportunity – physical

The increased political and consumer pressure to reduce emissions is separately identified and also reflected in rising price of carbon. Participants identified rising cost of carbon as a driver of EAF production, which was supported by the literature review which noted the cost of carbon can be a driver for decarbonisation and create financial incentives to reduce emissions.[86]

As discussed under Measure 3, scrap is expected to be available from markets accessible to the UK, with the availability of grades dependent on price.

For the energy required, participants commented that access to renewable energy sources, particularly lower-cost offshore wind could provide a competitive advantage for the UK steel producers, while literature also highlights the importance of low carbon energy sources to fully realise the emissions benefits of EAF.[87, 88]

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[83] WSP and Parsons Brinckerhoff (2015). Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Iron and Steel.

[84] International Energy Agency (IEA) (2020) Iron and Steel Technology roadmap: Towards more sustainable steelmaking

[85] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry

[86] WSP and Parsons Brinckerhoff (2015). Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Iron and Steel.

[87] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[88] International Energy Agency (IEA) (2020) Iron and Steel Technology roadmap: Towards more sustainable steelmaking

As previously discussed for Measure 3, improvements to the characterisation of scrap are key for increasing the amount of high-quality steel that can be produced through EAF. Currently, UK EAFs produce rebar and constructional steel with tolerance to relatively high levels of contaminants such as copper (up to 0.4% as indicated by workshop participants). With a feedstock of higher quality scrap with low contaminants, EAFs produce correspondingly higher grades of steel and can substitute for more of the current BF-BOF production. EAFs have operational flexibility to also use sources such as sustainably sourced DRI.

The valorisation of by-products such as dusts were discussed in relation to Measure 4 drivers but did not receive any votes here. Investment in H2-DRI as a driver for a transition to EAF steelmaking was raised in the discussion but did not receive any votes.

4.3.2 Barriers

Six key barriers to a transition to EAF steelmaking were presented for voting (see Table 13).

Table 13: Barriers for steel Measure 4

Barrier	PESTLE	COM-B
High & volatile energy prices.	**Economic**	**Opportunity – physical**
Significant upfront costs & time to construct new EAF infrastructure.	**Economic**	**Opportunity – physical**
Continued development of a decarbonised electricity supply	Technological	Capability – physical
Potential relocation of jobs and industry.	Economic Political Social	Capability – psychological
Characterisation of scrap supply.	Technological	Opportunity – physical
Retraining of large numbers of staff.	Economic Political Social	Capability – psychological

The most significant barrier identified was the high prices and volatility within the energy market. The price of electricity is a key determining factor in the economic viability of EAF steelmaking, and uncertainty around future energy prices is a barrier to investment in EAF and associated infrastructure. A workshop participant identified that decisions for a national transition to EAF need to be made in the next 12-18 months, and these decisions are being impacted by the currently high energy prices. Economic and political influences on the UK energy market were raised as concerns affecting access to affordable electricity for EAF steelmaking.

The next most significant barrier was the upfront costs and time involved with building new EAF infrastructure. The literature review identified an indicative capital cost of £400m for constructing a 1Mtpa EAF at an existing steel production site which would scale to £3.6bn for replacing 9Mtpa of ore-based production in the UK.[89] However, estimates vary considerably

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[89] UK Steel (2022). Net Zero Steel. A vision for the future of UK steel production

according to the type of EAF. One EAF steel manufacturer in the workshop provided a potential timeframe for construction of a new EAF.

Delivery for a new EAF could take place by 2025 with supporting infrastructure developed in advance. Electricity use could then commence in 2026 and the EAF could be fully operational by 2027 suggesting a roughly 4-year timeframe for fully implementing a new EAF. Delay in EAF development results from the supply chain constraints of a limited number of EAF production companies globally and significant wait times for grid connections especially to renewable UK energy sources. There was also a concern that EAF could be at the “back of the queue” with regards to access to renewable energy markets.

The characterisation of the UK scrap supply was also identified as an important barrier, though it received fewer votes than the barriers described above. Whilst there was consensus that 100% of UK steel could theoretically be produced through EAF, improved scrap sorting and management and/or access to other supplementary feedstocks (e.g. from DRI), would be required. Global scrap supply is also limited and there were concerns that DRI sources would be needed, regardless of improvement in scrap quality, if EAF was used at this scale.

In both workshops, some participants commented that a transition to EAF is not sufficient on its own to transition the UK to net-zero steelmaking and should be better seen as a steppingstone towards green-hydrogen steelmaking involving technologies such as electrolysis or open slag furnaces. The availability of other technologies and pathways to low emissions steelmaking could also act as a barrier to EAF uptake. To counteract this, transition to EAF may need to be combined with other measures, such as hydrogen DRI steelmaking (Measure 2).

The impacts on jobs and the potential need to relocate or retrain staff was not discussed and did not receive any votes. Participants noted that preferential locations for new EAF sites may not coincide with existing steelmaking sites and may require new infrastructure and so create jobs away from existing locations.

Many participants reiterated that any large-scale transition to EAF production will require significant government intervention. This intervention would also need to be directed at the entire supply chain not just at constructing new EAF sites and would need investment in up and downstream processes.

4.4 Levels of efficiency

Table 14: Levels of efficiency for steel Measure 4

Indicator: percentage of UK crude steel produced using EAF			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	18%	100%	N/A
Evidence RAG	Green	Amber	N/A

4.4.1 Current level of efficiency

The current level of efficiency of 18% is reported in Make UK statistics (2022)[90] which indicate that 1.3Mt of steel was produced in 2021 in the UK by EAF out of a total of 7.2Mt. The voting by participants reinforced confidence in the 18% estimate with most assessing the "level of efficiency about right".

A Warwick University source gave the 2018 efficiency level as 22% with 1.6Mt out of a total of 7.3MT produced through EAF[91] Both these sources have IAS scores of 5 but the most recent source with the 18% efficiency level was chosen for the current level of efficiency. As the 18% figure is supported by a recent literature source and confirmed by the stakeholders it has a green evidence level.

4.4.2 Maximum level of efficiency in 2035

There was consensus in the workshops that 100% of steel could theoretically be produced through EAF as participants confirmed that EAF steelmaking is able to produce the same grades of steel and steel products as BF-BOF, subject to feedstock characteristics and furnace features. However, the size of the UK supply of well-characterised scrap may require supplementing if EAF is to substitute for all steel produced from BF-BOF. In reality the maximum feasible level of efficiency may be lower than 100% with some workshop participants citing figures between 60% and 80%. As a result, this has an amber RAG rating.

4.4.3 Business-as-usual in 2035

There was no voting on a business-as-usual scenario for this measure, as the BAU scenario for the transition to EAF steelmaking is influenced by a huge range of factors, many of which fall outside the scope of resource efficiency considerations. For this reason, it was decided that the BAU level of efficiency for this measure could not be estimated as part of this research.

Instead of exploring a 2035 business-as-usual scenario, the discussion addressed the determinants of the timescales for transition. Blast furnaces typically need their internal refractory lining replaced every 25 years[92]. It was generally suggested that the UK is unlikely to either construct new blast furnaces or reline existing ones, with the unavoidability of relining informing the timeline for transition. The blast furnaces in Scunthorpe and Port Talbot need relining before 2035. As discussed in the barriers section an approximate 4-year timeframe was indicated by a participant for development of a new EAF site. A large-scale transition to EAF will require the construction of multiple facilities, potentially competing for production resources and infrastructure connections. Other participants stated that by 2035 it is unlikely that 100% of production could be transitioned to EAF and it is likely that high energy prices in the UK will mean BF-BOF will continue to compete with EAF for 15+ years.

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[90] Make UK UK Steel (2022). Key Statistics Guide April 2022.

[91] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[92] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

4.5 Other insights

The possible development of BF-EAF hybrid plants was also raised as an option.[93] Hybrid plants would produce pig iron using a traditional blast furnace which would then supply the EAF and allow a more gradual transition. Retaining blast furnaces would mitigate financial effects from these otherwise potentially stranded assets and reduce the economic, social and political impacts associated with closing basic oxygen steelmaking sites.

Emerging steelmaking technologies such as molten oxide electrolysis were also discussed as alternatives to EAF, or to be implemented alongside EAF as pathways to low emissions steelmaking. Although these technologies have demonstrated potential, they currently have a low technology readiness level (TRL) and may not be feasible especially considering a 2035 timeframe.[94] [95]

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[93] Note that the term “hybrid” used here differs from “hybrid” used elsewhere in literature sources to refer to combined use of hydrogen and/or DRI technologies.

[94] Green Steel for Europe. (2021) Technology Assessment and Roadmapping

[95] Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A. (2020). Technology innovation system analysis of decarbonisation options in the EU steel industry

5. Measure 5 – Recovery and utilisation of process off-gases

5.1 Steel resource efficiency measure

5.1.1 Description

This measure aims to recover gasses produced during steelmaking and reuse them in the steelmaking process to reduce the demand for carbon reducing agents.

Gases arising from steelmaking processes can be recovered and reused. This reduces greenhouse gas emissions[96, 97] while decreasing the demand for coke (by recycling coke gas)[98]. During the blast furnace stage of BF-BOF steelmaking, hot gas rises to the top of the furnace where it can be recovered (“top gas”). The carbon dioxide and nitrogen can be separated from top gas, as well as from the waste gases from coke ovens used for converting coal to coke, to leave a gas rich in hydrogen and carbon monoxide. This gas can be reinjected to the furnace as a reducing agent for the iron ore. The greenhouse gas emissions are reduced from the lower demand for coke as well as from the potential to capture CO_2 from the top gas.

At a 90% top gas recycling ratio the carbon input requirements for a blast furnace can be reduced from 470kg to 350kg per tonne of hot metal (thm) giving a 25% carbon saving[99]. This reduction in carbon inputs was observed in the Ultra-Low CO_2 Steelmaking (ULCOS) experimental blast furnace program[100] .

Gases can also be recovered and used as an energy source however this report only refers to the material resource efficiency savings that result from recovery and reuse of process gasses in the steelmaking process to reduce the demand for carbon based reducing agents. Energy recovery applications of process gas recovery are not included, and neither are carbon capture, usage and storage (CCUS) applications, as they do not meet the definition of resource efficiency for this project.

5.1.2 Measure indicator

An indicator of “**% reduction in carbon inputs used in steel making**” has been chosen for this measure. A second indicator of “**% reduction in carbon emissions**” was also presented at the workshops but has since been removed, as carbon inputs are already directly correlated with carbon emissions and can be used as a proxy.

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[96] Colla, V., Branca, T. A. (2020) "Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"

[97] Peters, K.; Malfa, E.; Colla, V.; Brimacombe, L. (2015). Resource efficiency in the Strategic Research Agenda of the European Steel Technology Platform

[98] Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A (2020). Technology innovation system analysis of decarbonisation options in the EU steel industry

[99] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

[100] Van der Stel, J. et al (2013). Top gas recycling blast furnace developments for ‘green’ and sustainable ironmaking

5.1.3 Examples in practice

This measure is already widely practiced within BF-BOF steelmaking in the UK. The ULCOS experimental blast furnace program explores different methods of recycling steelmaking process gases.

5.2 Available sources

5.2.1 Literature Review

Four academic papers and industry reports address gas recovery technologies but with a focus mainly on energy recovery measures [101, 102, 103, 104]. Six papers specifically discuss the recycling of process gasses to act as a reducing agent in the furnace [105, 106, 107, 108, 109, 110] and most were papers from the last 10 years relating to steel production either in the UK or in Europe. As a result, all the sources used to inform this measure have IAS of 4 or 5.

A key source was the reporting by the European Commission of their Ultra-Low CO_2 steelmaking project and experimental blast furnace (ULCOS). It covers trials and prototypes of gas recycling technologies which improve the efficiency of BF-BOF steelmaking [111].

There was little literature relating to the application of gas recovery technologies to EAF steelmaking. It was suspected that this was due to the significantly smaller need for reducing agents for EAF steelmaking. Whether this measure was relevant at all to EAF steelmaking was not established from the literature review.

5.2.2 Workshops

Stakeholders included both academics and those involved in the steelmaking industry with specific knowledge of the technical aspects of gas recovery technologies in steelmaking. Participants confirmed that this measure was only relevant to BF-BOF steelmaking and also confirmed that recovery and reuse of process gases was already widely adopted in the UK.

During the workshop, participants engaged in extensive discussions of potential energy recovery technologies, including heat recovery and the use of process gases to generate

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[101] WSP and Parsons Brinckerhoff (2015). Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Iron and Steel

[102] Gonzalez, H.A., Paoli, L., Cullen, J. (2018). How resource-efficient is the global steel industry?

[103] Johansson, M.T. & Söderström, M. (2011). Options for the Swedish steel industry – Energy efficiency measures and fuel conversion

[104] Grubeša, I. N., Barišic, I., Fucic, A., & Bansode, S. S. (2016). Application of blast furnace slag in civil engineering.

[105] German Environment Agency (2021). Sustainable resource use in the health care sector – exploiting synergies between the policy fields of resource conservation and health care

[106] Van Straten, B.; Dankelman, J.; Van der Eijk, A.; Horeman, T. (2021). A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste

[107] Outokumpu. Six key facts about stainless steel in commercial kitchens

[108] Schoeman, Y., Oberholster, P., Somerset, V. (2021). A decision-support framework for industrial waste management in the iron and steel industry: A case study in Southern Africa.

[109] Williams, R., Jack, C., Gamboa, D., & Shackley, S. (2021). Decarbonising steel production using CO_2 Capture and Storage (CCS): Results of focus group discussions in a Welsh steel-making community.

[110] Yeung, J. (2016). Development of analysis tools for the facilitation of increased structural steel reuse.

[111] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

electricity. Participants also discussed the commercial and environmental value of CCUS as it may affect UK steelmaking. Detail of these discussions have not been included in this report as their scope does not meet the definition of resource efficiency.

The level of engagement in both workshops was as follows:

- **Workshop 1** – Nine stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Seven stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.

5.3 Drivers & Barriers

5.3.1 Drivers

One key driver was identified for this measure and is presented in Table 15.

Table 15: Drivers for steel Measure 5

Driver	PESTLE	COM-B
Emissions reduction polices and drivers	Political Social	Motivation – Reflective

There was an indication that off-gasses[112] are generally used as a substitute for natural gas in furnaces with the price of natural gas a key driver of investment. However, as UK furnaces already employ this technology it would not be a driver for increased recycling but for the continuation of current practice.

5.3.2 Barriers

Table 16: Barriers for steel Measure 5

Barrier	PESTLE	COM-B
Upfront financial costs of implementing technologies	Economic	Opportunity - physical
Already widely used in UK BF-BOF steelmaking	Technological	Opportunity - physical
Not relevant to EAF steel production	Technological	Opportunity - physical

Three barriers against increasing the recovery and utilisation of process gasses are presented in Table 16 but did not receive any votes in the workshop. During the workshops, one participant from the EAF sector was asked whether there was potential to use gas recycling technologies and confirmed that it was not relevant to EAF. As a result, any potential transition to EAFs was identified as a barrier as the technology is only relevant to BF-BOF steelmaking.

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[112] Off gasses are gaseous by-products of industrial processes or gasses given off during manufacturing

Furthermore, the potential of a future transition to EAF steelmaking could disincentivise investment in new gas recycling technologies which are only relevant to BF-BOF steelmaking.

Another barrier to the increased adoption of gas recycling technologies is the fact that the technology is already widely deployed in the UK. While it may be an important resource efficiency measure globally, participants confirmed that the technology is common practice in UK steelmaking and likely not a relevant resource efficiency measure for the UK steel sector.

5.4 Levels of efficiency

Table 17: Levels of efficiency for steel Measure 5

Indicator: % reduction in carbon inputs used in steel making			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	N/A	N/A	N/A
Evidence RAG	Red	Red	Red

5.4.1 Current level of efficiency

The baseline for the current level of efficiency is steelmaking technology without recovery and utilisation of process off-gases.

The current levels of efficiency were mainly informed by the ULCOS experimental blast furnace project which has extensive information on top gas recovery technologies.[113] Whilst it is from an authoritative source (the European Commission), the reference document is from almost 10 years ago (2014) and does not cover recent advances in technology.

For voting on the current level of efficiency, most participants indicated “don’t know”, with some indicating that the 25% reduction in carbon inputs figure from the ULCOS project[114] seems correct and one participant suggesting a 10-14% figure. The annotated voting of participants reflected their opinion that the level of efficiency is potentially much higher if the effects of CCUS and energy/heat recovery are included. While the ULCOS source is authoritative, it is almost 10 years old, and it appears that gas recovery technologies are more widespread now. Due to the age of the source and the lack of consensus among workshop participants, it was not possible to reach a consensus on the current level of efficiency for this measure. As such the level of efficiency is presented as N/A, with a red evidence RAG rating.

5.4.2 Maximum level of efficiency in 2035

In common with their responses on the current level of efficiency, most participants indicated they did not know what the maximum level of efficiency would be. Some included reference to CCUS and energy/heat recovery in their answers. Stakeholders indicated little scope to increase the implementation of this technology and there was no evidence in the literature to suggest that higher levels of efficiency for carbon input reductions were possible (unless CCUS

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[113] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

[114] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

and/or energy recovery are included). As such, the ULCOS figure of a 25% reduction in carbon inputs[115] could be used for the maximum level of efficiency. However, due to the lack of evidence from the literature and workshops, this level of efficiency is also presented as N/A as we could not conclude a value.

5.4.3 Business-as-usual in 2035

Along with consideration of the current and maximum level of efficiency, the discussion of the business-as-usual case often returned to energy recovery and CCUS measures that participants believed would be more valuable than the measure as defined solely for other aspects of resource efficiency. As a result, voting on the business-as-usual case was mainly "I don't know" with some votes for the same range as the current level of efficiency. Participants again indicated that the measure in its current scope is already at near full utilisation in UK steelmaking, and so it is unlikely to increase by 2035 under any scenario, including business-as-usual.

With the same range for the current, maximum and business-as-usual levels of efficiency, there is considered to be no potential for additional improvements from this resource efficiency measure in UK steelmaking. Instead of recycling process gasses to use as reductants, participants focused on the CCUS and energy recovery applications for these gases. Participants indicated that these applications would represent better uses of steel making process gases, however energy recovery and CCUS measures are not in scope for this project. Again, the lack of evidence from the literature and workshops means this level of efficiency is presented as N/A, with an evidence RAG rating of red.

There was limited evidence to support conclusions for this measure. More research would be beneficial to understanding the current uptake of this measure and any potential for resource efficiency savings.

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[115] European Comission (2014). ULCOS Top Gas Recycling Blast Furnace Process

6. Measure 6 – Recovery and use of steelmaking by-product materials

6.1 Steel resource efficiency measure

6.1.1 Description

Steelmaking produces a variety of by-products. This measure aims to increase the recovery and use of these materials.

The recovery of steelmaking by-products (such as slag, sludge, scrap, dust, tar, process gases and benzol) is an important resource efficiency measure which can enable a circular model of reuse and reduce raw material use, energy use and waste generation from steel production.[116] On average, 1,000 kg (one tonne) of steel results in 400kg of by-products when produced via BF-BOF and 200kg of by-products when produced via EAF.[117] The specific consideration of process gases reused on site is covered under measure 5. This measure covers other uses, including links to offsite uses.

By-products and residual materials arising from steelmaking can be both re-introduced during steel manufacture through internal reuse and recycling within the production process, as well as used externally through synergies with other sectors.[118] As well as improving resource efficiency, some by-products can be valorised and provide economic benefits for steel manufacturers.

6.1.2 Measure indicator

An indicator of **“% of steelmaking by-products recovered and used**” was used for this measure as the aim was to identify the proportion of by-products that are reused instead of being treated as waste. A percentage indicator was used instead of a tonnage indicator to account for any variations in UK steel production.

6.1.3 Examples in practice

The diversity of steelmaking by-products means there is a wide range of recovery and reuse options.

Blast furnace slag can be used as a material substitute in cement and concrete manufacturing[119] and 46.8% of slag in Europe is used in this way[120]. The second most

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[116] Hernandez, A.G.; Paoli, L.; Cullen, J. M. (2017). Resource efficiency in steelmaking: energy and materials combined

[117] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

[118] Colla, V., Branca, T. A. (2020) "Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"

[119] Grubeša, I. N., Barišic, I., Fucic, A., & Bansode, S. S. (2016). Application of blast furnace slag in civil engineering.

[120] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

common use of slag is in road construction (29.8% of slag[121]) where it is used as an aggregate in asphalt[122]

Sludges and dusts can be recovered for their metal content (either iron or alloys) and either reused within the steelmaking process or sold commercially[123]

There is also significant potential for use of steelmaking by-products as feedstocks within the chemicals industry. Benzene, toluene and xylene from coke oven gas can be used in plastic production and naphthalene can be used to produce electrodes.[124]

There are also innovative new uses for by-products such as use of slag to protect and restore marine environments, the use of coke-making tar in medical applications, sulphur for agricultural fertilisers, and greenhouse gas removal via enhanced weathering [125, 126.]

6.2 Available sources

6.2.1 Literature Review

The literature review identified several papers which highlighted the importance of recovering and using steelmaking by-products to reduce waste and promote circular economy production methods. [127, 128] These sources were all from within the last 10 years and had an IAS of 4 or 5. The sources covered both reuse of by-products within the wider context of resource efficiency in the steel sector and specific examples of reuse methods. [129, 130]

There was good coverage in the literature of by-products such as slag, which have a long history of reuse as cement/concrete additives and in road construction, while there was less information on other by-products such as tar and sludge.

There was a gap in literature evidence regarding the current level of reuse in the UK. Despite a wide range of possible types of reuse, the extent of uptake in the UK was not clear.

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[121] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

[122] Dondi G, Mazzotta F, Lantieri C, Cuppi F, Vignali V, Sangiovanni C. (2021). Use of Steel Slag as an Alternative to Aggregate and Filler in Road Pavements.

[123] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

[124] World Steel Association (2021). Steel industry co-products fact sheet. Available online: https://worldsteel.org/wp-content/uploads/Fact-sheet-Steel-industry-co-products.pdf

[125] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

[126] The negative emission potential of alkaline materials | Nature Communications Available online: https://www.nature.com/articles/s41467-019-09475-5/

[127] Gonzalez, H.A., Paoli, L., Cullen, J. (2018). How resource-efficient is the global steel industry?

[128] Hernandez, A.G.; Paoli, L.; Cullen, J. M. (2017). Resource efficiency in steelmaking: energy and materials combined

[129] Hernandez, A.G.; Paoli, L.; Cullen, J. M. (2017). Resource efficiency in steelmaking: energy and materials combined

[130] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

6.2.2 Workshops

The workshops included participants with a good understanding of the potential reuse of steelmaking by-products, particularly slag. The manufacturers were also able to give insight into the by-products they currently recover and which they would consider recovering. There was potentially a gap in evidence for end uses of steelmaking by-products that were not in the steel sector as no participants were from the chemicals industry, roadmaking or cement manufacture.

The potential reuse of slag was also discussed in the cement workshops (Measure 1).

The level of engagement in both workshops was as follows:

- **Workshop 1** – 10 stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Six stakeholders across industry and academia were active on the mural board and four stakeholders actively contributed to verbal discussion.

6.3 Drivers & Barriers

6.3.1 Drivers

Table 18: Drivers for steel Measure 6

Driver	PESTLE	COM-B
Wide range of options for reuse of by-products.	Technological	Opportunity – physical
Emission reduction policies and drivers	Political Social	Motivation – Reflective

Two drivers were presented for voting (see Table 18) but did not receive any votes in the workshop. However, the diversity of by-products identified implies a wide range of potential reuse applications are available. For example, slag, the most abundant by-product has established uses in roadmaking and cement production but also has innovative applications in the restoration of marine environments. [131] Demand for low carbon cement was also mentioned in the workshop as increasing the demand for slag.

During discussion, participants identified the need to increase the value from recycling not just the volume. One participant noted that this measure was an example of more general industrial symbiosis where waste from one industry (i.e. steel) is used as raw material for another industry (e.g. chemicals). Another participant commented that disposal costs for waste materials could incentivise their recovery.

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[131] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

6.3.2 Barriers

Table 19: Barriers for steel Measure 6

Barriers	PESTLE	COM-B
Risk of hazardous materials in by-products.	**Technological**	**Capability – physical**
Current level of reuse is already high and, in some cases, imported to meet demand.	Economic	Current level of reuse is already high and, in some cases, imported to meet demand.
Lack of regulatory frameworks supporting reuse of by-products	Political Economic	Motivation – Reflective

The key barrier identified in the first workshop was many of the main by-products are already being recovered and reused at very high levels, limiting further increases. For example, slag is already widely recycled in the UK (and also imported) for use in cement and concrete manufacture and in road making. However, participants stated that there may be scope for improving the recovery rates for by-products such as sludges, dusts and contaminated materials.

Hazardous materials in by-products act as another potential barrier raised by participants. The degree to which this would hinder reuse is unclear, but participants commented that there would be challenges associated with reusing some contaminated dusts, sludges and other by-products.

The current lack of legislative frameworks incentivising the use of industrially co-generated by-products received can act as a barrier. Legislation could be introduced to support the use of steelmaking by-products and not discourage their use through stricter regulatory requirements than alternatives.[132]

One participant also identified that the cost of recovery could act as a barrier to increased reuse. This was also discussed in relation to drivers were participants raised that increasing value of recycled products was important to incentivise recovery and reuse.

6.4 Levels of efficiency

Table 20: Levels of efficiency for steel Measure 6

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[132] World Steel Association (2020). Steel industry co-products. Available online: https://worldsteel.org/publications/policy-papers/co-product-position-paper/

Indicator: % of steelmaking by-products recovered and used			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	95 – 100%	95 – 100%	95 – 100%
Evidence RAG	Red-Amber	Amber	Amber

6.4.1 Current level of efficiency

During the workshops it became clear that the level of reuse varied considerably for the different by-products being considered and there was no overall opinion on the combined level of recovery and reuse across all by-products (e.g. including dusts, sludges and tar). Participants also highlighted that efficiency levels may differ between BF-BOF and EAF due to the production method and the fact that the two methods produce different by-products. BF-BOF slag is recycled at close to 100% but sludges and dusts may be lower. For EAFs one participant indicated in the pre-workshop survey that EAFs are currently about 95% efficient, and another commented in the workshops that EAFs are around 99% efficient.

A range of 95-100% has therefore been chosen as the current level of efficiency with red-amber evidence RAG rating, due to the lack of literature sources.

6.4.2 Maximum level of efficiency in 2035

There was consensus that there was limited potential to increase by-product use which would lead only to “marginal gains” because of the existing high levels of use and, for sludges, dusts and tar, the barrier of potential hazardous materials. As a result, the maximum level of efficiency remains 95-100% with an amber evidence RAG rating due to the lack of literature sources.

Participants again highlighted the potential emphasis required on maximising the best environmental and economic destinations for by-products, not increasing the rates of reuse. Whilst this would not technically improve resource efficiency, it could produce greater overall environmental and commercial benefits.

6.4.3 Business-as-usual in 2035

There was consensus in the voting for the business-as-usual by 2035 that the level of efficiency would be 95-100%, the same as the current level of efficiency based on high existing levels of reuse and minimal scope for improvement. For similar reasons to the maximum level of efficiency, the evidence RAG rating is amber.

This measure shows the same ranges for the current, maximum and business-as-usual levels of efficiency, suggesting that there is limited opportunity for additional improvement.

7. Measure 7 – Light-weighting and use of higher grades of steel in consumer products

7.1 Steel resource efficiency measure

7.1.1 Description

The light-weighting of steel-based products can be achieved in two ways: through decreased use of steel, and through the use of higher-grade steel in product manufacturing.

This measure identifies resource efficiency savings which reduce the nation's overall stock of steel in use, while maintaining the same level of function. The changes may be identified at societal and more detailed levels. Particular engineering-driven incentives are based on better design to reduce the steel in individual products and are generically called 'light-weighting'. Better design includes incentives which enhance useful product lives and use of different materials.

Light-weighting through reducing the use of steel

Light-weighting can be applied across a wide range of sectors and products. A main application is in the construction industry which makes up 60% of the UK demand for finished steel[133]. Significant steel volumes are also used in the automotive, oil and gas, packaging, yellow goods, rail, general engineering and machinery sectors. One example of light-weighting in the packaging industry is thinning the tinplate of steel cans without diminishing the product lifecycle or effective strength.[134]

Light-weighting through the use of higher grades of steel

Use of higher-grade steel can make components more durable which extends product lifetimes and reduces lifecycle resource use and carbon emissions.[135, 136] Light-weighting approaches based on higher-grade materials have a wide range of applications (such as commercial kitchens).[137]

These two methods can potentially be applied simultaneously, with the higher grade of steel allowing the weight to be reduced. The steel packaging industry, for example, has increased the steel grades available in order to enable a market in material which results in lighter steel cans.[138]

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[133] Department for Business Energy and Industrial Strategy (2017). Future Capacities and Capabilities of the UK Steel Industry: Technical Appendices.

[134] Apeal (n.d.). Steel for packaging, designed for efficiency

[135] The European Steel Association (Eurofer) (2015). Steel and the Circular Economy

[136] Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W-Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts

[137] Outokumpu. Six key facts about stainless steel in commercial kitchens

[138] Frauman, E. & Hatscher, N. (2011). Enhanced Resource Efficiency with Packaging Steel

7.2.2 Measure indicator

The indicator for Measure 7 is the "**% of reduction in weight of consumer product**". This indicator aligns with quantitative data on light-weighting in steel-based products, such as vehicles and constructional steel which makes up 67% of finished steel demand.[139] Other economic sectors with products containing significant steel include oil and gas (4% finished steel demand), machinery and engineering (6% finished steel demand), packaging (5% finished steel demand), yellow goods and rail (2% finished steel demand each).[140]

During the workshops, it was suggested that the indicator be based on absolute rather than relative mass of a product given the current market tendency towards larger products (such as SUVs).[141] However, this indicator was inappropriate for the purpose of this study as it would require different indicators for each product type.

7.3.3 Examples in practice

The most prominent examples of steel light-weighting involve the vehicles and construction sectors, and examples of these can be found in the respective sector reports. Other examples of light-weighting have been applied to steel-based products and structures such as packaging, containers, commercial kitchens, machinery as well as medical instruments and tools. Light-weighting methods for such products usually involve a reduction of steel thickness in the manufacturing of their components.[142] Another enabling practice that can facilitate more significant weight reductions is materials selection.

During workshops, it was mentioned that steel products have seen a high level of development during the past 25 years, especially in comparison to other alloy classes. One participant added that steel light-weighting allows recycling methods that cannot be used for alternatives such as composites and artificial intelligence and, in comparison, is better for affordability and circularity and opportunities in the near future.

7.2 Available sources

7.2.1 Literature Review

The literature review for Measure 7 identified that main sources of examples of steel light-weighting are the construction and vehicles sectors, which are covered in separate reports, but there is also increasing literature on steel packaging.

Two academic reports (with IAS of 5) cover the overarching resource (and energy) efficiency of the global steel sector[143] and opportunities for steel packaging.[144] Industry sources included

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[139] UK Government (2017). Future capacities and capabilities of the UK steel industry: technical appendices (Exhibit 32).

[140] UK Government (2017). Future capacities and capabilities of the UK steel industry: technical appendices (Exhibit 32).

[141] Sports Utility Vehicle, a type of large private car.

[142] Apeal (n.d.). Steel for packaging, designed for efficiency

[143] Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W-Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts

[144] Frauman, E. & Hatscher, N. (2011). Enhanced Resource Efficiency with Packaging Steel

website articles from manufacturing leaders and other steel experts representing organisations including Outokumpu,[145] Eurofer,[146] The World Steel Association,[147] and Apeal.[148]

A particular challenge was the identification of quantitative data to represent the level of resource efficiency that could be achieved through this measure, while not drawing on the more evident sources from the structural steel and vehicles sectors.

7.2.2 Workshops

Verbal discussions during the review of Measure 7 were minimal, although numerous comments were contributed through other workshop functions, such as interactive boards, as well as via surveys prior to the workshops. Multiple stakeholders identified their lack of knowledge of this area, which was justified due to most stakeholders being primary and secondary steel manufacturing experts. Some academics expressed their views on light-weighting for steel but raised their concerns with regards to the level of resource efficiency that could be achieved.

Representatives of the vehicles and construction industries attended the respective workshops of each sector and provided further insight on the equivalent light-weighting measures. These are, for vehicles, Measures 1 and 2 and, for construction, Measure 4.

The level of engagement in both workshops was as follows:

- **Workshop 1** – Nine stakeholders across industry and academia were active on the mural board and three stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Six stakeholders across industry and academia were active on the mural board and one stakeholder actively contributed to verbal discussion.

7.3 Drivers & Barriers

The drivers and barriers associated with Measure 7 were identified from stakeholder feedback as no relevant material was identified during the literature review. The drivers and barriers are listed in Table 21 and Table 22 respectively, including their PESTLE and COM-B categorisation. The most significant drivers and barriers for Measure 7 were decided by stakeholders through voting during the workshops, and these are displayed in bold.

7.3.1 Drivers

Table 21: Drivers for steel Measure 7

Driver	PESTLE	COM-B
New design technologies like artificial intelligence could increase light-weighting, although there is a physical limit to this strategy.	Technological	Capability – physical

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[145] Outokumpu. Six key facts about stainless steel in commercial kitchens
[146] The European Steel Association (Eurofer) (2015). Steel and the Circular Economy
[147] World Steel Association (n.d.). Steel packaging
[148] Apeal (n.d.). Steel for packaging, designed for efficiency

Driver	PESTLE	COM-B
Scope 3 emissions reporting will enable a decrease in embodied carbon.	Environmental	Motivation – reflective
Potential cost savings.	Economic	Motivation – reflective

During the workshops, participants agreed that more significant weight reductions could generally be achieved through improved design configuration and selection of materials, rather than via the optimisation of a single component or grade.

While the following example regards use of structural steel, the general point applies in other sectors. By considering the combined overall use and configuration of the building structure, there is a much higher resource efficiency saving compared to isolated instances of light-weighting in structural steel (e.g. for a single beam) and this consideration also extends to the use of other substitute materials. The reduced weight achieved from using high grade steels may lead to cost savings compared to conventional steels both for in regard to materials used and the time required for finishing and assembly processes.[149]

One participant suggested that this measure depends greatly on the introduction of financial and policy incentives. These would encourage change in the current manufacturing methods and promote weight reductions. Two stakeholders also mentioned that an additional driver is the decrease in embodied carbon that can be achieved through light-weighting and this would become visible through the reporting of Scope 3 greenhouse gas emissions. The impact of this on light-weighting, however, depends on where the scope 3 reporting occurs in the supply chain. This could be on steel production or on steel-based products. Equally important for individual firms is the exact scope of the reporting, which could be of upstream, downstream, or of both upstream and downstream activities. For example, additional reporting of primary and secondary steelmaking would have a more limited impact than additional reporting on uses of steel in manufactured products.

7.3.2 Barriers

Table 22: Barriers for steel Measure 7

Barrier	PESTLE	COM-B
Lack of financial incentives for changing current manufacturing methods.	Economic	Opportunity – social
Corrosion may limit the level of light-weighting that can be implemented through use of high-strength steel.	Economic	Opportunity – social
The light-weighting process can impact the durability, lifespan and recycling potential of the product.	Technological	Capability – physical

Participants considered that implementation of Measure 7 depends on financial and policy incentives. In studies of light-weighting of construction beams mentioned by a participant, a 20% to 30% reduction in steel was achieved but at an unaffordable cost. This implies that the

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[149] ArcellorMittal (2020). HISTAR® Innovative high strength steels for economical steel structure

cost of labour and of the manufacturing process required to apply this level of light-weighting is significant and could outweigh the material savings. Greater financial challenges may also exist in a scenario where higher steel grades are used to contribute to weight reductions as this may also increase costs.

Another barrier raised by stakeholders is that it is not always clear that light-weighting leads to emissions reductions. It was observed that some light-weighting in the automotive sector has not decreased the weight of a vehicle nor are there resulting emission reductions. It was suggested that light-weighting strategies are effective at reducing the quantity of steel required for a given shape in the final vehicle, but they do not always reduce the total demand for steel compared to the previous version of the vehicle if the shape itself is larger. For instance, cars have recently shown a trend towards larger designs and so demand for steel per car is growing rather than shrinking. Light-weighting technologies are slowing this trend, but not reversing it, according to the stakeholder. This highlights the importance of a link with the overall stock of steel for overall resource efficiency savings to be achieved.

Another challenge mentioned was the increasing susceptibility to corrosion of a light-weighted material due to reductions in thickness and volume which may affect durability, lifespan and the recycling potential. Also, light-weighting involving alloys such as aluminium may detrimentally affect steel scrap, with research showing aluminium content affecting ductility and brittleness[150], though potentially mitigatable.

A final barrier mentioned by stakeholders was that the reduced use of steel in consumer products is currently very hard to track.

7.4 Levels of efficiency

Table 23: Levels of efficiency for steel Measure 7

Indicator: % of reduction in weight of consumer product			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Value	0%	10 – 40%	0 – 30%
Evidence RAG	N/A	Red - Amber	Red

The level of efficiency possible from light-weighting depends on multiple factors, including the type of product and the level and type of light-weighting (design/quality). Evidence is mainly from the vehicle and structural steel applications with some further examples from packaging. Some of these may provide proxies for applications in other industries within a general context of significant uncertainty for potential overall savings.

7.4.1 Current level of efficiency

The current level of efficiency (0%) has been set as the baseline for the reductions.

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[150] Czerwinski, F. (2021). Current Trends in Automotive Lightweighting Strategies and Materials.

7.4.2 Maximum level of efficiency in 2035

Examples of literature covering light-weighting includes vehicles (11% weight saving)[151] and constructional steel (no weight estimate but 20-30% savings in carbon emissions)[152]. No quantitative forecasts for 2035 were identified. Our research in the vehicles sector (outlined in the Unlocking Resource Efficiency Vehicles Report) has identified a 20% to 35% maximum reduction in average vehicle weight through light-weighting via material substitution, and a 20% to 40% reduction from light-weighting through reduced vehicle size.[153] For the construction sector, an estimated maximum of 10% material mass reduction could be achieved by reducing over-design in building structures[154].

One researcher stated that light-weighting could be achieved through additive manufacturing, where weight reductions of approximately 60% have been reported for some steel components,[155] however it seems an overly-specialised technique to be used as a proxy for general benefits.

The stakeholders provided estimates of maximum levels of efficiency which were inconclusive – very few stakeholders provided estimates through the voting. There was no consensus, and the overall voting range was very wide (between 0% to 30%). One of the stakeholders, who estimated a 30% maximum decrease in product weight from this measure, emphasised that this would assume the existence of financial incentives to prioritise material savings. One participant added that this value should also consider the impact that light-weighting in one component would have in another material. The example used was the reduction in steel weights occurring in offshore wind turbines which significantly reduces concrete use in the same application.

The maximum level of efficiency provided is therefore in the range of 10% to 40%, to encompass both the levels of efficiency identified in the vehicles and construction sectors, as well as the views of stakeholders. A red-amber evidence RAG rating has been given despite agreement between stakeholders and literature. This due to the number of different products this value aims to include, and the uncertainty associated with producing an average across these products.

7.4.3 Business-as-usual in 2035

For the BAU case, stakeholder views on the percentage of weight reduction in consumer products were highly divided. Participants identified difficulty in making an estimate when there is no information on the baseline level for the mass of steel in products, which was not provided as it could not be sourced from the literature. As a result, the weight reduction percentage was estimated to be in the range of 0% to 30%, with no majority opinion on a narrower range, subject to assumptions over the type of product and the level and type of light-weighting. Many stakeholders highlighted the current tendency to manufacture larger products that require more steel, rather than seek size reductions. However, it was suggested that if resource efficiency is further pursued for steel-based products, opportunities exist in light-

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[151] Hertwich, E.G.; Ali, S.; Ciacci, L.; Fishman, T. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics – A review

[152] ArcellorMittal (2020). HISTAR® Innovative high strength steels for economical steel structure

[153] Assuming a weight reduction of 30% from material substitution and 30% from vehicle size reduction, the overall weight reduction would be 50%.

[154] This figure is based on the BAU level of efficiency from the construction sector workshops.

[155] Keane, P. (2023). Engineers Use DfAM to Reduce Shaft Weight by over 50%

weighting. The level of impact in this case would depend on financial incentives, as well as research and development.

It is possible that in a BAU scenario that the level of efficiency can be zero or even negative. The Unlocking Resource Efficiency Vehicles Report estimated a level of 10% to 20% weight reduction by light-weighting through material substitution in the vehicles sector in a BAU scenario. The report also identified a possible negative BAU level of efficiency (-10% up to 0%) in weight reduction, implying an increase in the weight of a vehicles, as light-weighting incentives are more than offset by growth in consumer demand for larger vehicles.

This broad range of 0% to 30% level of efficiency and other uncertainty leads to a red evidence RAG rating. This is a measure that is being researched and developed only recently, and as a result it difficult to quantify the levels of efficiency that could be achieved. Since the BAU level is the same broad range as the maximum level of efficiency, it is not possible to draw any conclusions on the opportunity between the maximum and the business-as-usual levels in 2035. Additionally, the exact level will vary depending on the type of steel product, and it is important to understand further the opportunities in other steel uses (besides vehicles and construction).

8. Measure 8 – Increased reuse, repair, remanufacture and recycling of steel-based products

8.1 Steel resource efficiency measure

8.1.1 Description

Processes of reuse, repair, remanufacture and recycling facilitate more circular models of consumption and can lead to savings in the overall use of steel.

Reuse

Through direct reuse, end-of-life steel-based products or components with operational value can be used again for their original purpose. Products used in and across multiple sectors can be reused, such as steel packaging and containers. Reuse may require the product to be cleaned, sterilised or decontaminated.[156] Where required, restoration may also be needed, including replacement of damaged or obsolete components and associated repair and remanufacture.

Repair & Remanufacture

Repair and remanufacture of steel-based products contributes to a circular model of consumption with more reuse and lower levels of waste.[157] Such methods return a product to its original state, with the same functionality as a new product. They may involve combining other existing reused or repaired products and materials. This process saves the material and energy inputs associated with producing a new product.

Repair and remanufacture are covered together as they are similar processes that may be offered interchangeably depending on product requirements.

Recycling

Steel is the most recycled construction material globally, with approximately 40% of all steel production being based on recycled steel scrap and over 500 million tonnes of steel being recycled multiple times worldwide each year.[158] Recycling steel products reduces demand for raw materials needed in virgin steel production. In the UK, most of the steel derived from consumer products is currently recycled in BF-BOFs.

Management of contamination is important for scrap recycling using BF-BOF and EAF production methods and would benefit from improved information throughout the supply chain. The issues regarding scrap contamination and mitigation are explored in detail in Measure 3 –

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[156] German Environment Agency (2021). Sustainable resource use in the health care sector – exploiting synergies between the policy fields of resource conservation and health care

[157] Apeal (n.d.). Steel for packaging, designed for efficiency

[158] Steel is the world's most recycled construction material and approximately 40% of all steel production is based on recycled scrap. Over 500 million tonnes of steel are multicycled worldwide each year – equivalent to 180 Eiffel Towers every day.

Transition from ore-based to scrap-based steel production. It is more efficient for products to be reused than it is for them to be recycled, due to the associated energy inputs required to recycle materials.

8.1.2 Measure indicator

Four indicators based on weight were proposed for this measure which correspond to each the different methods of circular consumption:

- **% of reused steel in a product**
- **% of repaired steel in a product**
- **% of remanufactured steel in a product**
- **% of recycled steel in a product**

These generic indicators are applicable to all sectors which aim for greater circularity in the use of steel materials.

Whilst values are presented separately here for reuse, repair, remanufacture and recycling it is important to note that they will be interdependent with each other, the more steel that you reuse, repair, and remanufacture the less you are able to recycle etc. More research into how these measures overlap and interplay would be beneficial when understanding the best potential for the reuse, repair, remanufacture and recycling of steel.

8.1.3 Examples in practice

Reuse

Notable examples of reuse include recent efforts in the construction sector to reuse 10% of structural steel,[159] which the UK has already achieved, and reuse of steel components in the automotive industry.[160]

Repair & Remanufacture

An example of repair and remanufacture is the possibility of repeated repair and reuse of medical instruments made of stainless steel that would otherwise be disposed of as waste and replaced with new products.[161]

Recycling

A notable example of steel recycling is structural steel, of which 86% is used as scrap feedstock in blast furnaces.[162] Another high level of recycling for a steel-based product is packaging, at a rate of 78%.[163] In this instance, the steel sector often works with UK local authorities and waste management bodies to ensure that steel packaging recovered through

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[159] Galvanizers Association (2023). Steel recycling

[160] The construction and automotive sectors are covered specifically in other parts of the wider study.

[161] Van Straten, B.; Dankelman, J.; Van der Eijk, A.; Horeman, T. (2021). A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste

[162] Galvanizers Association (2023). Steel recycling

[163] WRAP (2020). Metal Flow 2025 – Metal Packaging Flow Data Report.

kerbside waste collections, incinerators and bring banks is reprocessed into new products at designated steelmaking plants.[164]

Specialist steels can also be recycled, with examples of the recovery and recycling of stainless steel surgical instruments within the medical sector allowing specialist alloys to be recycled and remanufactured in closed loops without diluting the quality of the stock of steel material.[165] [166] Another example is stainless steel for commercial kitchens which forms a stock of durable, corrosion-resistant material with almost infinite recyclability which can be continuously adapted for use in new situations.[167]

8.2 Available sources

8.2.1 Literature Review

19 literature sources were identified covering a broad range of topics relevant to circularity in the use of steel products, including 13 academic papers[168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178,

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[164] Tata Steel (2023). Sustainability in packaging.

[165] German Environment Agency (2021). Sustainable resource use in the health care sector – exploiting synergies between the policy fields of resource conservation and health care

[166] Van Straten, B.; Dankelman, J.; Van der Eijk, A.; Horeman, T. (2021). A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste

[167] Outokumpu (2023). Six key facts about stainless steel in commercial kitchens

[168] Schoeman, Y., Oberholster, P., Somerset, V. (2021). A decision-support framework for industrial waste management in the iron and steel industry: A case study in Southern Africa.

[169] Williams, R., Jack, C., Gamboa, D., & Shackley, S. (2021). Decarbonising steel production using CO_2 Capture and Storage (CCS): Results of focus group discussions in a Welsh steel-making community.

[170] Yeung, J. (2016). Development of analysis tools for the facilitation of increased structural steel reuse.

[171] Griffin, P. W., & Hammond, G. P. (2019). Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective.

[172] Fujita, M., Fujita, T., Iwata, M., Iwata, Y., Kanemitsu, T., Kimura, U., Wada, M. (2023). Japanese Efforts to Promote Steel Reuse in Building Construction.

[173] Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Cullen, J. M., & Allwood, J. M. (2018). Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain.

[174] Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Allwood, J. M., & Cullen, J. M. (2017). Real and perceived barriers to steel reuse across the UK construction value chain.

[175] Branca, T.A.; Colla, V.; Algermissen, D.; Granbom, H.; Martini, U.; Morillon, A.; Pietruck, R.; Rosendahl, S. (2020). Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe.

[176] Tingley, D. D., & Allwood, J. M. (2014). Re-use of structural steel: the opportunities and challenges.

[177] Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy.

[178] Berlin, D., Feldmann, A., Nuur, C. (2022). Supply network collaborations in a circular economy: A case study of Swedish steel recycling.

[179], [180], four industry reports[181], [182], [183], [184], one technical study[185] and one website article.[186] Four industry reports were also shared by stakeholders during workshop sessions.

These sources reflect contributions from steel manufacturers, researchers and academics including prominent organisations such as Tata Steel, Outokumpu, ArcelorMittal, the World Steel Association and Eurofer, and are considered credible sources (IAS of 3 or above). Collectively, they provide substantial description of the context for reuse, repair, remanufacture and recycling of steel but lack quantitative assessment of the measures resource efficiency potential, possibly because of the novelty of circular economy applications.

The indicator suggested for this measure applies to a diversity of steel products on the market, for which quantitative data is not similarly aggregated, and there is little comparative evidence.

8.2.2 Workshops

Stakeholders provided significant verbal and written contributions in the workshop discussion, particularly researchers and academics. Some participants highlighted their lack of knowledge on this topic, as their expertise was in steel production. Thus, some further representation of the end-of-life stage of steel would be beneficial for the assessment of this measure and its resource efficiency impacts.

The level of engagement in both workshops was as follows:

- **Workshop 1** – Twelve stakeholders across industry and academia were active on the mural board and seven stakeholders actively contributed to verbal discussion.
- **Workshop 2** – Six stakeholders across industry and academia were active on the mural board and two stakeholders actively contributed to verbal discussion.

8.3 Drivers & Barriers

The drivers and barriers from literature review and stakeholder feedback are listed in Table 24 and Table 25 respectively, including their PESTLE and COM-B categorisation, with the most significant shown in bold.

8.3.1 Drivers

Table 24: Drivers for steel Measure 8

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[179] Yeung, J., Walbridge, S., & Haas, C (2015). The role of geometric characterization in supporting structural steel reuse decisions.
[180] Tingley, D. D., Cooper, S., & Cullen, J (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective.
[181] Zero Waste Scotland (2021). How Should Scotland Manage its Scrap Steel?
[182] TATA Steel (2020). Steel and the four R's.
[183] World Steel Association (2015). Steel in the Circular Economy: A life cycle perspective.
[184] Outokumpu (n.d.). Sustainable stainless steel is key element in circular economy.
[185] Eder, P., Muchová, L. (2010). End-of-waste criteria for iron and steel scrap.
[186] Steel Technology (n.d.). Waste Disposal and Recycling in Steel Industry.

Driver	Focus of Measure	PESTLE	COM-B
Planning regulations in the construction sector.	General	Legal	Motivation – reflective
Material servitisation business models.	General	Economic	Opportunity – Social
Increasing consumer awareness around sustainability.	General	Socio-Cultural	Motivation – reflective
Increased use of steel scrap will increase the demand for and value of quality scrap.	Reuse, Recycling	Economic	Motivation – reflective
The high value of scrap steel drives the high levels of scrap recycling.	Recycling	Economic	Motivation – reflective
Employment opportunities in the repair sector may reappear in the global supply chains.	Repair, Remanufacture	Socio-Cultural	Opportunity – Social

Reuse was seen by stakeholders as an opportunity with significant potential for high levels of resource efficiency noting that sectors and industries are still developing circular economy practices. In particular, the recent increase in reuse of constructional steel was noted, with one stakeholder suggesting the use of material passports[187] to encourage steel reuse.

Remanufacture was also seen as important, but as mainly applicable to high quality products and in specific industries, such as in defence and decommissioning.

Steel recycling was confirmed by stakeholders as widely implemented, but with the suggestion of increased attention on reuse, repair and remanufacture to facilitate progress at higher levels of the waste hierarchy.

One participant suggested that the circular economy could generate higher values if there were corresponding levels of motivation, strong financial and political incentives, and favourable market conditions. The rental system involving repair and reuse of aerospace engines in multiple airframes was mentioned in this context, though end-of-life engines are not currently sorted and recycled back (in a closed loop) to the aerospace sector.

Participants contributed a number of additional drivers, including the market opportunities created by the increased use of steel scrap. With the transition from BF-BOF to EAF steelmaking, future scrap demand and value are expected to rise driving, in turn high recycling rates for steel.

Another stakeholder suggested that the promotion of repair systems may broaden existing employment opportunities or create new working sectors.

Servitisation is a shift from selling products to selling services, with new business models and opportunities for employment. It can act as a driver for this measure as it introduces strong incentives for extending the lifespan and use of products (as this maximises profit for the

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[187] Material passports are digital documents that contain information on the characteristics of materials and components, facilitating their traceability, use, recovery and future reuse.

service provider). Examples of servitisation include car sharing and other transformations in consumer behaviour which themselves depend on wider drivers of consumer awareness.

Lastly, industries, companies and sectors that work within planning regulations that involve sustainable production and consumption will contribute to a general increase in material efficiency. For example, in the construction sector, an Owner's Project Requirement (OPR) document is required for each building project which outlines goals, objectives and requirements for material and energy efficiency, including materials use such as steel.[188]

8.3.2 Barriers

Table 25: Barriers for steel Measure 8

Barrier	Focus of Measure	PESTLE	COM-B
The standards for product design may constitute a barrier in the enabling of the regenerative approaches of repair and remanufacture.[189]	**Repair, Remanufacture**	**Legal**	**Motivation – reflective**
Current business models do not incentivise circularity, but greater production.	General	Economic	Motivation – reflective
Lack of information on contaminants in the scrap supply chain and lack of provision of infrastructure to remove them.	General	Environmental	Motivation – reflective
Increased use of steel scrap will grow demand for steel recycling rather than reuse.	Reuse	Economic	Motivation – reflective
Product provenance may create safety issues around reuse.	Reuse	Legal Environmental	Motivation – reflective
Technical challenges in remanufacturing that require specialised workforces, maintaining consistent product quality standards, cost considerations, reverse logistics, and consumer perceptions.	Remanufacture	Technological Socio-Cultural Economic	Capability – Physical
Increased costs associated with material reprocessing.	Repair, Remanufacture, Recycling	Economic	Motivation – reflective
Recycling and shredding of certain steel-based products (e.g. ELVs) may result in the generation of low value materials as critical resources, such as zinc and neodymium, are not currently recovered in the UK.	Recycling	Economic	Opportunity – Social

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[188] UGREEN (2023). What is an Owner's Project Requirement (OPR)? A Guide For Architects, Engineers, and Designers

[189] For example, product design standards may be based on definitions of primary or virgin materials.

As the application of circular economy is still a work in progress for many sectors, including steel, there are a number of significant challenges.

Technical challenges in remanufacturing were considered to be a key barrier of this measure. Remanufacturing processes may require specialised workforces with new skillsets and product quality standards will have to be met. Integrated reverse logistics systems to collect material from end-users and return it to manufacturers are essential. These steps are likely to increase the costs associated with remanufacturing, which may ultimately hinder the commercialisation of this route.

Participants provided two more barriers:

- *concerns around the provenance of products*, leading to potential safety issues when reused.
- *current business models do not incentivise circularity* with market conditions making it more cost-effective to use new steel/steel products.

Examples of current business models which do not encourage circularity include: the charging of VAT when retrofitting buildings but not for new construction (so reducing reuse); the deconstruction of buildings is also incentivised to be fast (reducing the retention of materials in a high-value form suitable for reuse). As a result, the general consensus was that financial and policy incentives are required to implement regulations and establish guidelines on quality assurance.

One risk that accompanies the increased use of steel, is that demand will also inevitably rise, and therefore reuse will not be the primary choice of consumption. Moreover, contamination is a major issue in the scrap supply chain and current UK infrastructure is insufficient for managing it. This also correlates with product provenance, which is hard to track at present and thus the characteristics of contaminants may be unknown or vary largely. The better characterisation of all steel materials, not just scrap, would reduce uncontrolled contaminants and increase safety (and potential reuse).

A measure that could mitigate this challenge would be the development of material passports for steel products. Material passports are digital documents listing all the materials contained in the lifecycle of a product or component in order to facilitate circularity in supply chain management. These would enable an improved characterisation of steel-based products and identify contaminants and other safety issues.

Generally, stakeholders considered that all barriers presented within the workshop affected uptake; however, the majority agreed that the establishment of standards for product design would help overcome the most important barriers for enabling regenerative repair and remanufacture approaches. Circular design requirements on durability, re-use, reparability, dismantling and recyclability can be part of product design to ensure parts are easier and more cost-effective to reuse.[190] Another barrier mitigation solution suggested by participants involved embodied carbon reduction targets. It was specifically mentioned that reporting of Scope 3 emissions further facilitates circularity in end markets as it makes embodied carbon more apparent.

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[190] Eurofer (2015). Steel and the Circular Economy

8.4 Levels of efficiency

The levels of efficiency provided stem from a combination of literature review and stakeholder feedback from the workshops. Specifically, data regarding steel recycling in the UK was broadly available through literature, whereas data on reuse, repair and remanufacture was mainly provided in estimates by stakeholders. It is important to emphasise that these estimates were not informed by circular economy experts on steel, as no such stakeholders participated in the workshops. Therefore, the majority of levels of efficiency on reuse, repair and remanufacture are provided on the basis of general information by participants who attended the workshops. Additionally, the ranges were selected so that all votes by workshop participants are accounted for. A red RAG rating is chosen to demonstrate the low level of evidence and confidence in the figures.

Table 26: Levels of efficiency for steel Measure 8

Indicators: **% of reused steel in a product / % of repaired steel in a product / % of remanufactured steel in a product / % of recycled steel in a product**			
Level of efficiency	Current	Maximum in 2035	Business-as-usual in 2035
Indicator: % of reused steel in a product			
Reuse – Value	0 – 14%	30 – 44%	0 – 30%
Reuse – Evidence RAG	Amber	Red	Red
Indicator: % of repaired steel in a product			
Repair – Value	15 – 29%	15 – 29%	15 – 29%
Repair – Evidence RAG	Red	Red	Red
Indicator: % of remanufactured steel in a product			
Remanufacture – Value	0 – 14%	15 – 29%	0 – 20%
Remanufacture – Evidence RAG	Red	Red	Red
Indicator: % of recycled steel in a product			
Recycling – Value	80 – 90%	>90%	>90%
Recycling – Evidence RAG	Green	Amber-Green	Amber-Green

8.4.1 Current level of efficiency

Reuse

One option dominated in the current level of efficiency for reuse during workshops, with eight participants voting for the 0% to 14% range. Stakeholders suggested that reuse, along with other circular business models, can potentially lead to much greater resource efficiency in steel use with a strong level of financial and political motivation. The current rise in isolated cases of reused steel in large scale operations, such as construction where there is a 10% steel reuse rate, provides evidence that this measure is already applied in certain sectors. It was additionally raised during workshops that the scale of reuse is difficult to track at present, which explains the lack of quantitative data in existing literature. The current level off efficiency is therefore reported with an amber evidence RAG rating, as there was no literature that also supported this estimate by participants.

Repair and Remanufacture

There was minimal quantitative feedback on repair and remanufacture, as a number of participants pointed out that there are no significant inputs or data on current steel repair and remanufacture activities. However, one stakeholder commented that these activities may already exist but are largely hidden, providing the example of car body shops, which may repair damaged components to restore a vehicle to its former state. Another participant mentioned that some companies are additionally researching metal repair at the moment. A red RAG rating of evidence is associated with the estimated levels of efficiency of 15% to 29% for repair and 0% to 14% for remanufacture, as these are solely based on stakeholder views expressed during voting in workshops. The lower levels of efficiency in remanufacture may be a result of the technical difficulties associated with its implementation, as discussed in previous sections.

Recycling

Consensus from both literature and workshops was that recycling is already implemented on a large scale for steel and steel-based products. This may be justified by the recyclability of the material, which allows it to be reprocessed via this method continuously without risk of value loss. Steel-based packaging was evidenced to be recycled at a rate of approximately 80% in the UK currently.[191] Stakeholders agreed that the average rate is likely higher, voting for a 90% rate. As a result, the current level of efficiency for steel recycling is estimated to be in the range of 80% to 90% with significant evidence to support this. This value has a green evidence RAG rating because there was consensus from stakeholders who agreed with values identified in the literature.

8.4.2 Maximum level of efficiency in 2035

Reuse

Workshop views on the maximum level of efficiency for the reuse of steel products was voted to be between 30% to 44%. This range may have been selected due to evidence of structural steel reuse in construction, which participants may have used as an overarching proxy for steel reuse across all sectors. Stakeholders mentioned that there are greater opportunities for structural steel reuse, and this could be combined with better building optimisation to drive higher levels of efficiency. Two participants expressed the view that reuse should increase in the near future so that recycling decreases, suggesting a balance where the two methods combined achieve a total 100% circularity in a product. The 30-44% estimate is provided with a red RAG rating for evidence based on limited workshop attendee opinions and due to uncertainty on whether this data would be applicable to all steel-based products

Repair and Remanufacture

Due to the absence of a current baseline to demonstrate the level of implementation in steel repair and remanufacture, stakeholders expressed difficulty in estimating the maximum level of

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[191] WRAP (2020). Metal Flow 2025 – Metal Packaging Flow Data Report.

efficiency by 2035. There was a low level of voting and engagement during workshops which reflected this lack of knowledge on the subject, and therefore the maximum level of efficiency is estimated to in the range of 15% to 29% for both repair and remanufacture. The values are reported with a red RAG rating for evidence as literature sources do not include validating information. It is useful to consider, however, that these business models are surrounded by a number of limitations related to product contamination, technical expertise, quality assurance, and higher operating costs which may explain the lower level of efficiency compared to reuse.

Recycling

As mentioned above, steel is already widely recycled, one stakeholder noted that recycling will result only in marginal gains above the 80-90% currently estimated. Assuming improvement, a level of efficiency higher than 90% is expected by 2035, slightly above current levels.

8.4.3 Business-as-usual in 2035

Reuse

In the BAU case in 2035, stakeholders generally estimated lower levels of resource efficiency compared to maximum in 2035, including through reuse, where voting suggested a level of efficiency of up to 30%. This is higher than the current level of efficiency and a participant indicated that they had noted an increase in examples of steel reuse in recent years. It is however lower than the anticipated maximum level of efficiency in 2035 (largely based on structural steel) due to uncertainties from less developed policies and applications for other reuse pathways. This estimate is reported with a red RAG rating to reflect the limited evidence provided by stakeholders and the lack of validating data from literature.

Repair and Remanufacture

As with assessing reuse, the challenge in estimating levels of repair and remanufacture became apparent during workshops, where voting showed polarisation. For repair, there was a mixed level of votes, with two participants suggesting a maximum level of 40% to 60% for repair of steel-based products, while two other participants gave an estimate of lower than 20%. However, the BAU range cannot surpass the maximum technical level of efficiency and is set to an estimate of between 15% to 29%. These are estimates and are characterised by a red RAG rating as there is currently no literature to validate them.

For remanufacture, stakeholders broadly demonstrated views consistent with a low level of remanufacture under BAU (up to 20%). This is provided with a red RAG rating due to the range being limited to stakeholder evidence.

Recycling

Participants agreed that the level of recycling is already very high and suggested that in a BAU scenario it would reach a maximum rate of above 90% by 2035. This is according to four votes and the accompanying discussion and is reported with an amber-green RAG rating that reflects the trend of increase in steel recycling.

9. Interdependencies

This report covers the measures identified for the steel sector and presented estimates for the maximum and BAU level of efficiency they could achieve independently, that is, not considering any interdependencies or interactions between measures.

However, in practice these measures are likely to occur in tandem, and the levels of efficiency that are reached in each will depend on progress against other measures. The precise nature of these interdependencies should be considered when using any of the level of efficiency estimates from this report in further research, or in modelling exercises that attempt to produce an estimate of the cumulative impact of these measures over time.

A summary of the key interactions/interdependencies between the measures in this report with other measures in the sector, and with measures in other sectors is presented below. Note, as Phase 2 of this research project is still in the fieldwork stage, the dependencies with other sectors reflect dependencies with other Phase 1 sectors only. The Phase 2 reports will seek to capture any further interdependencies with Phase 2 sectors.

Note, the estimates for the current level of efficiency will by their nature reflect the interactions and interdependencies between measures as they currently occur.

9.1 Interdependencies within the steel sector

Measures 1, 2 & 4

- Measure 1 – Substitution of fossil-carbon reductants with waste-based alternatives
- Measure 2 – Substitution of fossil-carbon reductants with hydrogen direct reduced iron in EAFs
- Measure 4 - Transition from basic oxygen furnace to electric arc furnace steelmaking

Measures 1, 2 and 4 cover the substitution of fossil-carbon reductants, such as coke and natural gas, with more sustainable alternatives of biomass, waste materials and H2-DRI. The shift from BF-BOF to EAF steelmaking (Measure 4) affects the potential relative levels of use of Measures 1 and 2. Furthermore, levels of use may also depend on the mandatory levels of emissions abatement as well as available supplies, such as of H2-DRI.

Measures 2, 3 & 4

- Measure 2 – Substitution of fossil-carbon reductants with hydrogen direct reduced iron in EAFs
- Measure 3 – Transition from ore-based to scrap-based steel production
- Measure 4 – Transition from basic oxygen furnace to electric arc furnace steelmaking

Measures 3 and 4 are closely linked. While scrap usage can be increased in BF-BOF (from 20% to 25% in the UK (result in an additional 0.2Mtpa of scrap use)[192], the more dominant effect is from new EAF facilities (Measure 4) which can use 100% scrap. A large-scale transition to EAF requires well-characterised supplies of scrap feedstock so that the steel produced can match the standards of current BF-BOF production methods. Large-scale transition however also creates a larger market for scrap and increases the potential availability of specific scrap grades. The availability of scrap in the UK is indicated by the 8.7 MTpa of current exports[193] which would meet supply needs for a large-scale transition to EAF subject to effective sorting and characterisation to ensure quality while EAF may also use supplementary sources of iron, such as H2-DRI (Measure 2).

Measure 2 is also linked with Measure 3 as many participants commented that EAF should be viewed as a steppingstone towards green hydrogen DRI steelmaking. Investment in Measure 2 will require an investment in EAF infrastructure while EAF infrastructure could itself facilitate development of hydrogen DRI infrastructure.

Measures 3 & 6

- Measure 3 – Transition from ore-based to scrap-based steel production
- Measure 6 – Recovery and use of steelmaking by-product materials

During discussion of Measure 3 and the use of scrap in steel production, participants commented that certain grades of scrap, particularly those containing high zinc contents, help manufacturers valorise their dusts. It was stated that dust needs to be at least 35% zinc oxide for recovery to be financially viable. If scrap can be sorted effectively and scrap with high alloy contents used in production, it may incentivise manufacturers to recover dusts and potentially then other materials.

Measures 3 & 8

- Measure 3 – Transition from ore-based to scrap-based steel production
- Measure 8 – Increased reuse, repair, remanufacture and recycling of steel-based products

Measure 8 discusses the different end-of-life pathways for steel and Measure 3 discusses the incorporation of scrap steel into the production of new steel. Thus, the two measures are very connected – the quantities of recycling from measure 8 will influence the availability of scrap for Measure 3.

Participants mentioned that the high value of scrap is currently a driver for recycling, and to the detriment of other end-of-life activities that are higher in the waste hierarchy, such as reuse, repair and remanufacturing.

Measures 7 & 8

- Measure 7 – Light-weighting and use of higher grades of steel in consumer products

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[192] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

[193] Hall, R.I., Zhang, W., and Li, Z. (2021). Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)

- Measure 8 – Increased reuse, repair, remanufacture and recycling of steel-based products

Measure 7 discusses light-weighting of steel products while Measure 8 discusses the end-of-life paths of steel products. Stakeholders have discussed that there could be trade-offs between these two measures: light-weighting could reduce the potential for reuse, repair, remanufacture.

9.2 Interdependencies with other sectors

Measure 6 - Recovery and use of steelmaking by-product materials

The stakeholders raised the potential for the steel sector to increase engagement and industrial symbiosis with other sectors and so provide by-products from steel production as feedstocks for other industries. This could be particularly relevant to the chemicals sector which could make use of dusts, sludges, and tars and otherwise hazardous contaminants, subject to addressing safety concerns.

The widespread use of slag as a clinker substitute for cement manufacture is an application already established and, as recovery and reuse of slag is already close to 100%, there is very limited possibility of further increase.

The different properties of EAF and BF-BOF slag was raised as an issue. Different slag chemistries result from the different production processes and impart different properties on the slag. A participant stated that EAF slag is generally used in road making whereas BF-BOF slag is used in cement making. The transition to EAF could impact the slag market and could reduce BF-BOF slag for use in cement manufacture though the degree to which the slags are substitutable was not determined.

Measure 7 - Light-weighting and use of higher grades of steel in consumer products

Light-weighting steel products is discussed in three other measures of other sectors:

- Vehicles Measure 1 – Light-weighting through material substitution
- Vehicles Measure 2 – Light-weighting through reducing vehicle size
- Construction Measure 4 – Reduction of over-design & delivery in building structures

Measure 8 - Increased reuse, repair, remanufacture and recycling of steel-based products

This measure aims to increase the resource efficiency across multiple steel-based products and affects all sectors involved in their manufacture and use. For example, there is considerable implementation of this measure in the vehicles and construction sectors.

The extent to which reuse, repair, remanufacture and recycling is applied to steel components within other sectors is further explored in each respective sector report through the following measures:

- Construction Measure 7 – Reuse / recycling of building materials
- Vehicles Measure 8 – Remanufacturing, reuse and reconditioning of parts

Glossary and abbreviations

BAU	Business-as-usual
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BOF	Basic Oxygen Furnace
CCUS	carbon capture, usage and storage
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EPD	Environmental Product Declaration
H2-DRI	Hydrogen Direct Reduced Iron
HDPE	High Density Polyethylene
Off-gases	Gaseous by-products of industrial processes or gasses given off during manufacturing
PCI	Pulverised Coal Injection
PET	Polyethylene terephthalate
POPs	Persistent Organic Pollutants
PP	Polypropylene
TRL	technology readiness level

Appendix A: IAS Scoring Parameters

Table 27: IAS Scoring Parameters

Criteria	High	Medium	Low
Geography	Specific to UK	Non-UK but applicable to the UK	Non-UK and not applicable to the UK
Date of publication	< 10 years	10 to 20 years	> 20 years
Sector applicability	Sector and measure-specific, discusses RE and circularity	Sector and measure-specific, focus on decarbonisation	Cross-sector
Methodology	Research methodology well defined and deemed appropriate	Research methodology well defined but not deemed appropriate / Minor description of research methodology	No research methodology
Peer Review	Explicitly mentioned peer review	Not explicitly mentioned, but assumed to have been peer reviewed	Unknown

Appendix B: Search strings

- container steel AND (resource efficiency OR material efficiency)
- efficient steel AND industrial catering
- green steel UK
- steel AND best available techniques
- steel AND circular economy
- steel AND circular economy AND business models
- steel AND end of life AND option*
- steel AND energy efficien*
- steel AND lightweight*
- steel AND manufact* AND (value chain optim*)
- steel AND manufact* efficiency
- steel AND material passport
- steel AND (resource efficiency OR material efficiency)
- steel AND (resource efficiency OR material efficiency) AND medical equipment
- steel AND reuse AND option*
- steel AND recycl*
- steel AND remanufactur*
- steel AND (waste minimisation OR waste reduction)
- steel decarbonis* AND technolog* OR option*
- steel decarbonis* AND investment AND UK
- steel decarbonis* AND funding AND UK
- steel decarbonis* AND (barrier* OR challenge*) AND UK
- steel efficiency AND solar panel*
- steel packaging AND resource efficiency
- steel policy AND UK
- UK steel statistics
- UK steel sites

- UK steel AND scrap market
- UK steel AND resource efficiency AND (measure OR initiative)
- UK steelmaking AND proportion of coke

Appendix C: Literature sources

Table 28: List of literature sources for the steel sector

Title	URL	Author	Year	IAS
Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Iron and Steel	link	WSP and Parsons Brinckerhoff	2015	5
How resource-efficient is the global steel industry?	link	Hernandez, A.G.; Paoli, L.; Cullen, J. M.	2018	5
Future Capacities and Capabilities of the UK Steel Industry: Technical Appendices	link	Department for Business Energy and Industrial Strategy	2017	5
Options for the Swedish steel industry – Energy efficiency measures and fuel conversion	link	Johansson, M.T. & Söderström, M.	2011	4
Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts	link	Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W-Q.	2021	5
Technology innovation system analysis of decarbonisation options in the EU steel industry	link	Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A	2020	5
Policy and pricing barriers to steel industry decarbonisation: A UK case study	link	Richardson-Barlow, C., Pimm, A. J., Taylor, P. G., & Gale, W. F.	2022	5
Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production	link	Colla, V. & Branca, T. A.	2021	5
Resource Efficiency: Potential and Economic Implications Summary for Policymakers	link	Ekins, P. Hughes, N. (UNEP)	2016	4
Domestic scrap steel recycling – economic, environmental and social opportunities (EV0490)	link	Hall, R.; Zhang, W.; Li, Z.	2021	5
Building the future: A faster route to clean steel	link	Viisainen, B. V. & Rowden, H.	2022	5
Control data, Sankey diagrams, and exergy: Assessing the resource efficiency of industrial plants	link	Gonzalez Hernandez, A.; Lupton, R.C.; Williams, C.; Cullen, J.M.	2018	5
Steel industry co-products	link	World Steel Association	2020	4
Resource efficiency in steelmaking: energy and materials combined	link	Hernandez, A.G.; Paoli, L.; Cullen, J. M.	2017	5

Title	URL	Author	Year	IAS
Resource efficiency in the Strategic Research Agenda of the European Steel Technology Platform	link	Peters, K.; Malfa, E.; Colla, V.; Brimacombe, L.	2015	5
Can methane pyrolysis-based hydrogen production lead to the decarbonisation of iron and steel industry?	link	Bhaskar, A.; Assadi, M.; Somehsaraei, H. N.	2021	5
Steel and the Circular Economy	link	The European Steel Association (Eurofer)	2015	4
Enhanced Resource Efficiency with Packaging Steel	link	Frauman, E. & Hatscher, N.	2011	5
Steel for packaging, designed for efficiency	link	Apeal	n/a	2
Steel packaging	link	World Steel Association	n/a	3
A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste	link	Van Straten, B.; Dankelman, J.; Van der Eijk, A.; Horeman, T.	2021	5
Sustainable resource use in the health care sector – exploiting synergies between the policy fields of resource conservation and health care	link	German Environment Agency	2021	4
Six key facts about stainless steel in commercial kitchens	link	Outokumpu	n/a	4
Best available techniques (BAT) reference document for iron and steel production	link	European Commission	2013	5
Resource revolution: Meeting the world's energy, materials, food, and water needs	link	Dobbs, R.; Oppenheim, J.; Thompson, F.; Brinkman, M.; Zornes, M. (McKinsey)	2011	4
Review on the Use of Alternative Carbon Sources in EAF Steelmaking	link	Thomas Echterhof	2021	5
Starting from scrap. The key role of circular steel in meeting climate goals.	link	Sandbag climate Campaign	2022	4
Iron and Steel Technology roadmap: Towards more sustainable steelmaking	link	International Energy Agency (IEA)	2020	5
How will copper contamination constrain future global steel recycling?	link	Daehn, K. E., Cabrera Serrenho, A., & Allwood, J. M.	2017	5
Biomass in steelmaking	link	World Steel Association	2021	5
Hydrogen Ironmaking: How It Works.	link.	Patisson, F. and Mirgaux, O.	2020	5

Title	URL	Author	Year	IAS
Influence of waste plastic utilisation in blast furnace on heavy metal emissions	link	Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., Fellner, J.	2015	4
Liberty Steel UK launches ecoke – a new method of electric steelmaking to reduce CO_2 emissions	link	Liberty Steel Group	2022	5
The Clean Hydrogen Ladder	link	Liebreich Associates	2021	4
Materials & Manufacturing	link	UK Fires	2022	4
Phasing out the blast furnace to meet global climate targets	link	Vogl, V.; Olsson, O.; Nykvist, B.	2021	5
Developing a low-carbon, circular economy for steel	link	Walter Swann (The Institution of Structural Engineers)	2021	5
Investigation on the sustainable use of electric arc furnace slag aggregates in eco-friendly alkali-activated low fineness slag concrete as a green construction composite	link	Amani, A.; Ramezanianpour, A.M.; Palassi, M.	2021	5
Scrap happens: A case of industrial end-users, maintenance and component remanufacturing outcome	link	Diener, D.L.; Kushnir, D.; Tillman, A-M.	2019	5
Enabling steel's circular economy potential	link	Michal Drewniok (The Institution of Structural Engineers)	2021	5
Delivering steel's circular economy potential	link	Leversha, D.; Moylan, D.; Firth, B.; Moss, N.; Gilchrist, S.	2022	5
(Steel) Recycling	link	Celsa Group	n/a	4
21.15: Resource efficiency in the building sector: Application to steel buildings	link	Gervásio, H., Dimova, S., & Pinto, A.	2017	5
A comprehensive review on energy efficient CO_2 breakthrough technologies for sustainable green iron and steel manufacturing	link	Quader, M. A., Ahmed, S., Ghazilla, R. A. R., Ahmed, S., & Dahari, M	2015	5
A decision-support framework for industrial waste management in the iron and steel industry: A case study in Southern Africa	link	Schoeman, Y., Oberholster, P., Somerset, V.	2021	4
A multi-method approach for analysing the potential employment impacts of material efficiency	link	Cooper, Simone, et al.	2016	5

Title	URL	Author	Year	IAS
A new class of lightweight, stainless steels with ultra-high strength and large ductility	link	Moon, J., Ha, H.-Y., Kim, K.-W., Park, S.-J., Lee, T.-H., Kim, S.-D., Jang, J. H., Jo, H.-H., Hong, H.-U., Lee, B. H., Lee, Y.-J., Lee, C., Suh, D.-W., Han, H. N., Raabe, D., & Lee, C.-H.	2020	5
A review of energy use and energy-efficient technologies for the iron and steel industry	link	He, K. and Wang, L.	2017	5
Are resource efficiency and circular economy politically desirable?	link	Schliephake H, Endemann G	2016	5
By-products, scrap and the circular economy	link	ArcelorMittal	n/a	4
Circular Economy Centre for Mineral-based Construction Materials	link	University of Leeds	2021	4
Circular Metal Visions 2050	link	Franconi, A., Ceschin, F., Godsell, J., Harrison, D., Mate, O.-A., Konteh, T.	2022	5
Circular Steel: How Information and Actor Incentives Impact the Recyclability of Scrap	link	Compañero, R.J., Feldmann, A. & Tilliander, A.	2021	5
Circular Steel: How Information and Actor Incentives Impact the Recyclability of Scrap	link	Compañero, R.J., Feldmann, A. & Tilliander, A.	2021	4
Data cited comes from McKinsey 2011 report "Resource revolution: Meeting the world's energy, materials, food, and water needs"	link	McKinsey (Richard Dobbs, Jeremy Oppenheim, Fraser Thompson, Marcel Brinkman, and Marc Zornes)	2011	4
Decarbonisation options for the Dutch steel industry	link	Keys, A., Van Hout, M., & Daniels, B.	2019	5
Decarbonising steel production using CO_2 Capture and Storage (CCS): Results of focus group discussions in a Welsh steel-making community	link	Williams, R., Jack, C., Gamboa, D., & Shackley, S.	2021	5
Development of analysis tools for the facilitation of increased structural steel reuse	link	Yeung, J.	2016	5
Earth-friendly story of "steel can = iron"	link	Nippon Steel	n/a	1
Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe	link	Öhman, A., Karakaya, E., & Urban, F.	2022	5

Title	URL	Author	Year	IAS
End-of-waste criteria for iron and steel scrap	link	Eder, P., Muchová, L.	2010	5
EU Ferrous & Non-Ferrous Metals Industry	link	European Commission	2007	4
European Commission announces import quotas on steel imports from UK	link	Eurometal	2020	4
European Union Tariff Rate Quota Periodic Limits	link	U.S. Customs and Border Protection	2023	4
Ferrous Metals Specifications	link	Just Recycling	n/a	4
From control data to real-time resource maps in a steel-making plant.	link	Hernandez, A. G., Lupton, R., Williams, C., & Cullen, J.	2017	5
Future of UK Steel: Five Steel Sector Priotities for a New Government	link	Make UK	2022	5
Global Steel Plant Tracker	link	Global Energy Monitor	2023	4
Green steel	link	UK Parliament	2022	5
Guide to resource efficiency in manufacturing: Experiences from improving resource efficiency in manufacturing companies	link	Greenovate! Europe	2012	5
How Should Scotland Manage its Scrap Steel?	link	Zero Waste Scotland	2021	5
How steel enables resource efficiency and innovation	link	Ekdahl, Å. (World Steel Association)	2019	4
Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective	link	Griffin, P. W., & Hammond, G. P.	2019	5
Industrial Strategy: Sector Deals	link	House of Commons: Business, Energy and Industrial Strategy Committee	2019	5
Iron-based chemical-looping technology for decarbonising iron and steel production	link	Bahzad, H., Katayama, K., Boot-Handford, M. E., Mac Dowell, N., Shah, N., & Fennell, P. S	2019	5
Japanese Efforts to Promote Steel Reuse in Building Construction	link	Fujita, M., Fujita, T., Iwata, M., Iwata, Y., Kanemitsu, T., Kimura, U., ... & Wada, M.	2023	4
Liberty Steel UK to curtail EAF production, turn to steel imports	link	EUWID	2023	4
Material efficiency: A white paper	link	Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E.	2011	5

Title	URL	Author	Year	IAS
Metal Flow 2025 – Metal Packaging Flow Data Report	link	WRAP	2020	5
Metal packaging industry provides new insight into efficient resource management	link	Metal Packaging Europe	n/a	4
Multi-agent systems to improve efficiency in steelworks	link	Vincenzo Iannino, Valentina Colla, Claudio Mocci, Ismael Matino, Stefano Dettori, Sebastian Kolb, Thomas Plankenbühler, Jürgen Karl,	2021	4
New UK Steel Key Statistics Guide - April 2022	link	Make UK	2022	5
Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain	link	Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Cullen, J. M., & Allwood, J. M.	2018	5
Pedal to the Metal: It's not too late to abate emissions from the global iron and steel sector	link	Caitlin Swalec (Global Energy Monitor)	2022	5
Policy support for and R&D activities on digitising the European steel industry	link	Merlene Arens	2021	5
Progress report on recycling and recovery targets for England 2020	link	UK Government	2022	5
Real and perceived barriers to steel reuse across the UK construction value chain	link	Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Allwood, J. M., & Cullen, J. M.	2017	5
Residue valorization in the iron and steel industries: Sustainable solutions for a cleaner and more competitive future europe	link	Rieger, J.; Colla, V.; Matino,I.; Branca, T.A.; Stubbe, G.; Panizza,A.; Brondi, C.; Falsafi, M.; Hage, J.;Wang, X.; et al	2021	5
Resource efficiency analysis of lubricating strategies for machining processes using lifecycle assessment methodology	link	Alessio Campitelli Jorge Cristóbal Julia Fischer Beatrix Becker Liselotte Schebek	2019	5
Resource Efficiency Challenges in the Steel Industry	link	Quinn, P. (Tata Steel)	2019	5
Resource Efficiency for the European steel industry	link	European Commission	2011	2
Resource Efficiency in the Steel and Paper Sectors: Evaluating the Potential for Circular Economy	link	Chattopadhyay, S.; Mitra, R.; Kumar, N.	2019	4

Title	URL	Author	Year	IAS
Resource efficiency: Potential and Economic Implications	link	UNEP	2017	5
Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe	link	Branca, T.A.; Colla, V.; Algermissen, D.; Granbom, H.; Martini, U.; Morillon, A.; Pietruck, R.; Rosendahl, S.	2020	5
Re-use of structural steel: the opportunities and challenges	link	Tingley, D. D., & Allwood, J. M.	2014	5
Role of manufacturing towards achieving circular economy: The steel case	link	Wang, P., Kara, S., & Hauschild, M. Z.	2018	5
Scrap groups unhappy with EU vote to tighten controls on ‘waste’ metal exports to non-OECD nations	link	Lee Allen (Fast Markets)	2022	4
Scrap Material Specifications for Suppliers	link	Charter Steel	2018	4
Scrap Metal Prices in the United Kingdom	link	Price of Scrap Metals	2023	4
Scrap Raw Materials Specification Manual	link	Commercial Metals Company	2020	4
Slow to decarbonize, global steelmakers face USD 518 billion stranded asset risk	link	Caitlin Swalec (Global Energy Monitor)	2022	5
Smart steel: New paradigms for the reuse of steel enabled by digital tracking and modelling	link	Ness, D., Swift, J., Ranasinghe, D. C., Xing, K., Soebarto, V	2015	5
Steel and the four R's	link	TATA Steel	2020	4
Steel in the Circular Economy: A lifecycle perspective	link	World Steel Association	2015	5
Steel made in Europe is the backbone of sustainability	link	Eurofer	n/a	3
Steel, metals scrap merchants, recyclers fear trade impact of revised EC shipment rules	link	Eurometal	2023	4
Steel’s recyclability: demonstrating the benefits of recycling steel to achieve a circular economy	link	Broadbent, C.	2016	5
Strategy Paper On Resource Efficiency in Steel Sector Through Recycling of Scrap & Slag	link	Ministry of Steel Government of India	2019	4
Study finds recycling metal packaging reduces GHG linked to production by up to 60%	link	Peter Dennis (Circular Online)	2022	4

Title	URL	Author	Year	IAS
Supply network collaborations in a circular economy: A case study of Swedish steel recycling	link	Berlin, D., Feldmann, A., Nuur, C.	2022	4
Sustainable stainless steel is key element in circular economy	link	Outokumpu	n/a	4
Technology and material efficiency scenarios for net zero emissions in the UK steel sector	link	Garvey, A., Norman, J. B., & Barrett, J	2022	5
The Current Capacity Shake-up in Steel and How the Industry is Adapting	link	Chalabyan, A., Mori, L., & Vercammen, S.	2018	5
The evolution of resource efficiency in the United Kingdom's steel sector: An exergy approach	link	Carmona, L. G., Whiting, K., Carrasco, A., & Sousa, T.	2019	5
The future is circular: Enabling a circular economy	link	TATA Steel	n/a	4
The prospects for ‘green steel’ making in a net-zero economy: A UK perspective	link	Griffin, P. W., & Hammond, G. P. .	2021	5
The recycled content of steel for packaging	link	Apeal	n/a	2
The role of geometric characterization in supporting structural steel reuse decisions	link	Yeung, J., Walbridge, S., & Haas, C	2015	4
The Roles of Energy and Material Efficiency in Meeting Steel Industry CO_2 Targets	link	Milford, R.L., Pauliuk, S., Allwood, J.M., and Müller, D.B.	2013	5
The use of steel in the United Kingdom's transport sector: A stock–flow–service nexus case study	link	Carmona, L. G., Whiting, K., Haberl, H., & Sousa, T.	2021	5
Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry	link	Winning, M., Calzadilla, A., Bleischwitz, R., & Nechifor, V.	2017	5
Towards Deep Decarbonisation of Energy-Intensive Industries: A Review of Current Status, Technologies and Policies	link	Bataille, C.	2020	5
Trade remedies notice 2022/02: safeguard measure: tariff-rate quota on steel goods	link	UK Government	2022	5
UK exports most steel scrap in Europe in 2020	link	Joshua Dohert (letsrecycle)	2021	4
UK Steel Industry: Statistics and policy	link	House of Commons Library	2021	5

Title	URL	Author	Year	IAS
UK Steel Sites	link	Make UK	2023	4
UK Steel: Foundations for a Sustainable Steel Sector	link	Make UK	2021	5
Understanding and overcoming the barriers to structural steel reuse, a UK perspective	link	Tingley, D. D., Cooper, S., & Cullen, J	2017	5
Unlocking Plant-level Resource Efficiency Options: A Unified Exergy Measure	link	Hernandez, A. G., & Cullen, J. M.	2016	5
Waste and Recycling Statistics	link	UK Government	2013	5
Waste Disposal and Recycling in Steel Industry	link	Steel Technology	n/a	4
Water management policy paper	link	World Steel Association	2020	5
Engineers Use DfAM to Reduce Shaft Weight by over 50%	link	Philip Keane	2023	3
How we make steel	link	British Steel	2023	3
Safety of the Electric Arc Furnace (EAF): Risk analysis of Electric Arc Furnaces	link	GT Engineering	2023	2
Sustainability and Steel: FAQs	link	British Constructional Steelwork Association	2023	3
Contribution of the steel industry to the UK economy. House of Commons Library Debate Pack	link	Keep, M.; Jozepa, I.; Ward, M.	2023	5
European Steel in Figures 2022	link	Eurofer	2022	5
Short Range Outlook October 2022	link	World Steel Association	2022	5
Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics – A review	link	Hertwich, E.G.; Ali, S.; Ciacci, L.; Fishman, T.	2019	5
HISTAR® Innovative high strength steels for economical steel structure	link	ArcellorMittal	2020	5
Steel recycling	link	Galvanizers Association	2023	3
Embodied carbon, embodied energy and renewable energy: a review of environmental product declarations	link	Anderson, J.; Moncaster, A.	2022	5
UK Hydrogen Strategy	link	UK Government	2021	4
Current Trends in Automotive Lightweighting Strategies and Materials	link	Czerwinski, F.	2021	5

Appendix D: List of discarded measures

During the literature review, several measures were discarded for reasons, such as overlaps in definition, or outside of the agreed scope (See Table 32).

Table 29: List of discarded resource efficiency measures

Theme	Sub-theme	Measure name	Measure indicator	Reason
Manufacture	Material substitution	Partial substitution of fossil-carbon reducing agents with renewable biomass in steelmaking.	% reduction in carbon emissions from UK steelmaking from substituting fossil carbon reductants with biomass	It was impossible to separate the resource efficiency benefits from the fuel switching benefits for this measure and as a result the measure was excluded from this study.
Manufacture	CCUS	Carbon abatement of steel production	Tonnes of carbon captured and stored	CCUS is out of scope for this project
Manufacture	Energy recovery	Energy efficiency	% Reduction in energy consumption	Energy efficiency is out of scope as this project is focused on resource efficiency.
Manufacture	Yield improvement	Use Exergy and Sankey diagrams to monitor resource and energy efficiency	Exergy	This is already commonplace in UK steel manufacture and was considered redundant
Manufacture	Yield improvement	Automation and process control of coke making, sintering, blast furnace operation	% of production sites automating their processes	Automation is already readily employed where appropriate in UK steel manufacturing sites
Manufacture	Material substitution	Replacement of scrap with Direct Reduced Iron (DRI)	% of DRI per tonne of crude steel produced	Limited potential for resource efficiency benefits from replacing scrap with DRI
Manufacture	Energy Recovery	Recovery and utilisation of heat and steam	Litres of hot water recovered from cooling beds	Both water management and energy efficiency are out of scope for this project

Theme	Sub-theme	Measure name	Measure indicator	Reason
Manufacture	Yield improvement	Production yield improvement	% reduction in semi-manufacturing scrap	This measure was only mentioning in one source and with minimal detail.
Manufacture	Scrap management	Reduction of scrap generation in product manufacturing	% reduction in scrap generated during product manufacturing	Scrap generated during production of steel is already immediately recycled internally in the steel mills
Manufacture	Energy recovery	Use of HIsarna technology	Tonnes of carbon emitted during primary steelmaking	A source from the literature review indicated this technology would not be available before 2035[194]
Manufacture	Water management	Use of water footprint calculation (ISO 14046: 2014) based on a lifecycle assessment for water use monitoring	Water footprint	Water management is out of scope for this resource efficiency study.
Manufacture	Water management	Decreased water consumption through reduced evaporation	Volume of water consumed	Water management is out of scope for this resource efficiency study.
Manufacture	Water management	Decreased water consumption through prevention of leaks	Volume of water consumed	Water management is out of scope for this resource efficiency study.
End-of-Life	Water management	Increased recycling of water from steel production	Volume of recycled water	Water management is out of scope for this resource efficiency study.
End-of-Life	Water management	Increased reuse of water from steel production	Volume of reused water	Water management is out of scope for this resource efficiency study.

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[194] UK Steel (2022). Net Zero Steel. A vision for the future of UK steel production