DEMAND-LED INNOVATION FOR THE AUTOMOTIVE SECTOR: MATERIALS REQUIREMENTS IN 2030 AND BEYOND

D2 Literature Assessment

Report for: Innovate UK

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Glossary

Term	Definition
AHSS	Advanced High Strength Steel
ALFED	The Aluminium Federation
ALUPRO	The Aluminium Packaging Recycling Organisation
ASM	Asynchronous Induction Motors
ASR	Automotive Shredder Residue
ASTM	American Society for Testing and Materials
BEIS	Department for Business, Energy, and Industrial Strategy
BEV	Battery Electric Vehicle
BF	Blast Furnace
BF-BOF	Steel production process using BF and BOF
BF-CCS	BF where CCS technology is applied
BIW	Body in White
BOF	Basic Oxygen Furnace
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes (collectively called BTEX)
CAEF	The European Foundry Association
CBAM	EU Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CED	Consumed Energy Demand
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymers
CISL	Cambridge Institute for Sustainability Leadership
CO2	Carbon dioxide
CtG	Cradle-to-Gate
DEFRA	Department for Environment, Food, and Rural Affairs.
DESNEZ /	
DESNZ	Department for Energy Security and Net Zero
DG CLIMA	Directorate-General for Climate Action
DR	Direct Reduction
DRI	Direct Reduced Iron
DRI-CCS	DRI where CCS technology is applied
DRI-EAF	Steel production process using DRI and EAF
EAF	Electric Arc Furnace
EC	European Commission
ELV	End-of-Life Vehicle
EoL	End of Life
EPD	Environmental Product Declaration
ESO	Electricity System Operator
ETC	Energy Transitions Commission
EV	Electric Vehicle
Fe	Iron
FES	Future Energy Scenarios
GDP	Gross Domestic Product
GFRP	Glass Fibre Reinforced Polymers
GHG	Greenhouse Gas
GJ	Gigajoule
GJ/t	Gigajoule per tonne
Gt	Gigatonne
GVW	Gross Vehicle Weight

GW	Gigawatt
GWP	Global Warming Potential
H2GS	H2 Green Steel
H-BF	Hydrogen injection into the BF
HDPE	High-Density Polyethylene
HDPE	High-density Polyethylene
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
HFQ	Hot Form Quenching
HSS	High Strength Steel
HTP	Human Toxicity Potential
IAI	International Aluminium Institute
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICEV-D	Diesel ICEV
ICEV-G	Petrol (Gasoline) ICEV
IEA	International Energy Agency
JLR	Jaguar Land Rover
kg	kilogram
LCA	Life cycle assessment
LCE	Lifecycle Energy
LDPE	Low-density Polyethylene
LDV	Low Duty Vehicle
LGV	Light Goods Vehicle
MCDA	Multi-criteria Decision Analysis
MDPI	Multidisciplinary Digital Publishing Institute
MJ	Megajoule
Mt	Megatonne
MVR	Mechanical Vapour Recompression
NdFeB	Neodymium magnets
NFC	Natural Fibre Composites
NFRP	Natural Fiber Reinforced Plastic composites
NG	Natural Gas
NG-DR	Direct Reduction using Natural Gas
NOx	Nitrogen oxides
OECD	Organization for Economic Cooperation and Development.
OEM	Original Equipment Manufacturer
ONS	Office for National Statistics
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbons
PAN	Polyacrylonitrile
PBM	Pressure Bag Moulding
PBT	Polybutylene Terephthalates
PCB	Polychlorinated Biphenyls
PE	Polyethylene
PHEV	Plug-in Hybrid Electric Vehicle
PM	Pollutant Matter
PP	Polypropylene
PSM	Permanent Magnet Synchronous-traction Motor
PU	Polyurethane
PUR	Polyurethane
PVB	Polyvinyl Butyral

PVC	Polyvinyl Chloride
REA	Rapid Evidence Assessment
REALITY	Recycled Aluminium Through Innovative Technology
RiCK	Ricardo Centre of Knowledge
RTF	Resin Transfer Moulding
SMMT	Society of Motor Manufacturers and Traders
SOx	Sulphur oxides
SSD	Solid State Drive
SUV	Sport Utility Vehicle
SX-EW process	Solvent Extraction and stripping before undergoing Electrowinning
t	tonne
TGR-BF	Top-gas Recycling in a BF
TWDCI	thin-walled ductile cast iron (TWDCI)
UHSS	Ultra High Strength Steel
UKRI	UK Research and Innovation
VOC	Volatile Organic Compound
WEF	World Economic Forum
ZEV	Zero Emission Vehicle

EXECUTIVE SUMMARY

UKRI's Transforming Foundation Industries Challenge, delivered by Innovate UK, EPSRC and ESRC: Economic and Social Research Council, aims to reduce energy and resource use within the foundation industries (metals, glass, chemicals, ceramics, cement and paper). The purpose of this study is to support these industries to understand the anticipated demand for materials in 2050 by their downstream customers in the automotive sector. The goal of this "Demand-led Innovation research" is to support the foundation industries to understand the market opportunities and challenges, potential impact of disruptive products or business models, and the relevant research and development efforts required to meet the automotive sector's needs.

This report forms part of a wider study on demand-led innovation for the automotive sector which comprises of a number of tasks to achieve the goal stated above:

- Task 1 – Seeks to identify key automotive stakeholders who could be interested in demand-led innovation initiatives.
- Task 2 – A desk-based research activity that provides the evidence base for the study which is presented in this report.
- Task 3 – Stakeholder engagement with the identified organisations via interviews and workshops to gather information on current and future innovation challenges.
- Task 4 – The identification of potential demand-led innovation interventions and gathering of an engaged stakeholder community.

The goal of this report (Task 2) is to build the evidence base of this project, particularly in terms of material trends for the automotive sector, quantify the demand of foundation materials from the automotive sector from 2030 onwards, and identify examples of demand-led innovation initiatives in the automotive sector as 'case studies'. The outputs of this task are also expected to inform the extensive stakeholder engagement activities equipping interviewers with key insights from the critical review of the collected published literature. These observations will focus on the innovation challenges related to foundation industry products by studying the current knowledge gaps, identified opportunities, synergies and trade-offs.

Task 2 initiated with a literature collection and review via rapid evidence assessment, aims to gather evidence of existing and future demand for foundation industry materials and to generate a list of innovation challenges stemming from automotive material requirements. Beginning with a longlist of foundation materials used in UK automotive manufacturing, the literature was assessed to understand the policy context for automotive manufacturing in the UK, its key export markets, and comparisons were made with high-level trends in material demand resulting from a bespoke quantitative assessment on material demand in UK automotive production. This longlist material analysis also emphasised currently reported domestic material production and production volumes, in addition to their sustainability credentials.

A shortlisting process was undertaken to identify key materials which exhibit the following characteristics which include material share of vehicle weight, UK material production rates, UK's influence on the material's supply chain, innovation potential and material sustainability. The resulting shortlist contained six groups of materials: **Cast iron & steel, Aluminium, Plastics, polymers and composites, Copper, and Glass.**

Shortlisted materials were then subjected to a deep dive, utilising relevant observations made from a critical review of the collected literature, emphasising their current method of production, innovations in production methods, the estimated current and future demand for these materials, and their sustainability performance.

Four key findings and cross-cutting trends were identified to run through each of these material deep dives.

1. **Manufacturers continue to explore mass reduction in vehicles (although for cars, at least, there is a clear preference for larger vehicles which is still driving an increase in average mass), and therefore lighter materials, to deliver use-phase emissions savings.** This may drive demand away from traditional cast iron & steel to lightweight alternatives like high-strength steels, aluminium, and non-metal composites. However, **the current lack of efficient means of producing low-cost lightweight materials and ensuring their stable supply is identified as one of the key innovation challenges**.
2. **Manufacturers are actively seeking closed-loop supply chains to reduce the sustainability impacts of automotive materials and preserve scarce resources.** This is driving demand towards

suppliers with materials that contain increased amounts of recycled content, and towards materials that have high recyclable potential. While this may be ideal, **current lack of close to 100% pure recycled material could be perceived as an innovation challenge**. A key contributor to this hurdle is identified as the current lack of an economically feasible method to convert alloys to 100% pure base metals.

3. **Manufacturers are increasingly favouring materials from suppliers using low or zero-carbon energy.** This is driving demand towards suppliers that can evidence full use of renewable energy in their production processes, and towards materials where the use of electricity in their supply chain comprise a large part of their sustainability impacts. Nevertheless, **the significant reliance of foundation industries on grid electricity** (which is slowly but steadily decarbonising) **could be counted as a key challenge**, due to the feasibility-issues associated with retrofitting production plants with zero carbon energy generation technologies.
4. **Manufacturers are ultimately concerned about the end-users (vehicle users) and may not adopt material innovations beyond a certain degree without incentives.** A key balance through the above trends is that any material or vehicle design changes must be cost-effective for the manufacturer and ultimately the end consumer, as well as maintaining favourable outcomes such as good fuel economy and durability. **High-cost differential related to the use of low-carbon or zero carbon electricity and relevant innovative raw materials** (e.g., secondary resources, bio-based resources), lead to the higher mark-ups of the final product, thus leading to decisions relating to cost of ownership. Also, the **lack of innovative sustainability-driven business practices such as "access-based" business models**, between material producers and automotive OEMs, could limit the means of enabling material circularity and overall material life cycle cost reduction capabilities.

This rapid evidence assessment sheds light on many of the challenges and opportunities that face the UK foundation industries, but also identifies a number of knowledge gaps. The remaining part of this study aims to fill those knowledge gaps by engaging with UK stakeholders in automotive manufacturing, with the ultimate goal of producing a defined list of industry-level innovation challenges that could be addressed by the foundation industries, followed by the definition of common innovation challenges that cut across the automotive sector as a whole.

1 INTRODUCTION

1.1 STUDY AIMS AND OBJECTIVES

This study focuses on the automotive sector, a key consumer of foundation industry materials and a stakeholder with significant influence over the foundation industry materials supply chain. This work will gather evidence to quantify existing and future demand for foundation industry materials and generate a list of innovation challenges stemming from material requirements from the automotive sector. This will be used to inform further options for demand-led innovation programmes/initiatives, enabling foundation industry companies to gain more certainty on where to focus future research efforts and investments. A list of key project outputs is given below.

Key project outputs:

- An engaged community of automotive sector stakeholders committed to involvement in a demand-led innovation programme (Task 1).
- Literature analysis of current and future material requirements from the automotive sector; including trends and innovation areas (Task 2).
- Lists of innovation challenges from the automotive sector on a company and industry level (Task 3 & 4).
- Suggestions on further areas of activity to support demand-led innovation in the automotive sector (Task 4).

1.2 REPORT STRUCTURE

This report outlines the findings of Task 2 on the study Demand-led innovation for the automotive sector. It focuses on a literature analysis of current and future material requirements from the automotive sector for foundation industry materials and is structured in the following manner:

- The remainder of this section introduces the foundation industry materials.
- Section 2 sets the policy context for the study and outlines political influences on potential future material demands from the automotive sector.
- The methodology used to conduct the literature review, including how the shortlist of materials presented for detailed analysis, is presented in Section 3.
- Section 4 provides quantification of expected material demands trends up to 2050, based upon literature analysis and Ricardo's own work.
- The key focus of this study is contained within Section 5. Here, extensive analysis of all the shortlisted materials is presented which includes detailed information on production methods and volumes, emerging innovation, current and future use, and the sustainability performance of each material. This analysis is supplemented by case studies where appropriate, to highlight existing areas of demand-led innovation in practice across the automotive sector.
- Section 6 is dedicated to a discussion on the overarching trends that emerged during the literature review.
- A concluding discussion along with key findings is presented in Section 7 before an overview of how the results from this literature analysis will be used further in the context of this study is outlined in Section 8.

1.3 INTRODUCTION TO THE FOUNDATION INDUSTRY MATERIALS

The foundation industry materials include metals, chemicals, cement, glass, ceramics, and paper. These materials form a cornerstone of all UK construction and manufacturing industries, including the automotive sector. The UK has existing foundation materials production facilities that already supply materials into the UK automotive sector. An example of these is included in Table 1-1 . Specific details of their use in the automotive sector including quantities are presented in Section 5.

Table 1-1: UK foundation industry production site examples

Material	Company	Location
Steel	British Steel Tata Steel	Scunthorpe Port Talbot
Aluminium	Novelis Alcoa	Kingston upon Hull, Warrington Banbury
Chemicals	INEOS BASF Croda International	Grangemouth (HDPE & PP), Hull (Acetyls), Runcorn (Chlorine and sulphur chemicals) Bradford (Dispersions and additives) Snaith (Speciality chemicals)
Cement	Hanson UK Cemex Lafarge Cement	Ketton Rugby, South Ferriby Hope Valley
Glass	Guardian Glass Pilkington Owen-Illinois	Google, Deeside St Helens Harlow
Ceramics	Churchill China Steelite International Portmeirion Group	Stoke-on-Trent (all)
Paper	DS Smith* Mondi Group Smurfit Kappa	Kemsley Scunthorpe Blackburn

*Recently agreed merger with Mondi Group

Current innovation trends across the foundation industries centre around the need to become more sustainable including drives for increased circularity, improved recyclability, increased efficiency of production and emission reduction across the production process. Further advancements in material science also drives innovation with improvements on material strength, high-performance and production from a wider range of raw or secondary materials. External pressure from consumers, the political landscape and competition from non-foundation industries materials are creating challenges, and therefore opportunities, for the foundation industries to address. The remainder of this study will seek to highlight those main challenge areas and identify where further support/direction is needed.

2 POLICY CONTEXT

Securing reliable, sustainable and stable access to both foundation and critical raw materials has currently become imperative to governments and businesses. The UK Government has continued to establish partnerships with global businesses, to provide a stable business environment and an innovation test bed, in return for employment and economic growth. For example, the Automotive Sector Deal established in 2018, as a part of the Industrial Strategy, has supported and improved the productivity of the automotive sector. This includes the value of vehicle and engine exports rising from 81.5% in 2018 to 88.6% in 2022 (SMMT, 2020) and R&D innovations in the sector increasing by about 10-20% on an annual basis (BEIS, 2018). Some of the key support commitments provided in this deal include a significant share of investment into automotive R&D and a transition to ultra-low and zero-emission vehicles.

Within the “Net-Zero Strategy: Build Back Better”, published in 2021, one of the key strategies includes improving the sustainability of some of the most used, high-impact automotive materials by identifying innovative strategies for their retention in the consumption loop (via resource efficiency and circularity) and supporting innovative clean methods for producing raw materials, particularly steel and critical materials (HM Government, 2021). This guidance also introduces the UK Critical Minerals strategy which has now been published and sets out approaches for securing the UK’s access to critical materials. Considering the competitiveness in the space of critical materials security at a global level, the UK aims to establish stable international supply chains for specific critical materials. There is also a greater emphasis on building mineral production capacities and supply chains within UK borders, as a means of mitigating supply risks and developing resilience. The core strategies proposed include upskilling current labour force, supporting and exploiting innovation capital and enhance material circularity by updating the current regulatory framework (HM Government, 2022). Crucially, enhancing material circularity through reuse, recover and recycle, is anticipated to bear some of the demand burden over the medium and long-term, as proposed in the research brief by the UK Parliament published in 2022 (UK Parliament, 2022a).

Sustainability of automotive parts and components is expected to become a highly regulated space, particularly in geographies where the UK has strong automotive markets, such as the EU and the US. The EU Industrial Strategy which has led to the adoption of the EU Strategy for plastics (European Commission, 2023a), clean steel (EUROFER, 2023) and circular textiles (European Commission, 2023b), aims to target the design and production of these materials using clean green energy, and ensure that materials can be reused, recovered and recycled by 2030. The EU Carbon Border Adjustment Mechanism (CBAM) introduces a carbon reporting requirement and ultimately a tariff on specific goods (iron, steel and aluminium, in relation to this study) from carbon-intensive sectors imported into the EU. The regulation aims to reduce carbon emissions from goods imported to the EU by encouraging cleaner industrial production in non-EU countries and preventing competitive disadvantage against countries with weaker environmental regulations (so called 'carbon leakage'). CBAM further serves to protect EU companies that have invested in green technologies, promote the implementation of carbon market policies in non-EU countries (to keep revenues within producer countries), and generate revenue that could be used to support climate policies in the EU or other countries (EU Commission, 2023c). EU Sustainable Batteries Regulation, which is at the forefront of implementing best practices in sustainability across a battery’s supply chain is expected to be a ‘precedent’ for most global policies on automotive battery sustainability. This policy sets stringent requirements and targets on the recycled content for specific critical raw materials from the time of the policy implementation for “economic operators”[1] placing batteries on the EU market for the first time (European Commission, 2023d). Similarly, the End-of-Life Vehicle (ELV) Directive sets targets for vehicle and component reuse, recycling and recovery to prevent waste from vehicles and improve the environmental performance of a vehicle overall (European Commission, 2023e). More specifically, the EU Critical Raw Material Act, published simultaneously with the UK Critical Minerals Strategy and ostensibly in line with the UK’s objectives, proposes a set of packages that ensures the EU’s access to secure, affordable and sustainable supply of critical materials (European Commission, 2023f).

In the US, the Inflation Reduction Act of 2022 is a significant piece of legislation that aims to fast-track the electrification of transport. There are provisions in this Act through which large sums of investments ($370 billion) are allocated as tax credits and incentives towards deploying EVs, including commercial vehicles in

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[1] *Economic operator refers to the manufacturer, the authorized representative, the importer, the distributor, the fulfilment service provider or any other natural or legal person who is subject to obligations in relation to the manufacture, preparation for re-use, preparation for repurposing or remanufacturing of batteries, the making available or the placing of batteries on the market, including online, or the putting of batteries into service* (European Commission, 2023d)

bolstering the domestic EV supply chain and more specifically, the domestic critical mineral value chain (Circulor, 2023).

With governments and businesses increasingly leaning towards clean growth, sustainable sourcing and resilient supply chains, the automotive material supply chain has become a highly competitive field. There is an increasing demand to comprehend the relationship between raw materials as a commodity and as products for the automotive sector as well as the associated opportunities and risks to the sector overall.

3 MATERIAL ANALYSIS

3.1 METHODOLOGY

3.1.1 Literature collection and review

A Rapid Evidence Assessment (REA) three step approach was applied to gather the evidence base within Task 2.

Step 1: Key search terms were selected to identify some of the most relevant automotive material for review within this task. As well as general web search tools, Ricardo utilised accessible databases such as Science Direct, and Ricardo's own knowledge portal, RiCK (Ricardo's Centre of Knowledge) database that has over 320,000 abstracted references from trusted sources. For each successful search, the key words used and the sources identified were recorded. The sources reviewed included peer-reviewed journal articles, patents, scientific papers, industrial publications such as statistical data, press release, environmental product declarations, government and industry reports, outputs from projects, and manufacturer websites.

Step 2: An initial screening process was applied to the list of references to determine which were to be included in the review. Screening used appropriate review parameters established at the start of the review process to identify sources that closely align with the objectives and deliverables of this study. An index (spreadsheet) was used to document the results from the screening including information about the subject matter coverage and ratings for quality and relevance.

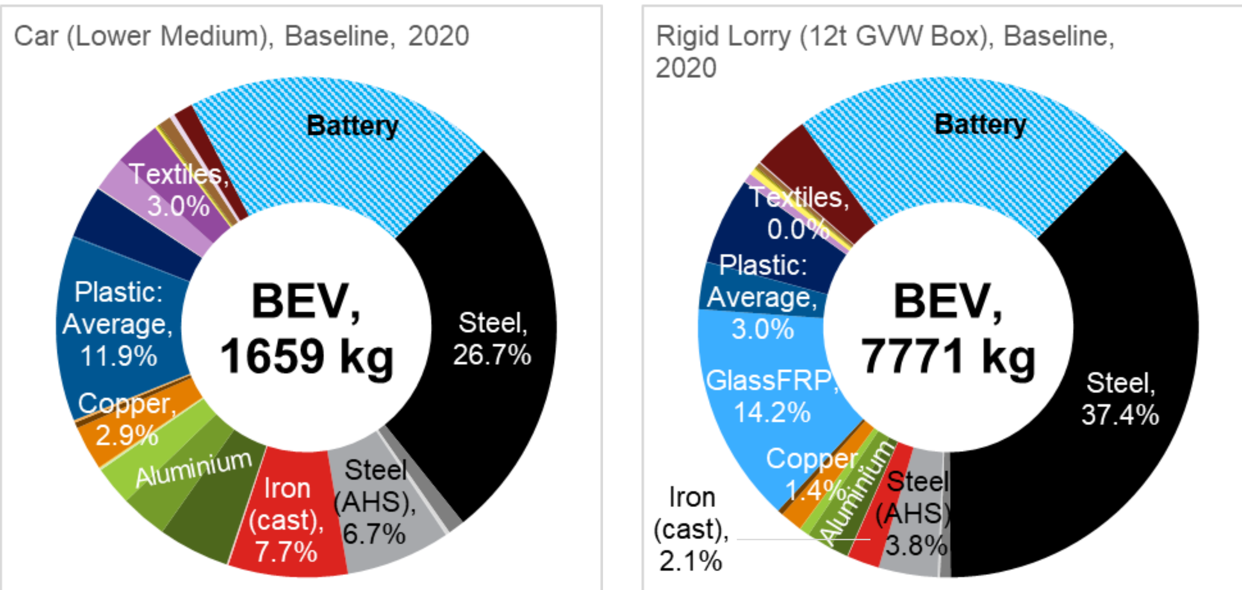
Step 3: Evidence relevant to the scope described above was extracted from the material to support the delivery of the objectives and questions outlined above.

3.1.2 Shortlisting of Foundation Materials

Owing to the complex composition of materials in a vehicle's construction, including their presence through a multitude of alloyed components, a deep dive of all materials could prove to be time consuming. As a result, this study was initiated with the identification of a longlist of materials, following which the most promising and highly relevant shortlist of materials are identified and subjected to a deep dive.

For the longlist of materials, Ricardo's own flagship research, for the European Commission, on vehicle life cycle assessment was adopted. This study undertook an extensive review of light and heavy duty vehicles including diverse material composition by vehicle and powertrain types (Ricardo, 2020).This study led to the identification of seven most used foundation materials in the automotive sector across different vehicle segments (please see Figure 3-1).

Figure 3-1: An exemplary breakdown (by weight) of automotive materials used in the manufacture of BEVs; Source: (Ricardo, 2020)



Materials which are primarily used for glider construction in vehicles, and also have a potential to pose sustainability-related challenges include:

1. Iron and steel (low alloy and AHSS)
2. Aluminium (including wrought aluminium)
3. Plastics
4. Polymer composites
5. Textiles
6. Glass
7. Copper

NOTE: While the longlist emphasises materials used for glider construction, battery-related materials that are currently in high-demand but also pose significant environmental impact such as lithium, cobalt and nickel are also recommended for an in-depth analysis. Besides the high-environmental impact, stemming from their processing methods and resource demands, the critical nature of these materials has posed further challenges in terms of their availability (stable supply) and affordability. Figure 3-2 and Figure 3-3 sourced from Ricardo's study for the European Commission, emphasises the significance of other key battery active materials, including an indication of their potential GHG evolution over medium and long-term periods. However, in line with the scope of this study, we limit their coverage with the emphasis of their importance in this section.

Figure 3-2: Generic composition of EV battery system – average across the different chemistries by battery component area, as a % of total battery pack mass [Source: (Jan Diekmann, 2017)]

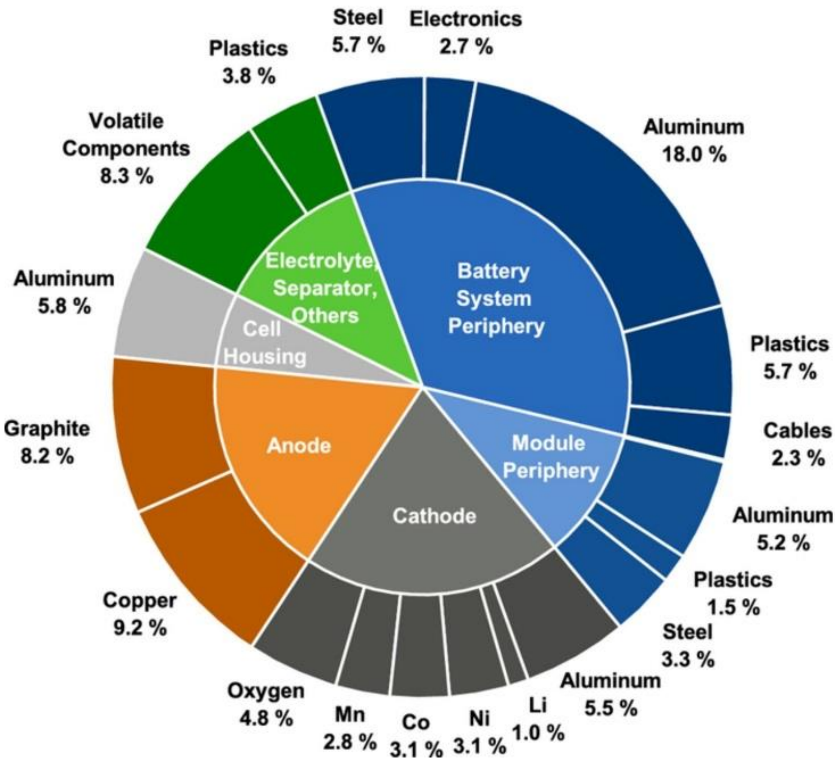
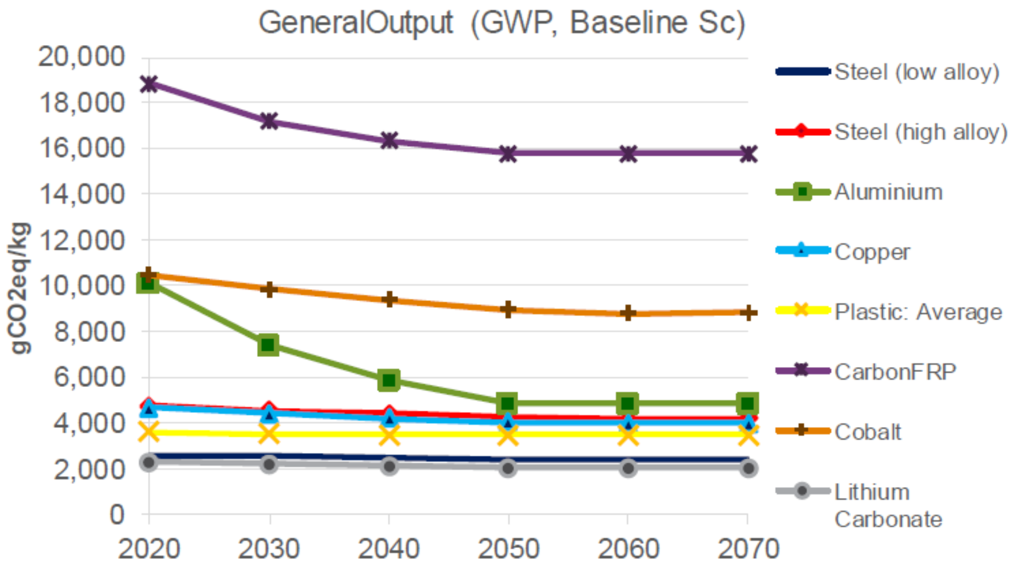


Figure 3-3: Projected future trajectory, reported by Ricardo for a separate study on vehicle LCA, on evolving GHG intensities for key structural and battery materials, under baseline scenario [Source: (Ricardo, 2020)]



To identify a shortlist of materials, the long list of materials needed to be evaluated against a set of cross-cutting selection criteria, for which multicriteria decision analysis (MCDA) approach was adopted. Multi-criteria Decision Analysis (MCDA) is a valuable tool for decision making employing most relevant parameters as 'selection criteria' and applying appropriate weighting factors, depending on the goal and scope of the study. This is particularly suitable for studies which account for a number of complex multi-disciplinary factors.

MCDA was adopted in this study to identify and prioritise foundation materials facing significant challenges in terms of innovation, demand pressure, and sustainability. The goal was to pinpoint materials that may require additional support to address these challenges effectively, such as the manufacturing method. The step-by-step approach to developing the material shortlist has been presented below.

Step 1: Development of selection criteria: A set of selection criteria were adopted, which are based on the overarching goal and the scope requirements of this study (as established section 1.1). These criteria reflect the key attributes of the long list of materials, in relation to the UK supply chain and the automotive sector. These include:

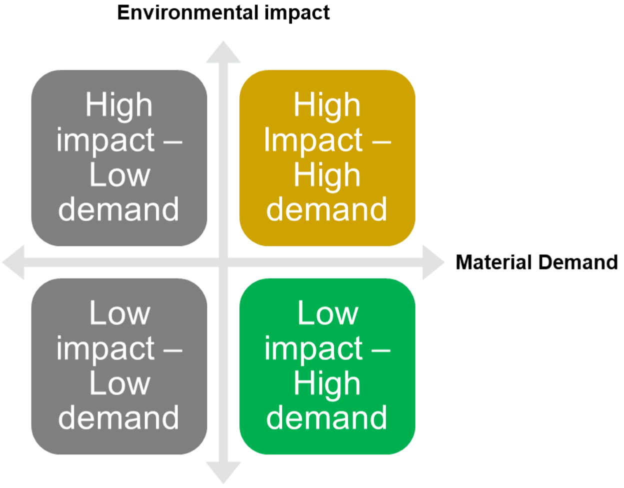
1. Share of contribution to the automotives, in the medium (2030) and long term (beyond 2030)
2. Current material production rates in the UK
3. Domestic influence on the material's supply chain, current and potential
4. Expectations for future evolution of the material (from production and final-product demand perspectives, addressing innovation potential)
5. Sustainability characteristics and potential evolution of these materials, in the medium (2030) and long term (beyond 2030)

The relevance of a specific material to the automotive sector is being accounted as the first and foremost selection criteria. From the literature review, the percentage share of specific materials used in the construction of automotives (cars, LGVs, buses, coaches) is reviewed and explored as crucial input to create the material shortlist. Based on the data availability within Ricardo's major study on vehicle LCA, seven key materials that contribute dominantly to vehicles and traction batteries, were identified (Ricardo, 2020).

Following the consideration of domestic production or refining of the material in the UK, domestic influence of stakeholders on the supply chain was evaluated for each material. From the context of this study, innovative materials could be defined as the anticipated capability of such materials to meet user needs by integration into existing products and improving product performance, while driving down product costs. Innovative materials are expected to potentially contribute towards building the future fleet of automotives, while adhering to core sustainability requirements, mainly environmental performance, and economic feasibility. To devise these innovative strategies, a test bed that will help integrate scientific interventions at production or material-use level; optimise efficiency across supply chains; and therefore, improve the sustainability characteristics of materials, is needed. To enable such innovations, material supply chain, as a whole or in large part, must ideally be based in the UK and/ or managed domestically, from the outset.

Then, the innovative material shortlisted must exhibit market-desirable characteristics (possess high-demand while being environmentally credible[2]). This criterion accounts for the current and anticipated innovative approaches that are currently being proposed or practiced in the relevant industry. These innovations are expected to drive down materials costs and improve their sustainability characteristics, in the medium and long-term. Nevertheless, this criterion also introduces a qualitative element requiring the application of "Material demand - Env. Impact" matrix to this selection process. The purpose of this matrix (Figure 3-4) is to acknowledge, in the selection process that, while materials that are "high demand_ low env. Impact" are most desirable, materials of "high demand- high-env. impact" materials which are promising for current and long-term application, should ideally be treated with equal emphasis. This ensures that potential "breakthroughs" in material innovations, in the temporal scope of this study, and also any changes to the market dynamics are accounted for. NOTE: low-demand materials do not carry value in this voting process and are hence excluded.

Figure 3-4: Material demand vs. environmental impact matrix established to assess the position of materials in the materials long list



Finally, the key sustainability characteristics related to the choice of materials is evaluated. Owing to the complex nature of this criteria, the sustainability of materials is assessed from three key viewpoints:

- **GWP or Global Warming Potential:** measured as percentage share of total GHG contribution per vehicle, in the medium and long-term. Percentage GHG contributions per vehicle is estimated for the long list of materials using data available in the Ricardo's own exhaustive vehicle LCA model developed for the EC commissioned report to DG CLIMA (Ricardo, 2020).
- **Recycling efficiency**: measured as percentage (%), this sub-criterion includes the consideration of overall material recyclability and thus the potential scope for innovation in improving the current recycling rates.
- **Recycled content**: measured as percentage (%), this criterion accounts for the current rates of integrating recycled material into the virgin pool.

Step 2: Development of Weighting factors: With the identification of the selection criteria, the representativeness of these criteria and the potential to upcoming activities, particularly the material deep-dive, were needed. While these aspects are "difficult-to-predict" at this stage or within the scope of this study, applying weighting factors establishes preference towards specific criteria. For the purpose of this work, however, to avoid subjective bias, each of the selection criteria have been uniformly weighted as "1".

Step 3: Partial Scores: Partial score allocation is a step prior to the finalisation of full scores which leads to the 'ranking' process. This step is a key determinant of the quality of the selection process and hence it was

[2] *A condensed set of sustainability credentials, based on life cycle GHG intensity and circularity aspects of the material that focuses on the status of their recyclability at the EoL of their automotive applications and currently used recycled content, have been adopted for this shortlisting exercise. More elaborate sustainability evaluation to be included as a part of the selected material analysis.*

imperative that the contributor was well-informed of the main attributes of the materials. Based on the data collected from the literature review, the long list of materials is partially scored between '0.25' and '1' per selection criteria, informed by their performance under the specifications of that criteria. A score of 0.25' represents 'low-preference' and 1' represents 'high-preference'. The rationale for the adoption of these figures is to purely provide a scale of meaningful measure towards to the final ranking or rating process and not to represent any quantitative thresholds or data under such criteria.

For example, in the case of iron and steel, the dominance in their current contribution (nearly 40-55% depending on vehicle type) towards the construction of vehicles could potentially yield a score of "0.75". However, an assessment of their demand from an initial analysis (based off our initial analysis in section 4) shows that there is a gradual to drastic reduction in their demand over the medium- and long-term period, due to progressive automotive lightweighting efforts, over the medium and long-term periods. As a consequence, the iron and steel score is adjusted to "0.5" points under the "share of contribution towards automotives" criteria. A similar strategy involving a semi-qualitative analysis of the foundation material's performance under the relevant selection criteria is undertaken to inform appropriate allocation of points as "partial scores". These partial scores were then used to calculate the final score in the ranking process, in step 4.

Step 4: Ranking: With the identification of weights and partial scores for each of the material, under relevant selection criteria, the long list of materials were subjected to a final scoring process.

$$\textit{Final score per material} = \sum_{i=1}^{5} Criteria_{weight} \times Criteria_{score}$$

Following the consolidation of the final scores, a selection of 5-6 materials were selected for a multi-dimensional deep-dive relevant attributes captured as a part of the selection criteria. This is expected to provide further information on the trends anticipated with promising innovative material through qualitative and quantitative data. The deep dive of the shortlist of materials will be supported by the review of identified innovation trends in material design and demand and through relevant case studies, in the upcoming sections.

Step 5: Material shortlist: Applying the above MCDA approach led to the shortlisting of the following materials in Table 3-1, also supplemented by the partial scores acquired by each of the materials under relevant criteria. A more detailed account of the rationale for the allocation of appropriate partial scores has been provided in the appendix section A1.1.

Table 3-1: Shortlisted materials taken forward for further evaluation and their relative score established via MCDA

Material	Share of contribution to automotive construction	UK's influence on material supply chain	Innovation potential from customer[1] expectations	Sust. credentials[2]	Domestic production capacity	Score (Out of 5)
Iron and steel	0.5	0.75	0.75	0.66	1	*3.7*
Aluminium	0.75	0.75	0.75	0.8	0.5	*3.6*
Glass	0.75	0.5	0.5	0.66	0.25	*2.9*
Plastics and Polymers	0.75	0.25	0.5	0.66	0.5	*2.7*
Copper	0.75	0.25	0.75	0.66	0.25	*2.7*

[1] Customer, in the context of the automotive sector, refers to the different tier suppliers (parts and component manufacturers and vehicle OEMs;

[2] 'Sustainability credential' criterion was split into three other sub-criteria: % contribution of GHG emissions to the overall vehicle production, current recycling rate of the material and current recycled content achieved, each carrying a weight of '0.33'. Partial score allocation to each of these sub-criteria per material follows an approach similar to other criteria (between 0.25 and 1.0)

4 MATERIAL DEMAND TRENDS

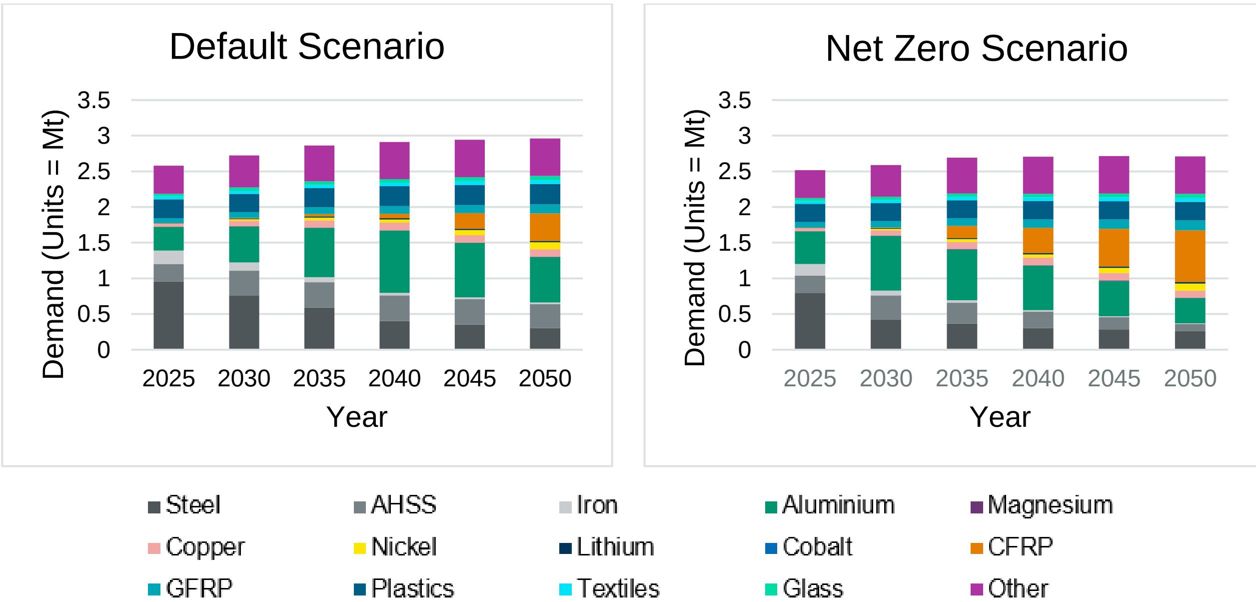
This section presents an overview of expected trends for automotive material demand in the UK. Quantitative estimates are made for the demand for each material used in vehicles between 2025 and 2050, and commentary is made linking these projections to policy developments in the UK and in its core export markets. Further cross-cutting trends are presented in Section 6, following deep dives into each of the shortlisted materials of interest.

High-level quantitative projections on material demand in the UK were made by combining vehicle material composition assumptions taken from Ricardo's proprietary vehicle LCA model based on our previous analysis (Ricardo, 2020), (Ricardo, 2022) with industry projections on vehicle production in the UK (SMMT, 2023a) (SMMT, 2023b). A simplified UK fleet consisting only combustions engine vehicles (ICEVs) and battery electric vehicles (BEVs) in representative vehicle sizes is used. The purpose of this analysis is to illustrate high-level trends rather than estimate accurate absolute values of material demand, and therefore outputs should be interpreted accordingly. More detail on the methodology used, and associated caveats, are provided in Section A1.1.

Figure 4-1 below displays the total annual demand for materials in the UK automotive sector between 2025 and 2050, highlighting materials of interest to the foundation industries. Two scenarios are presented consistent with Ricardo's previous flagship analysis (Ricardo, 2020), demonstrating a range of material demand projections that depend on the ambition to redesign vehicles in the UK and the ambition to create a more sustainable automotive supply chain.

1. **Default scenario**: a baseline scenario including all currently planned/ implemented UK/EU and national policies. This represents a scenario with more limited innovation in automotive material design, but still assumes some changes in materials due to vehicle mass reduction within vehicle segments. Changes in preference across vehicle segments (for example, a shift away from smaller cars to larger SUVs) are not accounted for, meaning that demand estimates across the industry may represent an underestimate.
2. **Net Zero scenario**: based on a long-term strategy to reach a climate-neutral UK/Europe by 2050[3]. This scenario assumes more significant innovation in material design and more significant/extreme levels of vehicle mass reduction being applied, such as more radical material substitution to support improvements in vehicle efficiency, driven by compliance with a more ambitious net zero agenda.

Figure 4-1: Material demand projections for UK automotive manufacturing 2025-2050 (Units = Mt per year)



[3] i.e., based on meeting the Paris Agreement objective of keeping global temperature increase to a maximum of 1.5 °C.

***Source**: Ricardo analysis (see Section 4 for more details on how these projections were derived). Notes: AHSS – Advanced High Strength Steel, CFRP – Carbon Fibre Reinforced Polymers, GFRP – Glass Fibre Reinforced Polymers.*

These figures display two major trends:

(1) **Total demand across all automotive materials flattens after 2035.** In this modelling exercise, vehicle production is assumed to rise in line with GDP growth for all vehicles from 2028 onwards (lacking alternative projections on UK production). However, a flattening trend in total material demand, when expressed in mass terms, maybe anticipated due to the need for significant material efficiency, to counter increased overall vehicle mass (for example growing demand for SUVs and EVs (see Section 6.1).

(2) **The composition of demand for automotive materials is expected to change.** In particular, we see a dramatic reduction in the use of steel in automotive manufacturing in the default scenario, an increase in the near term for aluminium and in the longer term by composites like reinforced carbon- and glass-reinforced polymers. This is even more pronounced in the Net Zero Scenario, where net zero targets necessitate very lightweight vehicles. Concerning critical raw materials used in batteries, an increase in lithium and nickel demand is estimated, owing to the growing share of battery-electric vehicles in the UK fleet. Nickel demand is estimated to increase as it is assumed to be used in the current collector in the cathode of a solid state drive (SSD) battery. However, there is some uncertainty on this aspect, and alternative materials may also be used once SSDs are finally introduced into the market (Kreher, et al., 2023).

4.1 REGULATIONS DRIVING MATERIAL INNOVATION

Several sustainability-related policies in the UK have significantly influenced the automotive industry's choice of materials to align with environmental goals and reduce the overall carbon footprint and are shown below. Likewise, policy developments in the UK's key export markets (particularly the EU) impact the decision-making of manufacturers based in the UK. Some key policies include:

- **The EU Emission Standards and CO_2 regulations**: these impose increasingly stringent limits on emissions of pollutants from vehicles including CO_2, NOx, and PM. The CO_2 regulations, in particular provide some incentivisation to automakers to invest in lightweighting options, including materials, to improve fuel efficiency and reduce exhaust emissions. The shift towards light alloys like aluminium and potentially further in the future the wider use of advanced composites like carbon fibre reinforced polymers may help in achieving these standards by reducing the overall weight of vehicles. However, it should be noted that there are also advances being made in the development of advanced high strength steels and lightweight steel structures (WorldAutoSteel, 2023). The UK complies with the Euro 6 standards (Vehicle Certification Agency, 2023) and transposed the EU's CO_2 regulations after Brexit (UK Parliament, 2021), meaning that these regulations only cover tailpipe emissions. If the UK were to keep pace with EU developments and transpose the new Euro 7 standards, non-exhaust emissions from brakes and tyres would also be included (Council of the European Union, 2023), potentially creating an additional incentive for lightweighting because heavier vehicles tend to create more tyre and brake wear. However, as the fleet increasingly electrifies, these policies may have a lowered impact on material demand in the automotive industry since they primarily incentivise change in ICEVs. However, mass reduction is also a valuable tool for improving efficiency of EVs and can help to minimise battery capacity requirements to meet electric range/utility design objectives.
- **Vehicle electrification policies**: introducing mandated levels of electric vehicles in the UK fleet as laid out in the **ZEV mandate** (Department for Transport, 2023) will lead to an increase in demand for battery related materials, encompassing not only the active materials within the batteries (e.g. lithium, nickel[4]) but also for current collectors (i.e. aluminium, copper) and also the casing materials. These policies will drive material demand significantly in the short term, especially for critical materials, but have relatively little impact when the fleet has been fully electrified.
- **Circular economy policies**: The UK government's **Resource and Waste Strategy** aims to minimise waste and encourage a circular economy (HM Government, 2018). This strategy influences the automotive sector to focus on sustainable materials, recycling, and reuse. Likewise, the **End-of-Life Vehicle (ELV) Directive** in the EU encourages the recycling and recovery of materials from end-of-life vehicles (European

[4] Note that while lithium and nickel are currently prevalent in EV batteries, novel battery chemistries are being introduced with zero nickel (e.g. LFP) and zero lithium (e.g. Na-ion) chemistries, which may offset some of this trend. However, since battery materials are not the focus of this study, this balance is not explored further.

Commission, 2023e). Automakers are exploring materials with lower environmental impact, and there is a push towards using recycled or bio-based materials in car manufacturing, driving the use of materials where there is greater potential for circular production. These policies will continue to drive the nature of material demand in the UK, placing greater scrutiny on the recycled content and recyclability of automotive materials.

- **The EU (and upcoming UK) Carbon Border Adjustment Mechanisms**:
  - The EU CBAM will require embedded emissions to be reported from January 2026 onwards, imposing additional costs on carbon-intensive imports of iron, steel and aluminium into the EU (EU Commission, 2023c). The long lead times and contract durations in automotive production will necessitate considerations in material choice before this date. To the extent that UK production of these materials is more carbon intensive than either (a) European production, for which additional costs are already imposed via the Emissions Trading System, or (b) production in the rest of the world, where export prices can be directly inflated by CBAM, this could make the **UK's exports** less competitive in the European market. This represents an opportunity in that this could incentivize UK iron, steel and aluminium industries to invest in reducing carbon emitted during production in order to maintain price parity with competitors in the EU market. This could also incentivise innovation in other lightweight, low-carbon, non-metal materials, although any demand substitution would naturally represent a threat to the covered UK metal industries.
  - The UK has also announced that it will implement its own CBAM by 2027. Unlike the EU CBAM, this is not only expected to cover scope 1 and 2 emissions from iron, steel and aluminium, but also glass and ceramics (DESNZ, 2023). This should provide reassurance that from 2027 onwards at least, **UK domestic supply** of these materials to UK automotive manufacturers will receive support against competition with carbon-intensive materials produced in the EU or in the rest of the world. This could increase confidence in the level of domestic demand in the medium and long term, galvanising low-carbon investment decisions in the near term.

5 DEEP-DIVE OF SELECTED FOUNDATION MATERIALS

Following the review of the collected literature, we aim to provide a detailed account of the foundation material's performance through:

1. A brief overview of the current production processes employed in the production of the foundation materials and production volumes;
2. A brief overview of the emerging technologies following changing requirements in product designs, material manufacturing technologies, from both customer perspective and from policy and regulatory influences;
3. A quantitative assessment of the current use and future demand of these materials in 2030 and beyond; and
4. An overview of the sustainability characteristics of these selected materials from the perspectives of emissions to air with emphasis on global warming potential[5] (GWP), resource demand and circularity considerations.

An overview of the environmental performance of each of the primary materials was developed from the review of relevant collected literature. This review is also supplemented with some key qualitative highlights that are crucial for addressing their current and long-term sustainability.

Energy consumption – *Ideally minimise* – each material's performance is qualitatively analysed in relation to the "cradle-to-gate" (CtG) energy intensity trends (where available) in the foundation material production.

Material consumption – *Ideally minimise* – refers to the ratio of 1 kg of final primary material acquired from quantities (kgs) of raw material (ore, in the case of metals), accounting for the mineral content of ores, and the current rate of extraction achieved (in %). The purpose of this indicator is to highlight the material efficiency of the current production processes.

Waste generation – *Ideally minimise* – a qualitative indication of the most relevant CtG waste streams (including material losses), that follows the review of relevant life cycle assessment (LCA) literature (e.g. LCA studies, including material EPDs).

Potential for circularity – *Ideally maximise* – To preserve the embodied carbon and energy in these materials, current practice and future potential for the use of production scraps and material recovered from ELV (end of life vehicle) scraps to reach 100% circularity is reviewed under this indicator.

5.1 CAST IRON & STEEL

Both cast iron and steel are produced from the main feedstock: pure iron refined from iron ore. However, final product refinement processes, use in the automotive sector, and EoL considerations differ. Therefore, these aspects alone have been differentiated between iron and steel in the subsequent sub-sections.

5.1.1 Material production methods and volumes

5.1.1.1 Pure Iron

The main production pathway for pure (pig) iron is from iron ore, which is extracted through drilling and blasting (use of explosives) of iron ore deposits. Harvested iron ore is then subjected to iron ore beneficiation process (crushing and screening of ore fractions for high iron concentrations). Fractions of high-quality lumps are then transported to an iron production facility. Iron ore production and processing, encompassing the upstream stages, is expected to be responsible for roughly 9-12 kgCO_2e per tonne of ore, depending on the location of the various sites (Haque and Norgate, 2015). Smelting of pre-processed pellets or sinter of raw iron ore in a blast furnace (BF), accounts for 90% of global iron production (Indus University, 2020). Raw iron ore is pre-processed into sinter or pellets at dedicated plants, at temperatures between 1,200 and 1,500°C (European Commission, 2022), using coke as the main energy source. The pellets or sinter of iron ore are then reduced in the blast furnace (BF) at around 1,500°C, to remove the oxygen and produce pure (pig) iron (Fe) (Eurofer, 2020).

[5] Global warming potential measures greenhouse gas equivalents that are emitted into the atmosphere and that are liable to cause global warming. The study uses GWP estimates for each of the materials, reported by relevant published literature which employ the IPCC 100a (Intergovernmental Panel on Climate Change) model to characterise all GHG emissions' as GWP of CO2 over a period of 100 years

To produce one tonne of pig iron in the BF, 1.4 to 1.6 tonnes of iron ore and around 500 kg of coke are needed. Limestone is also added to the BF as a fluxing agent to remove impurities such as sulphur, phosphorus, and silica. This leads to the production of CO_2 as process emissions and a secondary by-product called slag[6]. The pig iron is then further processed to create usable forms such as wrought iron, cast iron, and steel (see Section 5.1.1.2).

The majority of CO_2 emissions from the production of pure iron are created during the reduction of the iron ore in the BF, which produces 1.2 tCO_2 per tonne of iron and accounts for 75% of total emissions from pure iron production. The manufacture of iron and steel in the UK accounted for 10.9 million metric tons of CO_2 emissions in 2021. (Statista, 2021) (Statista, 2022). The emissions from the blast furnace include a combination of volatile compounds released from the use of coke to maintain high temperatures for smelting. The resulting emission profile includes SOx, PM and other particulate emissions. The sintering process released 0.2 tCO2e per tonne of steel, while pelletising and coke plants release less than 0.1 and 0.2tCO2e, respectively (European Commission, 2022).Accounting for the total production in the UK, iron and steel production-related emissions amounted to nearly 11 million tCO_2eq in 2021. (ONS, 2023a)

In 2022, global iron ore production reached 2.6 billion metric tonnes, producing 1.6 billion tonnes of pure iron (Statista, 2022). Iron ore mining activities is limited in the UK, with demand for iron ore of 6.3 million tonnes in 2022 for steel production met through imports (BBC, 2023).

Pure iron is soft and susceptible to corrosion (rusting) and must be combined with alloying elements to improve its durability and strength for use in the automotive sector. The two main uses of pure iron in the automotive sector are cast iron and steel, see Section 5.1.2.2 and 5.1.2.3.

5.1.1.2 Cast Iron

Cast iron is an iron-carbon alloy containing more than 2% carbon and is made by re-smelting pig iron with scrap iron and alloying elements, before removing impurities. Conventional cast iron requires a mass input share of 35% pig iron, 62% scrap iron and around 5% alloying elements (Si, Mn, Cu, Mg and Ni) (Jhaveri, K., et. al., 2018). Around 93-94% of total pure iron produced is used to produce cast iron, producing around 71 million tonnes of cast iron globally in 2019 (Modern Casting, 2021) and roughly 10 million tonnes in Europe in 2021 (CAEF, 2023). Total automotive consumption accounted for 12% of total iron produced in 2022 (Statista, 2022).

Grey cast iron and ductile iron are the most popular variants of cast iron in the automotive sector, used to produce disc brakes, cylinder heads, crank shafts and engine blocks due to the material's high thermal conductivity, stiffness and wear resistance.

Following the reduction of iron ore in the BF, the molten pure iron is cast (poured and hardened) into crude iron ingots called pigs. The molten pig iron typically contains between 3-5% carbon (Matmatch, 2023). The pigs are then remelted and combined with steel scrap and alloying elements, along with additional limestone and coke, in cupola furnaces in order to refine the chemical composition of the final products, before being recast into moulds. The cupola melting process is responsible for around 39% of total GHG emissions, whilst electricity consumption contributes 34% and waste materials 17% (Yilmaz, O., et. al., 2015), (Zhu, X., et. al., 2023), (Yongxian, Z., et. al., 2023).

As electricity consumption contributes substantially to the total emissions, the production emissions for cast iron are highly dependent on the fossil fuel intensity of the grid and the consumed energy demand (CED) of the process, as well as the weight composition of input material. As such, cast iron carbon intensity varies throughout the literature. Grey cast iron produces around 0.6 $tCO2_2$ per tonne of final product from the smelting in the Cupola furnace, excluding the embedded emissions of the pure iron consumed (see Section 5.1.1.1), as well as small amounts of methane, NOx, PM, and sulphur dioxide (Mitterpach, J., et. al., 2017). Ductile cast iron carbon intensity varies between 0.71 $tCO2_e$ (Joshi, 2011), 1.0 $tCO2_e$ (Abdelshafy, A., et. al., 2023), 1.2 $tCO2_e$ (Jhaveri, K., et. al., 2018), and 2.19 tCO_2e (Zhu, X., et. al., 2023) per tonne of cast iron product – with the latter considered an outlier for European production as a US grid electricity emissions intensity is used.

The transition from ICEVs to BEVs is expected to reduce the automotive demand for cast iron significantly, as its main applications are in the engine components of petrol and diesel vehicles. There is limited domestic UK

[6] Slag is the combination of the non-iron content of the iron ore with lime flux, produced during the chemical reduction of iron ore in the blast furnace.

production of cast iron. In 2022, production reached 136 thousand tonnes of cast iron, representing a 6% growth on 2021 levels, however made up less than 3% of total cast iron production in Europe (CAEF, 2023).

5.1.1.3 Steel

Steel is an iron-carbon alloy containing less than 2% carbon, with the primary production of virgin steel involving processing of pig iron in a basic oxygen furnace (BOF) to remove excess carbon and other impurities. Steel is the main final product of pure iron used in vehicle components, with applications for body panels, vehicle frame, suspension parts and engine components due to its strength and durability.

The most established and dominant method for primary steel production is the blast furnace and basic oxygen furnace (BF-BOF) pathway, producing around 71% of global crude steel (Fan and Friedman, 2021) and 56% of European crude steel in 2020 (European Commission, 2022). In the UK, steel production from the two integrated BF-BOF sites in Scunthorpe and Port Talbot have a combined capacity of 8.1 million tonnes of steel per year (EUROFER, 2021) and represented 80% of UK steel production (4.8 million tonnes) in 2023 (MAKEuk, 2023).

In the BF-BOF steel production pathway, iron ore is first processed in the BF to produce pig iron, (*please see section 5.1.1.1*). The molten pig iron is then poured into the basic oxygen furnace (BOF), where oxygen is blown into the liquid iron to reduce the carbon content of the metal from around 4% to steel grade level of below 1%. At this stage, steel scrap and direct reduced iron (DRI) can be fed into the BOF as additional metallic inputs, with up to 25% of recycled steel added at the BF stage to act as a coolant agent (WEF, 2023a) (UK Parliment, 2022c).

The BF-BOF steelmaking process consumes 15.8 GJ/ tonne of steel (MDPI, 2019) and emits between 1.8 and 2.2 tCO_2 per tonne of steel, with over 75% of emissions released during the refinement of iron ore for processing in the BOF (BHP, 2020), (Bogdanov. et al, 2023), (Conde. et al, 2022). The BF-BOF pathway is the major source of automotive-grade steel, with lower impurity levels allowing high performance panels and components to be formed.

An emerging approach to primary steel production is the secondary, scrap-electric arc furnace (EAF) route, where scrap steel is re-melted to produce new products. The scrap-EAF route comprised 20% of the steel produced in the UK in 2022 (MAKEuk, 2023). As this production pathway is fully electrified, the production related GHG emissions are primarily influenced by the carbon intensity of the electricity grid. Progressive decarbonisation of grid electricity, in line with the Future Energy Scenarios (FES), can therefore lead to significant decarbonisation of steel manufacture in the UK (by roughly 80%) (UK Parliment, 2022c), (National grid ESO, 2023). Currently, recycling rates for steel are between 80-90% (IEA, 2020), with up to 100% of steel scrap able to be recycled in an EAF and up to 25% of this fraction being integrated into the BF-BOF (Madias, 2014) (Ding. et al, 2023).

EAF-scrap steelmaking consumes between 5.2 and 5.5 GJ/ tonne of steel (MDPI, 2019) and around 0.3 tCO_2/ tonne of steel (IEA, 2020), representing a 90% reduction of CO_2 emissions and 70% energy savings compared with virgin iron ore in a BF-BOF (Ding. et al, 2023). Moreover, each tonne of scrap steel reused displaces 1400 kg of iron ore, 740 kg of coal and 120 kg of limestone (Ding. et al, 2023).

In 2022, 6.1 million tonnes of steel were produced in the UK, with 4.8 million tonnes from the integrated BF-BOF route and 1.1 million tonnes produced through the scrap-EAF route (MakeUK, 2023). In 2017, steel demand for the UK automotive production was 0.2 million tonnes, being the second largest steel consuming sector (DESNZ, 2017). Future growth of steel demand of the automotive sector depends on factors including vehicle electrification, policy drivers affecting vehicle lightweighting, and recycled content requirements. The application of recycled steel is currently limited in the automotive sector due to the high level of impurities introduced from combining different grades of scrap steel. Automotive-grade steel has a maximum copper content of 0.06%, whilst the current OECD steel scrap averages at 0.2-0.25% (WEF, 2023a). Although current recycled steel is not of sufficient purity for automotive-grade steel, 15-20% of recycled steel is added during the BF stage to act as a coolant agent (WEF, 2023a).

Moreover, a recent announcement from British Steel (British Steel, 2023), and proposal from Tata Steel (Jolly.J, 2023b) have raised uncertainty over the future of the two active BF plants in the UK, with proposed conversion of the sites to produce secondary steel from the scrap-EAF route removing the UK's capacity to produce primary iron and steel for the automotive sector.

5.1.2 Emerging innovations in material production and consumption

5.1.2.1 Pure Iron

Several innovative approaches have been developed to reduce the energy intensity and associated emissions of the BF process producing pure iron from iron ore, with varying levels of impact and feasibility.

Hydrogen injection into the BF (H-BF) partly replaces the use of coal products with hydrogen as an auxiliary reducing agent in the BF. The hydrogen can be generated using electricity in a separate plant via water electrolysis, allowing the partial replacement of fossil fuels as energy carriers in iron production with low-carbon or renewable electricity. This production process offers a reduction in CO_2 emissions compared to the BF-BOF pathway of up to 21.4% using 27.5 kg hydrogen generated from renewable electricity, or 2.1% when natural gas is used (Turek. et al, 2017). This production approach can be deployed without upgrades to existing iron production infrastructure, allowing immediate CO_2 emission reductions during the transition period to EAF production plants. However, the ability for H-BF to reduce emissions from conventional iron production is limited by the maximum share of hydrogen allowed in the chemical reduction process (between 5-10% in the gas injection to the BF), and is highly dependent on the energy mix used in the electrolysis plant to produce the hydrogen. The first operational production of iron from H-BF took place in 2019, however deployment of this appraoch remains low, with ArcelorMittal (ArcelorMittal, 2020), Voestalpine (Voestalpine, 2020) and TATA (World-energy, 2020) committing to use green hydrogen from electrolysis in their European BF-BOF plants, and Thyssenkrupp continuing with hydrogen injection tests in Duisberg, Germany (thyssenkrupp, 2021).

Direct reduction (DR) of iron is the leading alternative to conventional BF iron production, with direct reduced iron (DRI) responsible for 119.2 million tons of iron produced in 2021 and representing 4.4% of global iron production (MIDREX, 2021) (Statista, 2023b). The iron ore is reduced using coal, natural gas (NG-DR) or hydrogen (H-DR) whilst in a solid state to produce DRI, also called sponge iron. 70% of DRI production is based on natural gas, whilst coal is mainly used in India (MDPI, 2019). The DRI can then be fed into an electric arc furnace (EAF) or BOF to produce steel.

Several commercial technologies have been developed and deployed worldwide to produce DRI, including MIDREX (MIDREX, 2018) and HYL/Energiron (Tenova, 2023). Pre-processing requires 3 GJ/t of steel whilst the reduction process requires 9.2 GJ/t of steel, significantly lower than conventional BF energy consumption of 15.5 GJ/t of steel (MDPI, 2019). Moreover, NG-DR generates lower CO_2 emissions in the range of 0.77-1.1 t CO_2/t of steel, compared to approximately 2.0 tCO_2/ t of steel from the conventional BF process.

Furthermore, DR plants are able to easily transition from natural gas to hydrogen as the main reducing agent. Up to 30% of natural gas used in a NG-DR can be replaced with hydrogen with no change to the plant or process, whilst only minor retrofitting is required to transition to 100% hydrogen operation. Using green hydrogen produced from renewable energy sources in a DR plant allows almost complete decarbonisation of iron production.

Another technological innovation to reduce CO_2 emissions without changing the iron production is through integration of **carbon capture and storage (CCS)**, retrofitted to BF (BF-CCS) and DR (DRI-CCS) systems. Combining CCS with top-gas recycling in a blast furnace (TGR-BF) technology (designed to capture and dispose of the CO_2 from the BF top gas), the combined system supplied with renewable electricity can reduce CO_2 emissions by between 36 and 57% compared to a conventional BF plant (Kapure. et al, 2014). For a traditional BF without TGR-BF technology, a CCS system has a much lower recovery rate of CO_2 emissions of between 0.33-0.36 tCO_2/t of steel, or 15-17% emissions capture rate (Fan and Friedman, 2021). A CCS plant retrofitted to ArcelorMittal's Dunkirk integrated BF-BOF plant capturing 4.4 M tonnes of CO_2 per year, representing 31% of the total carbon emissions from the plant's 7 Mt steel production capacity (SMM, 2020).[7] Similarly, CCS retrofit of a DRI system captures CO_2 from the DRI reactor exhaust gas. Although deployed in small-scale projects, CCS technology has not been deployed on an industrial scale and remains economically uncompetitive to retrofit to current BF-BOF plants due to high operating costs of around USD 60 per tonne of captured CO_2 (Fan and Friedman, 2021).

5.1.2.2 Cast Iron

Several innovations to cast iron production and automotive components are being explored to lower the material's contribution to overall cost and environmental impact of vehicles.

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[7] Based off an average CO_2 emissions intensity for the BF-BOF steel production pathway of 2.0 t CO_2 per tonne of steel.

The development of **thin-walled ductile cast iron** (TWDCI) provides cost and lifecycle emission savings for lightweighting cast iron components versus conventional cast iron and aluminium. As automotive manufacturers pursue lightweighting strategies as a key trend to improving the sustainability of vehicles (*please see section 6.1*), aluminium castings have emerged as a potential replacement for conventional cast iron components. Aluminium castings production has grown from a share of 12% of global castings in 2000 to 15% in 2019 (Modern Casting, 2021) (SMM, 2022). Whilst aluminium is lighter and offers good thermal conductivity, its economically unviable and environmentally intensive nature makes OEMs lean more towards cast iron components than cast iron alternatives (Fras, E., et. al., 2014), (Stefanescu, D., Ruxanda, R., 2003), (Bayraktar, E., et. al., 2006). Therefore, reducing the thickness of cast iron, or thin-walling, whilst increasing the share of pig iron used has the potential to make cast iron competitive with cast aluminium, from overall mass perspective, whilst retaining its better mechanical properties and lower production emissions (Jhaveri, K., et. al., 2018). In particular, a TWDCI vehicle component, containing 50% pig iron with 40% lightweighting, leads to 39% lower energy consumption and GHG emissions, compared to conventional cast iron with 35% pig iron content. TWDCI has comparable LCEs to an aluminium casting component (Jhaveri, K., et. al., 2018).

The **increased use of scrap material**, such as iron, steel or aluminium alloys, has potential to reduce production emissions through lower demand for virgin pig iron. By removing 15% of pig iron content and increasing the amount of scrap iron to 25% scrap steel, an 18% reduction in production emissions can be achieved (Jhaveri, K., et. al., 2018). However, the use of more than 25% steel scrap leads to increased emissions due to the need for more alloying elements with a high carbon intensity. Therefore, increasing scrap use in cast iron production to reduce production emissions is limited, and must be balanced with economic feasibility.

Also, **changes to the manufacturing process** can increase energy efficiency and reduce process emissions. By reusing waste sand and performing sand regeneration, the significant environmental impact from disposal of solid waste disposal onto landfills can be reduced (Yilmaz, O., 2015). Increased use of external scrap materials and use of renewable electricity inputs also offer significant GHG emissions savings, with current electricity consumption contributing to 34% of total carbon emissions (Zhu, X., et. al., 2023).

5.1.2.3 Steel

The main alternative primary production process to the conventional BF-BOF pathway is the **direct reduced iron to EAF (DRI-EAF) route**. The iron ore is reduced using direct reduction in a solid state to produce pig iron (*please see section 5.1.1.3*), before being fed into the EAF and converted to steel. The iron is reduced in the DRI using either coal, natural gas or hydrogen as the reducing agent and main energy input. The DRI-EAF production process accounts for 7% of global steel production (Devlin. et al, 2023).

70% of current DRI-EAF production relies on natural gas rather than coal. A tonne of crude steel produced by natural gas-based DRI-EAF emits around 1.4 tCO_2 using electricity generated at the average global energy mix, whilst the coal-based DRI-EAF route has almost three times the emissions intensity (IEA, 2020). However, the combination of green hydrogen as a reducing agent in the DR plant (H-DR, see Section 5.1.1.3) and renewable electricity in the EAF allows near-zero emissions from steel production, with up to 95% emissions reduction (around 0.1 tCO_2/t of steel) compared to the BF-BOF pathway (European Parliment, 2019) (ETC, 2021). The steel produced via. the DRI-EAF pathway using green hydrogen and renewable energy is called green steel. Several full-scale green hydrogen DRI-EAF plants are currently under construction in Europe, with mass production of the H2 Green Steel (H2GS) (H2GS, 2023a) and SSAB (SSAB, 2023b) plants in Sweden set to begin in 2026.

Due to the widespread availability of necessary technology and significant CO_2 emission reductions compared to the BF-BOF pathway, **increased recycled steel from the EAF** offers huge potential for the decarbonisation of steel production in the automotive sector. Through improved scrap sorting of steel grades, voluntary OEM targets and mandatory recycled content targets, there is potential for recycled steel from EAFs to play a key role in the decarbonisation of automotive steel. Volvo have committed to use 25% recycled steel by 2025, BMW plans to use 50% scrap steel by 2030 (WEF, 2023a).

In the UK, there are established EAF recycling facilities used by Celsa, Liberty Steel Rotherham, Outokumpu, and Sheffield Forgemasters. (MAKEuk, 2018) Moreover, under plans from British Steel (British Steel, 2023) and Tata Steel (Jolly.J, 2023a), the two active BF-BOF sites in the UK will be converted to purely EAF plants for processing of steel scrap into recycled steel.

Whilst the UK currently produces 20% of steel using recycled scrap, this is much lower than the global average of 28% and much lower than the European average of 44% (Worldsteel, 2023). Furthermore, as a net exporter of 13.8 million tonnes of scrap steel per year, increasing the share of steel produced via. the scrap-EAF offers a cost-effective and logistically feasible path to reduce emissions from automotive steel production (EUROFER, 2023).

Case Study 1: Automotive demand for green steel

Although there is no current green steel production (using green hydrogen from renewable electricity in the DRI-EAF pathway) in Europe, announcements from OEMs show strong demand from the automotive sector.

H2GS, which plans to begin commercial production at the Boden, Sweden in 2026, has signed agreements with Mercedes-Benz (H2GS, 2023b)*, Scania* (Scania, 2023)*, BMW Group* (BMW, 2022)*, Porsche* (Porsche, 2023) *and ZF* (ZF, 2023) *to supply green steel for vehicle production. Similar agreements have been made between European OEMs and SSAB* (Volvo Trucks, 2022) *and Salzgitter* (BMW, 2022)*. In total, Mercedes-Benz have reached agreements with steel producers to source over 200,000 tonnes of CO_2-reduced steel from European suppliers by 2030* (Mercedes-Benz, 2023)*.*

Whilst steel from the hydrogen DRI-EAF pathway has large potential to reduce production emissions, achieving maximum emission savings relies on the use of green hydrogen from renewable energy sources. As the water electrolysis process to produce hydrogen is incredibly energy intensive, current planned production of green steel is concentrated in northern Europe, where supply of geothermal energy is abundant. As such, the availability and cost of renewable electricity for green hydrogen in other geographies may present logistical and economic barriers to the deployment of green steel facilities in Europe.

Furthermore, Mercedes-Benz and BMW Group will collaborate with H2GS to establish a steel scrap supply chain, returning steel scrap from the OEMs' vehicle manufacturing plants to H2GS to be re-processed in the EAF for new production (H2GS, 2023b)*,* (BMW, 2022)*.*

5.1.3 Current & Future use

The use of cast iron in the automotive industry has already fallen significantly due to lightweighting trends (*please see section 6.1*). Given the advantages in tensile strength that steel has over iron, relative to its weight, steel has been preferred in automotive manufacturing for some time and is currently the most abundant metal used in vehicles across the UK. It is estimated that the use of unalloyed iron in 2025 could range from 80kg in an average car (6% by weight of vehicle) to 1400 kg in an average large articulated lorry (9% by weight of vehicle). By contrast, over 500kg of steel is estimated to be used in a typical car in 2025 (45% of vehicle weight), with similar proportions for vans (53%), rigid lorries (46%), articulated lorries (52%). A slightly lower share is estimated for buses (23%), where aluminium is preferred. Table 5-1 below shows that the quantity of iron & steel used in UK vehicles is estimated to fall significantly in the future based on our assumptions around potential vehicle mass reduction from previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020).

Figure 5-1 below shows that the demand for iron & steel across all vehicles being produced in the UK (hereafter referred to as 'aggregate demand' for materials) is estimated to fall in the UK between now and 2050 in both scenarios considered. The total figures somewhat conceal that the AHSS share of vehicle weight is expected to increase in the near term for cars and rigid lorries since this delivers lightweighting benefits relative to conventional iron & steel (see Case Study 2), but the increase in demand for AHSS is outweighed by falling demand for other types of conventional steel in other vehicle types. This means that the downward pressure on demand from vehicle lightweighting and material substitution is estimated to exceed the upward pressure coming from an increase in UK vehicle production. The IEA also estimates the lightweighting will lead to a reduction in steel demand globally, but by a lower factor of 11% cumulatively by 2050 (IEA, 2022). These estimates are based on assumptions that the UK vehicle fleet can be represented by specific segments (e.g. all cars are assumed a 'lower medium' size), but for cars at least, there is a clear trend that the average total mass of cars is increasing, particularly due to the popularity of SUVs. A caveat here is that trends in shifts between vehicle segments are not currently reflected in our future projections, which only consider mass reduction in similar sized vehicles, rather than also the current trend to larger vehicles. The total masses of iron & steel could be even higher if the trend to larger cars/SUVs were to continue.

In these estimations, demand reductions are even more pronounced in the 'Net Zero scenario', where greater lightweighting is expected to take place and this is primarily achieved through material substitution to fibre reinforced polymers and light alloys. However, there is some commentary in the literature about a greater potential for the use of green steel in BEVs. This is because green steel is cheaper to produce than light alloys and composites, and the need for lightweighting is lower in vehicles with zero tailpipe emissions (Automotive

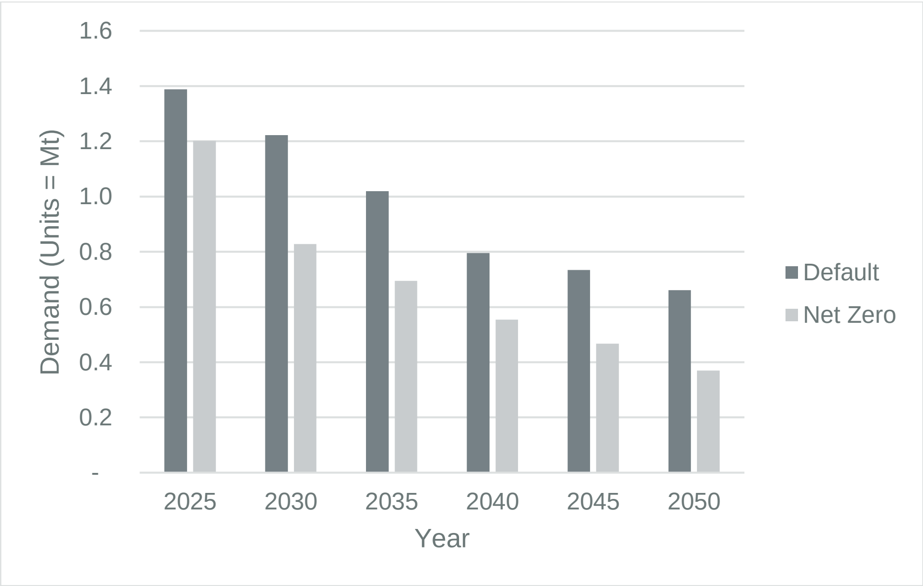
World, 2022). Therefore, it is worth noting steel demand may not fall as significantly as these estimates suggest, and there is a large degree of uncertainty around how lightweighting will be tackled by OEMs.

Table 5-1: Estimated current and future use of iron & steel in UK vehicles in the Default scenario, differentiated between ICEVs and BEVs (Units = kg/vehicle)

Vehicle	2025	2030	2035	2040	2045	2050
ICEV						
Car (Lower medium)	650	596	545	493	445	397
Van (N1 Class III)	1,267	1,124	977	831	702	573
Rigid Lorry (12t GVW)	3,371	2,759	2,132	1,504	1,294	1,085
Artic Lorry (40t GVW)	9,311	7,317	5,269	3,221	2,962	2,703
Bus (12m SD)	3,445	3,012	2,559	2,106	1,846	1,587
BEV						
Car (Lower medium)	669	583	522	461	411	362
Van (N1 Class III)	1,271	1,091	931	770	638	505
Rigid Lorry (12t GVW)	3,013	2,340	1,684	1,029	818	608
Artic Lorry (40t GVW)	9,199	6,859	4,662	2,465	2,163	1,861
Bus (12m SD)	2,833	2,345	1,888	1,431	1,193	954

Source: Ricardo's own estimates, based on previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020)

Figure 5-1: Iron & Steel demand; *Based on own estimates from Ricardo vehicles LCA model,* (Ricardo, 2020)



Case Study 2: HSS and AHSS for automotive lightweighting and sustainability

Steel E-Motive is an autonomous ride-sharing vehicle designed by WorldAutoSteel and Ricardo engineering consultancy which utilises HSS and innovative manufacturing processes to improve the sustainability, safety and performance of conventional designs (Steel E-Motive, 2023). *The vehicle uses several different types of HSS, including Press Hardened Steel, Martensite, Dual Phase and Complex Phase, High Strength Low Alloy and Bake Hardenable, and 3rd Gen HSS.*

The mix of HSS grades, along with an innovative structure, provided a 25% weight reduction of the body structure and 60% reduction in the LCE compared to a baseline C-segment EV in 2022 (assuming supply of renewable energy from a decarbonised grid). Furthermore, by considering future production of decarbonised steel, high (3+) passenger capacity, and extended vehicle life from enhanced durability, an 86% reduction in the LCE compared to the baseline EV.

Compared to other innovative materials and production processes, HSS provides an economically attractive option to lightweight vehicles and reduce emissions during the vehicle's use phase, whilst maintaining existing manufacturing and assembly processes and skills. Furthermore, the embedded emissions associated with the production phase of steel vehicle content is expected to reduce as the production of low-carbon steel from green hydrogen and renewable electricity increases. Major European OEMs have announced supply agreements for green steel from 2026 (see Case Study 1 above), signalling strong demand in the automotive sector.

5.1.4 Sustainability Performance of Iron & Steel

Iron, being one of the main foundation materials used in a variety of sectors is key to the production of steel. Nevertheless, iron (and steel) is identified as one of the last sectors to fully decarbonise in the net zero projections published by the international Energy Agency (IEA) (IEA, 2021b), owing to the current lack of innovative, energy and carbon efficient approaches to their production process. With steel production being highly reliant on coal, at a global level and in the UK, in the current timeframe, decarbonisation of iron production is taking priority (UK GOV, 2015) (UK Parliment, 2022b). To highlight the environmental impacts of materials through one of the most emphasised impact indicators, GHG intensity, we use GWP, which is usually measured as kgCO_2e/ unit material. Contemporarily produced through blast furnace (BF) and basic oxygen furnace (BOF), the global warming potential (GWP) of iron is 1.2 kgCO_2e/kg of iron produced. While the overall GHG intensity is relatively low, compared to other foundation candidates, the volume of iron production in the UK and its demand in other sectors has prioritised the need for its decarbonisation. Iron produced in a BF is primarily a key source of particulate and gaseous emissions (also known as blast furnace gas). Blast furnace gas contains dust and other GHG emissions including NOx, SOx, CO, in addition to CO_2 emissions. Other emissions to air include heavy metals, cyanide compounds, hydrocarbons and PAH. Often, heat energy from blast furnace gas is circularised to heat up coke for iron firing. Blast furnace slag, produced as steel by-product, is often used in cement production.

The high energy demand of the production process and, use of fossil fuels is likely to negatively impact fossil resource depletion. Wastewater generated from the various activities of iron production tend to be contaminated with heavy metals and carbon. Contemporarily, these effluents are treated, however, potential leakages could lead to nutrification of freshwater sources (also called eutrophication) (Carbotech, 2021). A study by Zhang et al, (2023) evaluated the impact of low carbon and green production of iron employing natural gas and renewable hydrogen, as alternatives to the conventional use of coke (Zhang et al, 2023) in BF-BOF production. Focussing solely on the GWP impacts, use of natural gas, as opposed to coke, was found to reduce iron's GHG emissions by roughly 30%, while the use of renewable hydrogen, reduced the overall production emissions by 60-70%, compared to baseline methods (BF, using coke). Undertaking a levelized cost analysis of these scenarios, this study inferred that further GWP reductions could be achieved (as much as -90% GWP emissions) using renewable natural gas and renewable electricity, however, at an extremely incremental levelized cost of steel. Reductions for carbon-negative production of iron through integration of CCUS (carbon capture, utilisation and storage) is also evaluated as a part of green and lean production strategies. However, these strategies, unless optimised, are likely to make steel significantly expensive (UK Parliment, 2022c).

Iron, similar to most metals, is 100% recyclable without any loss to its functionality. Scrap metals generated during iron production are contemporarily recovered and melted down to be cast into ingots. Iron components sorted and separated from ELVs, in accordance with the UK Waste Framework Directive (DEFRA, 2023), is sent for recycling. In the UK, iron from scrapped vehicles is recycled at a rate of 99% (TATA Steel, 2023a) and a fraction of the high-quality recyclates are sent back (closed-loop recycled) towards the production of hard-cast automotive parts including brake discs and suspensions, while the rest of the fractions enter other product systems (open loop recycling) (Worldsteel, 2023). These material recovery strategies provide multiple benefits: reducing the impact of the metal's production and consumption related impacts, in terms of resource depletion; conserve the metal's inherent embodied energy and carbon and support long-term lean manufacturing strategies reducing production waste. A qualitative overview of the sustainability credentials related to iron, as raw material, is provided in Table 5-2.

Table 5-2: Qualitative summary of key sustainability characteristics of primary material – Iron (98%) (unalloyed)

Energy consumption	• No specific reduction in the production energy demand reported since 2010 • Current CtG production-specific energy consumption 18-22 MJ per kg of iron (IEA, 2021b)
Material Consumption*	• Iron ores (depending on the type of ore) contain 50-66% iron content; • Current ratio of extracted material to ore required at 1:1.1 (at 65% iron content)
Waste generation	• **Emissions to air:** GHG emissions scrubbed, blast furnace gas used towards heating process. Co-products used in other product systems • **Emissions to water**: Scrubbing leads to sludge production; Wastewater generally contains heavy metals which is usually treated before being released into the environment
Potential for circularity	• 100% scrap metal recycled and introduced into primary metal production; • 99% reported for iron recovered from scrap vehicles; majority used in closed-loop recycling into automotive parts and components.
**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*	

Unalloyed **steel** that is contemporarily produced employing BF and BOF technologies shares sustainability characteristics with that of iron production. However, steel production has been recently shifting towards more efficient approaches, particularly EAF, which is likely to deliver carbon savings of up to 80% with steady decarbonisation of the UK's grid mix, compared to that of BF and BOF production process (National grid ESO, 2023). Like in the case of iron, slag is generated as a by-product which finds application in other industrial sectors such as slag bound mixtures in road construction, as surfacing materials and also in the construction of river canals and towpaths in the UK. However, the quality of steel slag is screened for hazardous substances such as lead and arsenic (Environment Agency, 2014) prior to use in construction. EAF slag follows a similar path to re-utilisation in other sectors. The remaining production slag that does not qualify for use in other applications is disposed of in landfill. Emissions to air, from the production of steel, include significant amounts of SOx, NOx and particulate matter, in addition to VOCs and PAH. Chromium plays an important role in steel making, particularly in enabling the recycling of steel scraps and is therefore, unavoidable. However, chromium compounds can be highly carcinogenic to humans and toxic to contaminated ecosystems. Chromium(IV) emissions, released as a part of the wastewater, is one of the other key waste streams with the most environmental impact (Carbotech, 2021).

Steel produced through BF and BOF, EAF and direct reduced iron -EAF have been found to carry a GWP of 2.33, 0.6 and 1.37 kgCO_2e/kg of unalloyed steel. The energy intensity of production routes were also determined to be 23-24 MJ, 10MJ and 22 MJ/kg of unalloyed steel, according to World Steel (Worldsteel, 2023).

Steel has a high recoverability (of about 97% by weight) of the end-of-life vehicle (ELV) scraps, in adherence with the UK Waste Framework Directive (DEFRA, 2023). Steel alloys that can be transformed into high-quality recyclates are often re-routed into virgin steel production process, which find closed-loop application in automotive parts and component production. For example, Tata Steelworks at Port Talbot, has recently signed a recycling agreement with Gestamp to support the production of automotive grade steel with 17-30% recycled content as a means of greening the overall steel production process (Gestamp, 2023). Closed-loop recycling has great potential in reducing the upstream demand for the materials, and downstream, on the vehicle's production related impacts. Some key deterrents that influence the theoretically permissible recycled content of 100% is the mechanical performance of the recycled automotive steel grade, which in turn is influenced by the level of impurities present in the scrap (such as nickel, chromium or other elements from the first life alloying process). This leads to the requirement of specialist separation/ sorting processes and pre-processing to remove any embedded impurities when scrapping an end-of-life vehicle, prior to recycling and producing desired automotive grade secondary steel.

Recycled steel that is rejected from automotive application find application in other product systems such as construction sector or manufacture of steel cans. Material recovery strategies, in general, are beneficial in reducing the overall resource depletion and conserving the embodied energy and carbon content of the recycled material, compared to virgin material production or other disposal strategies. A qualitative overview of the sustainability credentials related to steel, as raw material, is provided in Table 5-3.

Table 5-3: Qualitative summary of key sustainability characteristics of primary material - Steel (unalloyed)

Energy consumption	• No specific reduction in the production energy demand reported since 2010. • Current CtG production from iron: 1.3 -2.3 MJ/t steel) from iron (Worldsteel, 2023).
Material Consumption*	• *Similar to Iron*
Waste generation	• **Emissions to air:** GHG emissions scrubbed, blast furnace gas used towards heating process. Co-product slag used in other product systems. • **Emissions to water**: Wastewater generally contains heavy metals such as Chromium (VI) leading to human and ecotoxicity unless treated, prior to release into the environment
Potential for circularity	• 100% scrap metal recycled and introduced into primary metal production. • 99% steel recovered from scrap vehicles. • Roughly 17-30% integrated into automotive grade steel in the current timeframe
**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*	

5.2 ALUMINIUM

5.2.1 Material production methods and volumes

Aluminium is conventionally produced from bauxite, which is open-cast mined in the form of granules. Bauxite is primarily composed of aluminium oxide compounds (alumina), silica, iron oxides and titanium dioxide. Bauxite mining (upstream processes only) require 0.6 GJ of energy and emits less than 0.1 tCO_2/t aluminium (MPP, 2023). Bauxite is conventionally mined from areas close to where a previous mine has been closed, rehabilitated and restored, to improve the environmental characteristics of the upstream processes. Once mined, the bauxite is processed into alumina (aluminium oxide), following the Bayer process. Crushed ore is conventionally thermally treated and digested at high pressure with caustic soda to separate the dissolved aluminium oxide from the undissolved impurities (iron, silicon and titanium dioxide). These residues are often filtered and washed, and the fraction containing other elements are subjected to other extractive processes to extract those relevant metals. The liquor or slurry of sodium aluminate filtered, precipitated and calcinated in heated rotary kilns at high temperatures (1,000-1,300°C), removing any remaining impurities and forming aluminium oxide (or alumina). Between 2 and 3 tonnes of bauxite is needed to produce one tonne of alumina. This process consumes significant thermal energy and electricity, requiring 20.5 GJ and emitting 2.6 tCO_2 per tonne of aluminium (MPP, 2023).

The refined alumina is then transformed into 99.8% pure aluminium primary smelter using an electrolytic process. Powdered alumina is dissolved in a molten bath of cryolite (NA_3AlF_6) at around 950°C, before being fed into a reduction cell equipped with a consumable anode and permanent cathode. A high intensity electrical current with very high amperage (200,000A) is applied to produce pure aluminium. Molten aluminium collected from this process is cast into ingots for melting, extrusion billets or rolling slab. Owing to the very high temperatures of the smelting process, significant amounts of volatile fluoride compounds are generated from the cryolite. These emissions are efficiently removed through hooding, extraction and scrubbing of the gaseous effluents to remove 98% of the fluoride prior to being released into the environment. Collected fluorides are then recycled and consumed in the chemicals sector. Every tonne of aluminium requires 0.4-0.45 tonnes of carbon anodes and roughly 2 tonnes of alumina (MPP, 2023). The electrolysis process accounts for around 80% of total CO_2 emissions from aluminium production, with one tonne of aluminium requiring 53.8 GJ of energy and emitting 12.8 tCO_2 (MPP, 2023). The pure aluminium is then alloyed with other materials to improve strength, machinability, and other mechanical properties. Finally, the alloyed aluminium is fabricated into final products through finishing process such as sheet forming[8], extrusion and casting.

Overall, the primary aluminium production process is energy intensive, with the global average emission intensity around 16 tCO_2/t aluminium (MPP, 2023) and emitting a total of 1.0 $GtCO_2$ in 2021 (IEA, 2023).

[8] Sheet forming is a process of cutting and forming relatively thin metal sheets, strips and coils.

However, around 65% of total emissions in the production process comes from the generation of electricity (WEF, 2021) (MPP, 2023). As such, the emission intensity of aluminium produced in different regions is highly dependent on region-specific grid energy mix. Chinese primary aluminium, which relies heavily on burning coal to produce electricity, can typically have a carbon footprint of 20 tCO_2/ t of aluminium produced. European primary aluminium, which is largely powered by hydroelectric power and other renewables, typically has a carbon footprint of less than 7 tCO_2e/t of aluminium produced (ALUPRO, 2023).

Primary production of aluminium is limited in the UK with virtually no bauxite mining and with imports (from Jamaica, West Africa, and Australia) of refined alumina at 23.3 thousand tonnes reported in 2022 (Statista, 2023a). The only remaining aluminium smelter in the UK is the Lochaber smelter located in the Scottish Highlands, with a capacity of 48,000 tonnes (BBC, 2021). UK-based aluminium smelter in Lochaber in Scottish Highlands, uses hydroelectric energy generated from the Lochaber dam located nearby. In the UK, aluminium was responsible for roughly 500,000 tonnes of CO_2 emissions in 2021 (Statista, 2021).

The second main source of aluminium is through recycled scrap. Aluminium is an infinitely recyclable material, with the recycling process requiring only 5% of the energy needed to produce the primary metal and emitting 0.5 tCO_2/ t of recycled aluminium (representing a 97% reduction of primary production emissions) (MPP, 2023), Global collection rates of end-of-life aluminium are around 73% (WEF, 2021), with 90% of aluminium scrap from vehicles being recycled (Auto Recycling World, 2021) However, different aluminium alloys are combined in the recycling process to produce a single, mixed grade of recycled aluminium. Although this mixed grade can be used for some automotive components such as the engine block of ICEVs, the downgrading of the alloys constrains their wider use in vehicles. The UK currently produces 1.4 million tonnes of aluminium scrap per year, of which 500,000 tonnes is exported (ALFED, 2021).

5.2.2 Emerging innovations in material production and consumption

There are three main pathways to reduce emissions from aluminium production: electricity decarbonisation, direct emission reductions, and increased recycling and resource efficiency.

Scope 2, indirect emissions from the consumption of electricity accounts for more than 60% of the total aluminium sector emissions (Cooper. et al, 2017) (Environdec, 2013). Some of the innovative approaches explored include decarbonising the energy grid and increased deployment of CCUS technologies to capture emissions from remaining fossil fuel sources, and particularly where hydroelectric power sources are limited. Shifts from coal to hydroelectric power generation in China will move up to 8 million tonnes of aluminium production capacity to clean energy over the next few years (China Hongqiao & China Aluminum Corporation, 2021), whilst the United Arab Emirates is aiming to reduce the carbon footprint of power generation by 70% by using a mix of renewables, nuclear and other sources (UAE Government, 2017). However, the main barriers to CCUS deployment are cost and energy requirements, with operational costs of USD 40-80 /tCO_2 for coal- and gas-fired power plants (IEA, 2019). However, for 52% of Chinese smelters and 63% of European smelters (excluding Scandinavia and Russia) at risk of limited to no access to low-carbon power, CCUS may play an important role in the medium term to decarbonise primary aluminium production.

Scope 1, direct emissions accounts for over 30% of total aluminium emissions, stemming from thermal energy generation from fossil fuels (16%) and process emissions via the consumption of carbon anodes (15%) (IAI, 2021). The most promising approaches to reducing thermal energy emissions are fuel switching and mechanical vapour recompression (MVR) technology. By switching from low-temperature coal, gas or oil boilers to renewable electricity or green hydrogen, a 100% reduction in the emissions from digestion during aluminium refining and smelting can be achieved. Alternatively, MVR captures process waste heat and re-compresses it to the temperature needed during the process, leading to a 95% reduction in digestion CO_2 emissions (MPP, 2023). Also, conventional smelting facilities emit 2.13 tCO_2/ t of alumina (MPP, 2023) due to the consumption of carbon anodes used in the cells. Inert anodes are a promising substitute for carbon anodes, producing no process CO_2 emissions and offering operating cost savings due to a longer operational lifetime compared to conventional carbon anodes. The technology is mature and widespread commercial deployment expected by 2030, with the Elysis joint venture (Rio Tinto, 2021) and Rusal (Light Metal Age, 2021) leading industry-scale demonstrators of inert anode technology.

Case Study 3: BMW Group using low-carbon aluminium from Rio Tinto

BMW Group have reached an agreement with Rio Tinto for supply of low-carbon aluminium for the OEM's Spartanburg plant in South Carolina, US from 2024 (BMW, 2023)*. The low-carbon aluminium is produced in Rio Tinto's Quebec plant in Canada using the ELYSIS inert anode technology and renewable energy from* *six local hydroelectric power stations* (Rio Tinto, 2023). *By combining the low carbon primary production route and adding up to 50% aluminium scrap to the final product, BMW hopes to achieve a 70% emission reduction compared to conventional aluminium.*

This is in line with Ricardo analysis on the emission reduction potential of inert anode technology and renewable electricity used at the smelting stage of aluminium production. Considering the current grid carbon intensity in the US and Europe, combining 100% renewable electricity and inert anodes can reduce GWP of conventional European aluminium by 59% and North American aluminium by 75%, reducing the respective carbon intensity from 7.16 tCO_2e and 12 tCO_2e per tonne of conventional aluminium to 2.96 tCO_2e per tonne of low-carbon aluminium.[9]

Smelters can also be retrofitted with CCS facilities to capture between 45 and 90% of smelting process emissions (WEF, 2021) (MPP, 2023), depending on the source of thermal energy for the CCS plant. Deploying CCS in the aluminium sector is likely to be more expensive than other sectors because of the low CO_2 concentration in smelters' flue gas (MPP, 2023).

Closing the loop with secondary aluminium is anticipated to be the final pathway to meeting growing demand for aluminium sustainably. Although around 95% of new automotive scrap aluminium is recycled, recycled aluminium use is currently limited by the downgrading of aluminium alloy quality during processing. The UK has a continuous supply from around 1 million scrap cars each year (UKRI, 2021). As such, closing the loop on automotive aluminium through improved scrap collection, sorting and processing would provide a rapid and low-cost route to rapidly reducing production emissions (up to 95% compared to primary aluminium). Projections from the International Aluminium Institute show that an increase in recycled aluminium production from 33% in 2020 to 54% in 2050 is in line with meeting the 1.5°C climate target (IAI, 2023).

Furthermore, **increasing material efficiency** could limit demand growth to 50% by 2050, compared to 80% without any improvements in efficiency (MPP, 2023). Innovative technologies in forming processes are being explored to reduce material use by producing much thinner or low-weight parts and components for application in all transport sectors. These include hot form quenching (HFQ)[10], fluid cell forming (also called hydroforming)[11], superplastic forming processes[12] Cooper. et al, 2017). They may also be cast through die-casting and hollow casting to produce high-strength high-quality parts for vehicles e.g., engine blocks, cylinder heads and other parts. However, some of these forming processes can be relatively more energy intensive compared to conventional methods (600-650 MJ/ kg of alloyed aluminium part). Therefore, benefits and trade-off across these strategies need to be explored to identify the most efficient and sustainable means of optimising aluminium production and consumption.

Case Study 4: Closed-loop aluminium recycling by Volvo and JLR

In 2019, Volvo partnered with Novelis to implement a closed-loop recycling system to reduce the OEM's production emissions from reliance on primary aluminium, with production scrap from Volvo's plants being reprocessed and fed back into vehicle production. This reduced the carbon intensity of aluminium sheet delivered to Volvo Cars by 78%, whilst reducing waste (Light Metal Age, 2020). *This partnership forms part of Volvo's commitment to reaching 40% recycled aluminium content in its cars by 2025, as part of its wider transition to an automotive closed-loop system and net zero emissions production by 2040* (Volvo, 2023).

Moreover, the REALCAR project led by Jaguar Land Rover (JLR) and Novelis, introduced in 2015, established the first closed-loop recycling system in Europe for production scrap of aluminium sheet, linking Novelis' Nachterstedt Recycling Centre in Germany with JLR's production site in the United Kingdom with a railway service (Novelis, 2016). *This led to a 13.8% reduction in the LCE of the 2013 model Range Rover TDV6* (CISL, 2016)

In addition, JLR demonstrated technology to reduce demand for primary aluminium from 40-50% to 25% during the UKRI-funded REALITY (Recycled Aluminium Through Innovative Technology) research project in

[9] Ricardo internal analysis from the WorldAutoSteel Steel e-Motive project, using grid emission intensity values from Ecoinvent.

[10] HFQ is a hot stamping process for certain grades of aluminium, which press forms hot aluminium blanks at high speed, then quenches them in the press tool, followed by artificial ageing to achieve full strength.

[11] Fluid cell forming (FCF) is a specific process of hydroforming, where a liquid is pressurized on one side of the blank, forming the metal against a single stationary die. In FCF, the pressurized fluid is contained within a rubber bladder situated above a tray that can be filled with multiple dies, which is then pressurised and envelops the whole tray.

[12] Superplastic forming (SPF) uses pressurized air to form a flat, rectangular sheet metal blank against a single die at an elevated temperature of around 50–75% of the absolute melting temperature of the sheet.

2021 (UKRI, 2021). *The REALITY project developed an innovative recycling process to upcycle aluminium waste from household, industrial and EoL vehicle sources and produce automotive-grade aluminium. This process has the potential to reduce total production emissions of future vehicles by up to 26%* (JLR, 2020b), *whilst closing the loop on aluminium used in the automotive sector.*

Furthermore, Idra Group have developed a new mass-production method for producing automotive components from aluminium. Coined by Tesla as "Giga Presses", the large, single module aluminium die casting machine replace the need to weld together 60 different components, cutting costs by around 40% and increasing the economic viability of using aluminium content in future vehicles (Automotive News Europe, 2023). *So far, Ford, Hyundai and another European manufacturer have secured supply agreements with Idra, with Tesla having purchased 14 presses for their vehicle production plants* (Automotive News Europe, 2023a).

5.2.3 Current and future use

With road transport policies regularly reviewing and addressing energy efficiency of vehicles and recoverability and recyclability of ELVs, passenger cars and commercial vehicles are increasingly leaning towards lightweighting options involving aluminium (Alubend, 2021).Table 5-4 below shows that expected use in a typical car is 150kg per vehicle (12% of vehicle weight), with similar shares in vans (10%), rigid lorries (11%) and articulated lorry (14%). Aluminium is already the most prevalent material in buses (34%).

Table 5-4: Estimated current and future use of aluminium in UK vehicles in the Default scenario, differentiated between ICEVs and BEVs (Units = kg/vehicle)

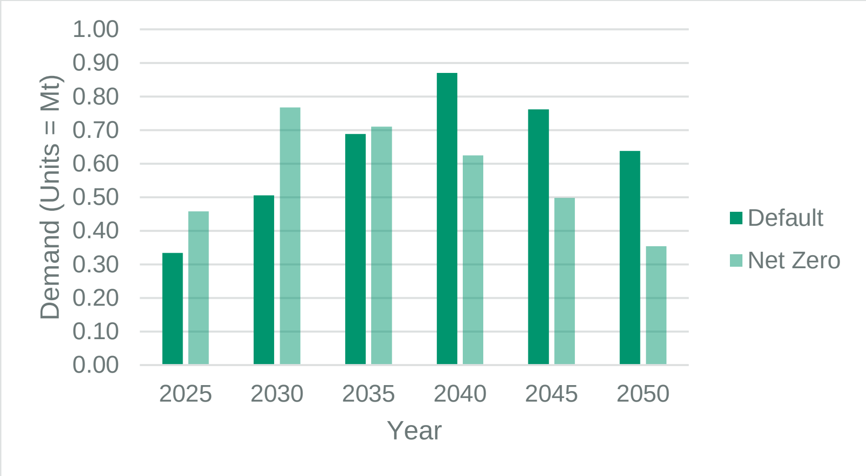
Vehicle	2025	2030	2035	2040	2045	2050
ICEV						
Car (Lower medium)	150	164	169	174	180	185
Van (N1 Class III)	204	286	368	450	378	305
Rigid Lorry (12t GVW)	697	1,138	1,574	2,010	1,535	1,061
Artic Lorry (40t GVW)	2,107	3,537	4,952	6,366	5,120	3,875
Bus (12m SD)	4,080	3,542	2,998	2,454	1,923	1,391
BEV						
Car (Lower medium)	208	196	197	197	194	190
Van (N1 Class III)	294	351	428	506	418	329
Rigid Lorry (12t GVW)	930	1,322	1,750	2,179	1,637	1,095
Artic Lorry (40t GVW)	3,159	4,323	5,705	7,088	5,578	4,068
Bus (12m SD)	4,253	3,656	3,106	2,556	1,979	1,401

Source: Ricardo's own estimates, based on previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020)

Independent estimates suggest that by 2030, global aluminium demand from Electric Vehicles (EVs) is expected to near 10 million tonnes, a ten-fold increase from 2017 (CRU, 2018). The BIW share for aluminium globally is expected to increase from 4% in 2010 to 18% in 2040 (Giampieri. et al, 2020).

This analysis suggests that aggregate automotive demand for aluminium is estimated to double in the medium term across both scenarios considered. In the default scenario, aluminium demand peaks around 2040 at just over 0.8Mt and falls thereafter, whereas in the Net Zero scenario, aluminium demand peaks in 2030. This implies that with different levels of sustainability ambition, different outcomes are to be expected, in terms of the pace of aluminium adoption and the rate of replacement by other materials, both of which are higher in the Net Zero scenario. As explained in Section 5.1.3, future absolute demand values may represent underestimates given that we assume the fleet comprises of specific vehicle segments and does not account for trends towards greater uptake of larger cars over time like SUVs, for example.

Figure 5-2 Aluminium demand projections



***Note**: the graph above includes demand for 'Aluminium', 'Aluminium (cast)' and Aluminium (wrought). Please see section 4 for a description of the scenarios considered*.

With increased demand for aluminium, and especially recycled aluminium given the savings in production phase emissions, two risks have been identified (Billy and Müller, 2023):

1. Demand is likely to outstrip recycled supply due to long lifetimes of current vehicle stock, creating shortages, in the short term;
2. Electric vehicles require more wrought aluminium, and recycling of wrought aluminium requires lower levels of alloying elements than what is typically found in post-consumer scrap aluminium.

Despite the weight reduction potential and other promising benefits, there are a series of critical factors to be considered before the massive production of aluminium-based automobiles, primarily including technical (*e.g.*, the aluminium component performance, design flexibility, manufacturability, crashworthiness, and maintenance) and economic concerns (*e.g.*, the initial costs of raw materials and expenses during manufacturing or operating processes), as well as the environmental impacts (*e.g.*, the post-consumer recycling potential and disposal of scraps) (Zhang and Xu, 2022). The literature therefore suggests that supply-side constraints may be a limiting factor in uptake of aluminium in UK automotive production.

Furthermore, it is uncertain currently, what the effect of innovations in aluminium gigapress/giga-casting techniques developed by Tesla, and promise significant cost reductions as well as mass reduction, might have on future vehicle manufacturing and demand for aluminium (Automotive News Europe, 2023) (Automotive News Europe, 2023a).

5.2.4 Sustainability Characteristics of Aluminium

Versatile technical characteristics, such as formability, high strength-to-weight ratio, etc. makes aluminium one of the most desirable alternative to AHSS. From the review of collected literature, from an environmental impact standpoint, aluminium have been found to perform differently under each of these specific perspectives. As a lightweighting candidate from a life cycle perspective, aluminium was found to perform better than AHSS and carbon-fibre reinforced composites (Hutchingson. et al, 2015) (Tata Steel, 2017). Key environmental benefits were drawn from an overall reduction in GWP stemming from the lifetime performance of a relatively lightweight vehicle. As a raw material that is produced, aluminium has often been found to demonstrate significant environmental impact, compared to AHSS (Tata Steel, 2017) (AMS, 2022), (Gonçalves. et al, 2022).

Consulting a range of LCA studies, the life cycle GWP ranges established for aluminium were identified to be in the range of 4.45 - 5.78 $kgCO_2e$/ kg of primary aluminium, produced as billets, ingots or sheets (vedanta, 2023), (Environdec, 2013), (Cooper. et al, 2017), compared to 1.2 - 2.8 $kgCO_2e$/ kg of AHSS (Environdec, 2023a). A large share of the production emissions are attributed to the high energy demand, and often the forming/ casting process employed to produce a specific part or component (Cooper. et al, 2017) (Environdec, 2012). According to a study by Cooper et al, 2017, superplastic forming method (used to form AL SP5083) was observed to be the most energy intense forming process, compared to other techniques such as incremental sheet forming (used to form AA7XXX, AA6XXX, S5083) hydroforming (AA7XXX) and other conventional methods. Increased energy requirement could also affect other key impact indicators that capture the release of gaseous emissions leading to acid rain (acidification), which in turn are strongly linked to the electricity grid mix. One other key indicators aluminium performed negatively includes human toxicity potential (HTP), stemming from the process effluents associated with bauxite ore extraction.

According to the UK Aluminium Federation, aluminium used in automotive applications is being recycled by up to 95% (ALFED, 2017), however, only through open-loop recycling. This stems from the use of a range of aluminium alloys in a vehicle construction requiring separate high-quality separation and sorting requirements. Identification of innovative approaches to improve closed-loop recycling could lead to savings in the material's energy demand by up to 95%, also positively influencing other related impacts such as metal depletion, acidification and fossil depletion. A qualitative overview of the sustainability credentials related to aluminium, as raw material, is provided in Table 5-5.

Table 5-5: Qualitative summary of key sustainability characteristics of primary material – Aluminium (99.7%)

Energy consumption	• 15% reduction in specific production energy demand reported since 2010 (IEA, 2023); • High-energy demand production process (51 MJ/ kg), on the overall (Aluminium Federation , 2021a)
Material Consumption*	• Bauxite contains 40-50% by weight of aluminium oxide, amidst other components such as titanium, iron and other trace metals; • Current extracted material to ore ratio at 1:4 (Aluminium Federation , 2021a)
Waste generation	• **Emissions to air:** GHG emissions and fluoride compounds and SOx scrubbed at production facility; High impact materials (e.g. caustic soda, cryolite) and energy use contribute higher emissions; Co-product fluoride used in other product systems • **Emissions to water**: Wastewater generally contains heavy metals leading to human and ecotoxicity; However, liquid effluents treated at waste water treatment plant prior to release into environment
Potential for circularity	• 100% recyclable; Current aluminium supply containing 75% recycled content. Automotives now report use of 25% ELV scrap and 50% post-production scrap (UKRI, 2021a)
**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*	

5.3 PLASTICS, POLYMERS AND COMPOSITES

5.3.1 Definition of plastics and polymers

While all plastics are polymers, not all polymers are plastics. Polymers also exist in nature as cellulose, starch, rubber and some natural fibres. Natural fibres that are used in automotive sector include flax, hemp, jute in addition to other emerging materials (Vierya.H et al, 2022). However, 70% of a vehicle's plastics/ polymers are dominated by four key types of plastics: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and polyurethane (PU). Inevitably, the main share of plastics and polymers that remain in the automotive shredder residue (ASR), following the separation of ferrous metals from the ASR mix, include PP, PE, PUR, PVC and PA (Passarini.F et al, 2012). As a result, this study has opted to focus on these primary materials, and to this effect, we have included only qualitative discussions on other most relevant plastic-derived components such as carbon-fibre and natural fibre reinforced plastics (composites). Other relevant minority plastics have been excluded from a detailed evaluation.

5.3.2 Material production methods and volumes

Plastics are conventionally produced from petrochemicals, which in turn, are sourced from fossil-derived crude oil and natural gas. Due to the prevalence of numerous chemicals, including solids and gaseous elements in dissolved state, crude oil is subjected to fractional distillation at variable high temperatures to separate the different mixtures into different compartments. The two main products of this process are naphtha and natural gas. After distillation, the long-chains of hydrocarbons in naphtha are cracked (at 800°C) and refined to produce key monomers such as propylene, ethylene and so on. As a final step to producing the primary products (polypropylene, polyethylene, for example), the monomers are subjected to additional polymerisation, where monomers are added together, one next to the other, into a long chain. Another technique called condensation polymerisation is a process where two monomers combine to form a dimer, and dimers join together to form teams creating complex molecular structures, like in the case of polyamide, polyurethane, to name a few (BPF, 2023).

Automotive plastics are prepared from primary materials mainly through injection moulding, which uses high-pressure plastic injection to form a variety of plastic parts such as body panel, engine parts etc. However, CFRP, which are fundamentally made of carbon fibres and a matrix (made of coke, sintered carbon and graphite) are produced through either through resin transfer moulding (RTF) or vacuum bag moulding with autoclave curing (Forcellese.A et al, 2021). In the case of natural fibre composites, the natural fibres are first treated to alter their hydrophilic properties and to support the adhesion of natural fibres (in the matrix) to the polymers, thus forming high-strength, low-density, low-cost composites (Kusuma SSW et al, 2021). Plastics and composite production can have very high environmental load, especially where volatile compounds released from the production and moulding processes.

The UK has a robust **plastics and polymers** industry employing mature technologies and supportive infrastructure. In 2020, 1.7 million tonnes of plastic materials were produced, while 3.4 million tonnes of plastic products are generated in the UK. Of these, only 8.8% of these plastics find application in the automotive sector in the UK (BPF, 2022) and this is anticipated to affect the extent to which automotive plastic supply chains can be influenced. Global plastic production accounts for nearly 1.8 billion tonnes of CO_2 emissions, while UK-related emissions accounted for 3.3 million tonnes in 2021 (Ritchie.H, 2023) (Statista, 2021). Additionally, the persistent nature of plastics in the environment through prevalence as non-degradable waste and as microplastics demand their evaluation for continued application in the automotive sector, unless there are breakthroughs in innovative approaches achieved through the use of hybrid materials such as natural-fibre reinforced composites or potentially circularising these composites through material recovery strategies. For materials which are quite prevalent in the automotive sector and investigated significantly for light-weighting strategies, emerging approaches addressing their sustainable production and consumption need to be explored.

5.3.3 Emerging innovations in material production and consumption

As the conventional feedstock into automotive plastics are fossil fuel products, efforts to decarbonise and improve the sustainability of the production process are limited by the embedded emissions in the final product. One of the main pathways explored to reduce emissions related to achieving material efficiency, eliminate production-level emissions and non-biodegradable waste from automotive scrap is to develop ambitions for the integration of **recycled plastics** in the automotive sector. Currently, most EoL vehicle plastic is shredded as part of the ELV management processes, where ferrous and non-ferrous metals are separated from the plastic and composite residues of the automotive shredder residue (ASR). Owing to the potential hazardous contaminants in this fraction, ASR is typically landfilled in the UK and the EU (Khodier, et al., 2018). Although plastic separation from ASR is technically possible, the technology is still under development, but has low recovery rates and are yet to be commercialised. BMW and Alba Group are collaborating with BASF to improve scanning and sorting of the plastic mix in ASR for chemical recycling (BASF, 2023b).

Mechanical recycling involves disassembly of individual vehicle components before sorting, shredding, and shaping. Scrap automotive plastics can also be chemically recycled to produce virgin-like polymers, with pilot plants and early-stage commercial operations beginning in Europe (NESTE, 2019), (Total Energies, 2023). Moreover, an estimated 18-20% of total plastic content in current vehicles could be replaced with recycled sources without any adjustments to design or production. Several automotive companies have targets for increasing recycled plastic content in new vehicles, which will require a substantial increase from the 2021 level of 2.5% of the total plastic used in the automotive sector (Oakdene Hollins, 2021). Volvo have committed to using at least 25% recycled plastics in their cars from 2025 (Volvo Cars, 2018), Renault will increase recycled plastics by 50% between 2013 and 2022 to use up to 20% recycled content in European cars (Renault Group, 2020), and Toyota have set 2025 recycling targets in their Environmental Action Plan (Toyota, 2020).

The main barriers to increasing recycled plastic content in vehicles is the lack of economically viable methods for dismantling and segregation of plastics from ELVs, limited infrastructure to recycle plastic, and poor market demand for secondary plastics. Whilst recycled plastic is 8-10% cheaper than virgin plastic in the automotive sector (Reuters, 2020), additional investment will be required in the future to increase the supply of high-quality plastics for all automotive applications.

An emerging alternative for plastics from fossil-fuel feedstocks is **bio-based plastics**. These materials are (partly or fully) derived from biomass feedstock such as corn, sugarcane, or wood, with the renewable feedstock able to be "dropped-in" to replace fossil fuel feedstock. Bio-based alternatives to common automotive plastics, such as PE and PP, have already been developed, as demonstrated in the case study below.

Case Study 5: bio-based plastic engine cover used by Mercedes-Benz

In the drive for weight and emission-savings, Mercedes-Benz uses a bio-based polyamide from DSM for their engine cover in the A-class, with 70% of the compound derived from castor oil plants (Bioplastics News, 2020)*. The engine cover is a complex component of the vehicle, which is subject to operating temperatures over 200°C and high dynamic loads from engine vibrations* (Reneweable Carbon News, 2013).

Since 2020, Royal Neste and DSM have been developing high-performance polymers from sustainable feedstocks for use in the automotive industry (Neste, 2020)*. The advanced polyamide/polyester materials replace fossil feedstocks with feedstock produced from recycled waste plastics and/or 100% bio-based hydrocarbons from renewable raw materials (such as waste or used cooking oils)* (AZO Materials, 2020)*.*

The bio-plastic compound material used in the A-class model provides high melting point to tolerate high temperature environment, low moisture absorption, high crystallization rate, and good chemical resistance. The use of a bio-based engine cover reduces CO_2 emissions by 40% compared to a conventional polyamide component and lowers the weight to 1.32 kg.

CFRPs and other polymer composite materials have high environmental impacts due to their raw materials and energy-intensive production processes – the production impacts are particularly high for carbon fibre. Therefore, reducing the energy intensity of the production phase is important in developing sustainable fibre reinforced polymers. Alternative manufacturing processes to the established vacuum bag moulding with autoclave curing process include resin transfer moulding (RTF) using different pressure variants and pressure bag moulding (PBM) (Forcellese, A. et. al., 2021). Compression RTF has the lowest GHG warming potential, emitting 45.4kg CO_2 equivalent per kg of CFRP, with vacuum bag moulding with autoclave curing process having a three-fold greater warming potential (Ansini, 2023).

Other novel production processes have been developed in recent years to lower the emissions and environmental impact of carbon fibre (CF) production. LeMond Carbon are producing low-energy intensive CF through a new production process. The innovative rapid oxidisation process decreases the oxidation process time by 80-85% from around 100 minutes to under 15 minutes, whilst using the same PAN fibre precursor to limit equipment and manufacturing process changes. This process results in a 75% reduction in capex per kilo of product, and a 70% reduction in energy consumption leading to lower GHG emissions (Green Car Congress, 2019). This process could facilitate the wide-scale deployment of CF components in the automotive sector, allowing significant lightweighting, improved performance, and reduction in use-phase emission (Mobility Engineering, 2020).

Also, Stora Enso and Cordenka are developing a new technology called NeoFiber to manufacturer CF out of bio-based (wood) raw materials (Stora Enso, 2020). This technology aims to replace oil-based feedstock with renewable and fossil-free materials to produce sustainable and cost-competitive CF. A pilot-plant in Finland began operation in 2021, producing 50,000 tonnes of lignin which is mixed with viscose from wood to make the precursor and, subsequently, carbon fibre (Stora Enso, 2021).

Recycling of polymer composite materials is particularly challenging; however, a number of novel processes are being developed, with a number of UK companies now offering carbon fibre composite waste recycling in the UK (Composites UK, 2016a). The most established and commercially available CFRP recycling facilities use either thermal (pyrolysis) or chemical (solvolysis) recycling process (Composites UK, 2016b). For the pyrolysis process, the resin matrix is degraded at temperatures between 450-600°C to recover the carbon fibres, fillers and inserts. The resin is then broken down further into gases and an oil fraction which is burnt away. For the solvolysis process, a heated solvent mixture is used to break down the resin – this uses a lot lower temperatures and produces cleaner fibres than pyrolysis, but also uses solvents and catalysts with negative environmental impacts. Mechanical recycling of CFRPs is an emerging low-energy intensive process, with the EoL material ground and sieved to separate the powders (ground resin and fillers) from the fibres. The energy demand for mechanical recycling is significantly less than for other CFRP recycling processes: chemical and pyrolysis recycling require around 50 MJ and 26 MJ/ kg of recycled product respectively, whilst mechanical recycling only uses around 0.2 MJ/ kg (Composites UK, 2016b). The French company Fairmat began operation of their CFRP recycling facilities in Bouguenais in 2022. Over 30% of total EoL CFRP waste from European industrial waste set to be processed in the facility via. the mechanical process, emitting 0.34 $kgCO_2$/ kg of processed EoL CFRP (JEC, 2022), (FAIRMAT, 2023).

5.3.4 Current and future use

Plastic, polymers and composites make up a number of components in a vehicle including air bags, seats fenders, dashboards, handles, engine covers, interior wall panels and so on. Table 5-6 below shows how plastics and composites are used in automotive manufacturing. The high absorption properties provide a safer option to drivers, whilst also minimising the mass of parts, resulting in fuel efficiency and thus lower GHG emissions.

Table 5-6: Examples of a selection of plastics and composite use in automotive construction

Plastic and composite type	Part of vehicle
PP	Engine covers, bumper fascia and cable insulation
PU	Seats, headrest, bumpers, tires and suspension insulators
PVC	Airbags, door panels and dashboard
PA (Polyamide)	Door handles, engine covers and fuel caps/ lids
PE	Glass-reinforced composites and plastic fuel tanks
Polystyrene	Knobs, sound dampening foam, door panels
Polycarbonate	Bumpers, headlamp lenses
Polyacrylates	Car light covers
PBT (Polybutylene terephthalates)	Plug connectors, bumpers and door handles
Fibre-composites	Structural systems, battery casings/ covers, cylinder heads, air intake manifolds etc

Table 5-7 below shows that, from the material demand analysis, around 200kg of a typical car is estimated to be made of plastics. In 2025, this represents 13% of car material mass, with similar proportions for vans (10%), rigid lorries (5%), articulated lorries (5%), and buses (14%). There are no significant differences estimated between plastics usage in ICEVs when compared to BEVs. In 2050, the demand for plastics in vans may increase by a small proportion (+1-3%) and slightly more in rigid lorries (+7%), but plastics composition is estimated to drop to below half its 2025 levels in buses, to 7% of total vehicle weight.

Table 5-7: Estimated current and future use of plastics in UK vehicles in the Default scenario, differentiated between ICEVs and BEVs (Units = kg/vehicle)

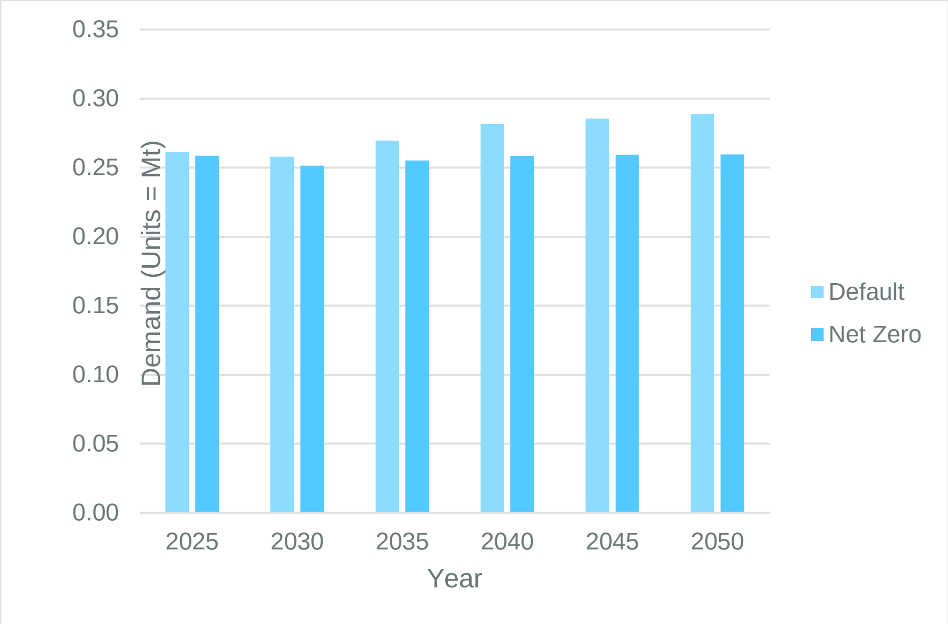
Vehicle	2025	2030	2035	2040	2045	2050
ICEV						
Car (Lower medium)	195	177	173	169	166	162
Van (N1 Class III)	247	248	255	262	258	253
Rigid Lorry (12t GVW Box)	286	321	358	395	394	393
Artic Lorry (40t GVW Box)	933	878	828	779	688	598
Bus (12m SD)	1,734	1,564	1,397	1,230	993	756
BEV						
Car (Lower medium)	187	170	166	163	159	156
Van (N1 Class III)	231	235	242	250	246	242
Rigid Lorry (12t GVW Box)	296	327	363	398	396	393

Vehicle	2025	2030	2035	2040	2045	2050
Artic Lorry (40t GVW Box)	1,014	935	876	817	722	627
Bus (12m SD)	1,743	1,570	1,401	1,233	995	757

Source: Ricardo's own estimates, based on previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020)

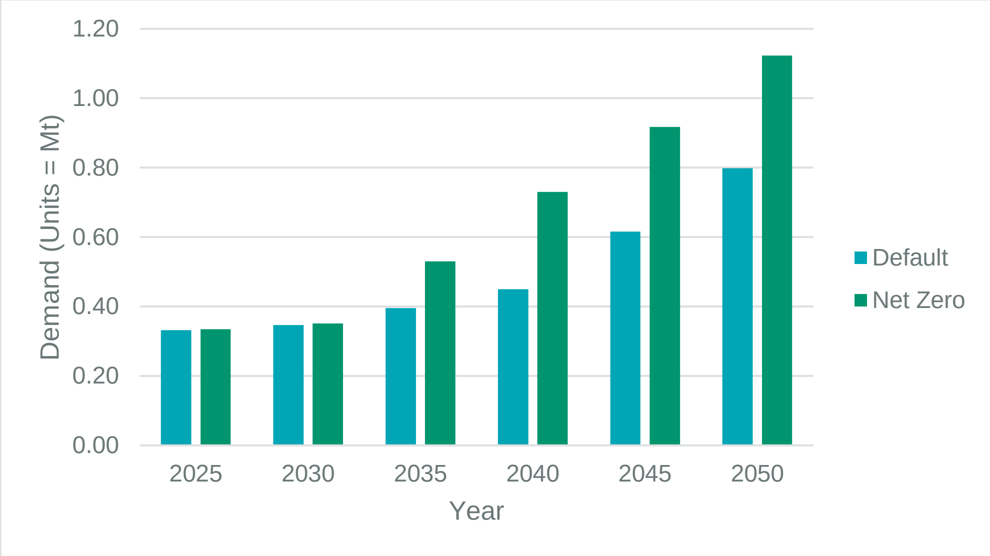
Despite the estimated reduction in plastics usage in most vehicle types, Figure 5-3 below shows that the upwards effect from the assumed increase in UK vehicle production over time outweighs this downward effect from reduced material use within a vehicle. Under the default scenario, demand is estimated to rise from 261,000 tonnes in 2025 to 289,000 tonnes in 2050, or a ~10% increase. Demand in the 'Net Zero scenario' is to estimated to rise to the same degree. As explained in previous sections, these estimates could be interpreted as being conservative given that we assume the fleet comprises of specific vehicle segments and does not account for vehicles becoming larger over time due to consumer preferences, as is currently being experienced in the increased popularity of SUVs.

Figure 5-3: Plastics and Polymers demand projections (excluding CFRP and GFRP composite materials)



In the core analysis above, only the main plastics used in automotive manufacturing were considered. However, other innovative materials that are derived from plastics could feasibly fall under the 'plastics, polymers and composites' heading, namely CFRP, GFRP, and NFRP, which deliver lightweighting potential compared to more traditional materials. Polymer composites like these are currently mostly restricted in use to sports vehicles and niche applications elsewhere (e.g., in the BMW i3 and i8 electric vehicles), however. Ricardo's previous analysis included projections on the potential for increased use of CFRP and GFRP in automotive manufacturing (Ricardo, 2020) (based also previous mass reduction potential studies (Ricardo, 2015a), (Ricardo, 2015b)). Figure 5-4 below shows two scenarios where these materials could potentially be used to replace traditional materials, including plastics and even structural metals, as a route to significant mass reduction in vehicle mass and consequently and energy consumption. In these scenarios, significant growth is projected (although it should be noted that these are only theoretical possibilities to support transport decarbonisation rather than market forecasts). Demand for plastics and plastics-derived composites including FRPs is estimated to rise by 3 times in the 'default scenario' and 5 times in the 'Net Zero scenario' between 2025 and 2050 (see Figure 5-4). The more significant growth in Net Zero scenario reflects the greater need for vehicle lightweighting.

Figure 5-4: Plastics and Polymers demand projections (including CFRP and GFRP composite materials)



In addition to CFRP and GFRP, a number of automotive OEMs have begun trialling natural fibre reinforced materials. These were not considered in the quantitative demand projections, but examples of demand-led innovation are provided in Case Study 6 below.

Case Study 6: Natural fibre composites from BComp integrated by Porsche, Volvo and Polestar

Automotive OEMs are increasingly demanding sustainable, low-carbon alternatives to conventional plastic and carbon fibre in vehicle components. Therefore, Porsche and Volvo have partnered with BComp to use natural fibre composites (NFCs) in interior and exterior car panels as a substitute for high-impact plastics and fibre reinforced polymers, such as CFRP. The natural fibre composites use 70% less plastic and provide a 50% weight saving compared to other composites, whilst matching the performance of CFRPs and reducing CO_2 emissions by 75%. Current challenges associated with commercial adoption of fibre-composites, in general, is the expensive nature of its production, durability concerns, in addition to the high production-level environmental load (Mewburn Ellis, 2021), (Autovista24, 2022b).

5.3.5 Sustainability performance of plastics, polymers and composites

Plastics and polymers that are dominant in their contribution to the automotive sector include PE, PP, PU, PA6/66 and PVC. HDPE and LDPE, used in the UK, has been determined to carry GWP of 3.3 and 2.6 kgCO_2e/ kg of bulk product, according to DEFRA (UK GOV, 2022). Some environmental product declaration (EPDs) of non-UK based PP granules used in automotive upholstery and components such as bumper fascia, engine covers, cable insulation, has been found to be responsible for a GWP of 1.38 – 2.17 kgCO_2e/ kg of bulk material (Environdec, 2023d), (LyondellBasell, 2012). PU (for seat cushions) and PVC (for underbody coatings, sealants and floor modules) demonstrate GWP values of 3 – 3.2 kg CO_2e, 3.4 kgCO_2e respectively (UK GOV, 2022).

Produced conventionally using crude-oil refinery co-products through polymerisation, plastic bulk products can be resource-intensive, doubling down on fossil resource depletion. This demand for fossil resources (as a resource and through processing energy demand) can also negatively impact other environmental indicators such as acidification and fossil resource depletion. Production of one kilogram of virgin plastics can require anywhere between 75-90 MJ of energy (electricity and fossil fuels), depending on the type of plastic produced. In terms of process level circularity, scrap plastic waste from plastic manufacturing plants is often recycled and fed into virgin plastic production process, without any loss to the material functionality. However, post-consumer plastics are likely to demonstrate undesirable performance characteristics for automotive applications, depending on the first-use and composition of those plastics.

Carbon-fibre composites, moulded and finished, are found to exhibit much greater environmental impacts, with GWP in the range of 45-150 kg CO_2e/ part (weighing 1kg), depending on the moulding process, where vacuum bag moulding process was found to account for the highest reported emissions, from the review of the published literature (Forcellese.A et al, 2021) (Delogu et al, 2017). Air emissions from the melting processes, high energy demand of the composite production and the manufacture of carbon fibre and epoxy resin towards compositive assembly were found to contribute the highest overall environmental impact, compared to other processes.

During use phase, these materials provide significant benefits offering durability and persistent mechanical performance (when subjected to regular maintenance), in addition to CO_2 savings from delivering a much lighter automotive design. Recent research shows that **CFRP** has been demonstrated to provide more emissions savings for its cost[13] when compared to AHSS in ICEVs (Shanmugam, et al., 2019), although AHSS performed better in BEVs (which have lower operational emissions). The costs of producing CFRP at small scale in the US have been demonstrated to fall by 25% in a five-year period, while greater than 80% recyclability has been demonstrated and embodied energy has fallen by 50% (IACMI, 2021). Promising research shows that 35% weight reduction can be achieved in mass-produced CFRP when compared with a series production steel version, delivering weight saving at lower cost than an aluminium version of the same part (Mainka, et al., 2019). Similarly, natural fibre composites have replaced the use of plastics in interior panelling and even bodywork in high-end light-duty vehicles, reportedly reducing CO_2 emissions by between 60-85% (Automotive World, 2022).

During the EoL phase, after automotive shredding and separation of recyclable fractions (ferrous/ steel alloys) from the ASR, much of the plastics and polymeric composites, in addition to other fractions, tend to be discarded as "automotive shredder residue". This fraction is particularly hard to recycle, due to the presence of non-reactive waste and other hazardous substances like polychlorinated biphenyls (PCBs), benzene, toluene, ethylbenzene, xylenes (collectively called BTEX). As a result, these fractions are often incinerated with energy recovery, rather inefficiently due to the loss of embedded energy, or much worse, landfilled (Khodier, 2019). Thermal treatment of ASR with energy recovery could be considered a strategy for resource efficiency, compared to landfilling. This, however, requires specialist scrubbing processes to prevent the release of harmful emissions to air. Some studies have evaluated the potential for pyrolyzing ASR to produce pyrolysis oil (Khodier and Williams, 2020) (Khodier, 2019), char and pyrolytic gas which could contribute to other sectors (including as furnace oil, industrial diesel etc). However, the presence of hazardous substances in the ASR, leading to potential emissions to air and water, need further monitoring and optimisations, prior to commercialisation and to make a case for sustainable management of automotive waste. A qualitative overview of the sustainability credentials related to plastics, polymers and composites is provided in Table 5-8.

Table 5-8: Qualitative summary of key sustainability characteristics of primary material – Plastics, polymers and composites

Energy consumption	• Processing energy use amounts only to a sixth of the total specific energy consumption. Rest of the energy used is embedded in the plastic material
Material Consumption*	• With 90-99% conversion efficiency, almost all monomers are converted to desired polymers. • High-impact materials required for the preparation of fibre-reinforced composites; Natural-fibre composites could potentially reduce impacts but require pre-processing to some extent
Waste generation	• **Emissions to air:** Demand for fossil-derived resources mean significant emissions to air (as GHG emissions (mainly methane and ethylene), VOCs and other halogenated organic compounds) • **Emissions to water**: through acidification potential due to electricity use (grid mix composition). Plastics and polymers being persistent in open environment tend to circulate as 'microplastics' which are rarely captured by water treatment plants;
Potential for circularity	• <1% of automotive plastic recycled after expensive and specialist sorting and collection process. • Presence of high levels of hazardous substances in the recyclates restricts scope for material or energy recovery through incineration; • Significant loss of embodied energy and carbon
**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*	

[13] The ratio of emissions savings was evaluated using the sustainable return on investment (SROI) metric: in this study, this depends on the lightweighted BIW's manufacturing cost and the difference in sustainable cost between a baseline (mild steel) BIW and the lightweighted alternative. The sustainable cost is the sum of the customer's lifetime fuel (or electricity) costs and the costs of environmental externalities.

5.4 COPPER

5.4.1 Material production methods and volumes

There are two sources of copper: primary copper from mined ore or secondary copper from EoL, production or manufacturing scrap.

Primary sources of copper are extracted from copper-bearing ores in open-pit or underground mines (Copper Alliance, 2023). The ores typically contain between 0.25-1% of pure copper. After extraction, the ore can be refined through either pyrometallurgical or hydrometallurgical production routes depending on the type (sulphide or oxide) and concentrations of copper in the ore. Sulphide ore is typically refined in the *pyrometallurgical process*, where the ore is first crushed, milled, and undergoes flotation to produce a copper concentrate containing 20-40% copper, before being shipped to smelting and refining plants (ibid.). The concentrate is then passed through a flash smelting furnace to create copper matte, with 50-70% copper concentrate. The matte is then transformed to blister copper with 98.5-99.5% purity through a conversion process, before being refined in an electrolysis to produce pure copper with 99.99% purity. 23% of total global copper emissions, or 27.9 Mt CO_2e emissions, comes from pyrometallurgical processing (Copper Alliance, 2023). In the final stage, the refined copper is shaped to produce the final and semi-final products.

For low-concentrate sulphide ores or oxide ores, a *hydrometallurgical process* is used to produce copper. The ore consists of leaching, solvent extraction and stripping before undergoing electrowinning (SX-EW process) to create pure (99.99%) copper. Around 19.6% of refined copper was produced using hydrometallurgy in 2022 (ICSG, 2023). 8.7% of total global copper emissions, or 8.4 MtCO_2e emissions, comes from pyrometallurgical processing (Copper Alliance, 2023).

Copper ore refinement produces several by-products, some of which are economically useful (i.e., silver and gold), significant for alloying or in emerging markets (i.e., nickel and cobalt), or toxic requiring careful disposal and management. Copper production produces large amounts of waste (tailings), representing 46% of global tailings by volume in 2016 (GRID-Arendal, 2020) and containing potentially dangerous elements such as pyrites and sulphides which must be safely contained to avoid contamination with water and air (US EPA, 2023).

Secondary copper is sourced either from EoL vehicle scrap or semi-finished and finished manufacturing waste, where it is first sorted into different grades and purities before being shredded. Depending on the quality of the copper scrap, it is then fed into the pyrometallurgical process at different stages. For low and medium grade copper, copper is mixed with copper ore at the start of the smelting process, whilst high grade copper scrap can be combined with blister copper for further processing during electrolysis. For the highest grades of copper scrap, mixing with primary copper is not necessary and the scrap can be remelted directly. Secondary copper production is significantly less energy and CO_2 intensive, with the highest purities of copper achieving an 85% CO_2 emissions reduction compared to primary production (Eurometaux, 2022). Copper from secondary sources already accounts for 55% of European production and is projected to increase to 66% by 2050 (ibid.). Globally, copper from recycled scrap is projected to account for a maximum of 25% of copper demand by 2050 (Copper Alliance, 2023).

In 2022, global copper demand reached 25 million tonnes, with primary production of copper from mines reaching 22 million tonnes (IWCC, 2022). The UK has no current domestic production or refining capacity for primary copper, although over 264,000 metric tonnes of scrap copper was exported in 2021 (Statista, 2023). Current exploration of the South Crofty region in Cornwall is taking place following the discovery of copper-rich ore during an exploratory drilling for lithium by Cornish Lithium (Cornish Metals, 2023). Another site in the Parys Mountain, Wales is also being explored by Anglesey Mining, with an estimated 9.4 million tonnes of copper resources in the zone (Anglesey Mining, 2023).

5.4.2 Emerging innovations in material production and consumption

In order to decarbonise conventional copper production, increasing the share of recycled copper whilst tackling emissions from primary production through electrification of equipment, and using alternative fuels and clean electricity is vital (International Copper Association, 2023).

Overall emissions from primary production of copper can be reduced by up to 95% through adoption of electrified equipment, decarbonised electricity, and the adoption of alternatives to fossil fuels to generate thermal energy. Operational production emissions from mining the ore can be significantly reduced by introducing battery or pantograph fully electric trucks and machinery to replace diesel trucks for material transport, and by replacing furnaces run on natural gas with electric or green hydrogen furnaces (International Copper Association, 2023). In order to reduce the scope 2 emissions from electricity consumption, decarbonisation of energy sources used for electricity generation will need to take place, either through grid-wide efforts or local installation of renewable energy capacity at plants. Several copper production companies have begun using renewable energy secured through purchase power agreements[14] or local renewable infrastructure, such as Codelco in Chile (Renewables Now, 2023a), Rio Tinto in Utah (Renewables Now, 2023b), and Grupo México's wind farm in Mexico (Renewables Now, 2023c).

Copper is 100% recyclable, however between 2009-2018 recycled content made up only 32% of total copper consumption (Copper Alliance, 2021). Feeding low-quality EoL copper back into primary copper smelting and refining stages creates a 50-65% energy saving and reduces emissions by 60-70%, whilst re-processing high-quality EoL copper can reduce emissions by up to 95% (Copper Alliance, 2023). As such, this is one of the major, currently practiced activities which can boost process material efficiency.

In Europe, 44% of total copper demand (around 4 million tonnes) comes from domestic and industrial scrap (Copper Alliance, 2019). ASTM is currently developing a common approach for scrap companies to collect, sample and process both manufacturing and end-of-life scrap with different alloy compositions and impurity levels (ASTM, 2022).

From a material innovations perspective, EV electrical component design that reduce the demand for copper are currently being explored owing to its criticality and high embodied emissions. This reduction in copper demand from EVs is forecast through shifting to more compact batteries for weight and cost savings, meaning that cells do not require copper wiring to modules; using thinner copper foil in battery cells; and shifting to higher voltage systems that require less wiring throughout the EV. Tesla have announced the replacement of the secondary battery (for auxiliaries) in their EVs with a new 48V battery, with the higher voltage batteries expected to reduce copper demand by a quarter from current levels by allowing thinner wiring (Mining.com, 2023). Tesla has also reportedly been developing a new wiring architecture, that offers to potentially reduce the length of wiring by an order of magnitude (Electrek, 2019), however this innovation has yet to be introduced into any of its models. These innovations will have a major impact on future copper demand, with EV copper demand expected to grow by 31% a year for the rest of the decade to reach around 3.0 million tonnes, or 55% of total global demand, by 2030 (Goldman Sachs, 2021). In light of the new battery technologies being explored, CRU Group have reduced their projections for copper demand in an average EV from 65-66 kg between 2023 and 2030 to 51-56 kg (Reuters, 2023). However, the need for copper as a part of the overall grid decarbonisation efforts, and particularly for charging cables (higher content needed for fast and rapid charging cables) means the demand for copper could be expected to counter these innovation efforts.

Copper alloy nanoparticles which can be applied to vehicle components such as the braking system, gearbox, electrical driving controls and heat exchangers are also being increasingly explored, providing enhanced efficiency, weight reductions and durability (Thangakani, J. A., et. al., 2022).

A major use of copper in EVs is for the electric motor, with the two most common electric motors, the permanent-magnet synchronous motors (PSM) and asynchronous induction motors (ASM), requiring around 3-6 kg and 11-24 kg of copper windings respectively to generate motion from electrical current (Ballinger, B, et. al., 2019). The only main alternative to the conventional PSM traction motor found in HEVs and EVs is the ASM, however these motors typically have lower efficiencies and require higher copper content. As such, PSM traction motors are expected to remain the dominant EV motor in the short-term (Pavel, C. C., et. al., 2017). However, there have also been recent innovations in the development of alternative processes where aluminium windings replace copper in motors in Germany (Green Car Congress, 2019) and in the UK (Ricardo, 2023).

5.4.3 Current and future use

While the UK mainly imports copper, the high durability and conductivity of copper with high potential for application in EVs makes it one of the other key primary material with limited low-impact alternatives. Roughly 20-30kg of copper is estimated to be found in ICEVs (cars, in particular, mainly in electrical wiring), while much higher contents are used in EVs (particularly 40 kg in PHEVs and 80 kg in BEVs) (Copper Alliance, 2017). This does not include copper used in manufacturing charging cables that are sold as a part of vehicles, which

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[14] Power purchase agreements are long-term agreements between electricity producers and consumers to enable the supply of electricity from specific electricity production assets at pre-determined prices. Conventionally applied for renewable energy supply

are anticipated to contain roughly a kilogram of the primary material. A fast-charging cable, connected to fast and rapid chargers can be expected to contain about 8kg (Majiba Hill, 2023).

Table 5-9 below shows the estimated use of copper for the production of different vehicle types in the UK. The amount used in a typical ICEV is not expected to change significantly, but it is estimated that copper will be used to a relatively lesser extent in BEVs in the future.

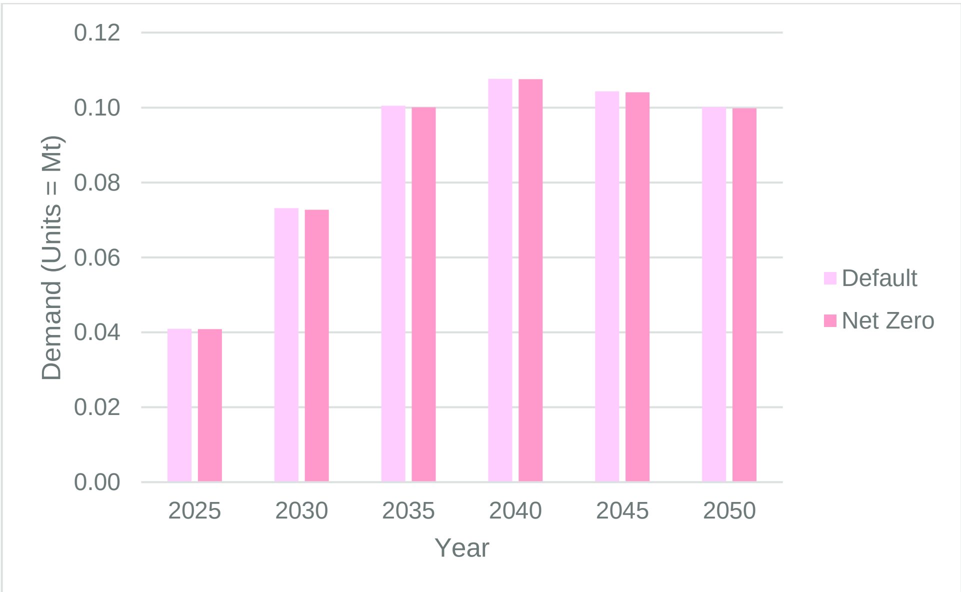
Table 5-9: Estimated current and future use of copper in UK vehicles in the Default scenario, differentiated between ICEVs and BEVs (Units = kg/vehicle)

Vehicle	2025	2030	2035	2040	2045	2050
ICEV						
Car (Lower medium)	23	23	22	22	22	22
Van (N1 Class III)	22	22	22	21	21	21
Rigid Lorry (12t GVW)	21	21	21	21	20	20
Artic Lorry (40t GVW)	84	84	83	82	82	81
Bus (12m SD)	31	30	29	29	28	27
BEV						
Car (Lower medium)	72	59	54	48	45	42
Van (N1 Class III)	84	76	71	66	61	56
Rigid Lorry (12t GVW)	272	232	204	177	157	138
Artic Lorry (40t GVW)	1,012	801	700	599	538	477
Bus (12m SD)	329	275	243	211	188	166

Source: Ricardo's own estimates, based on previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020)

Figure 5-5 below shows that aggregate demand for copper is estimated to rise between 2025 and 2040 due primarily due to the shift from ICEV to BEV production. After 2040, demand for copper is estimated to plateau and decline, with material efficient innovations in BEV design such as thinner wires and smaller, higher energy density batteries reducing the need for copper within the vehicles themselves over longer term. However, it is worth noting that these estimates do not account for changing preferences between vehicle segments over time. For example, we assume that all cars are in the lower medium segment since this is the most common car in the UK fleet, but consumer trends are tending towards larger vehicles over time – if most cars were large SUVs towards 2050, our projections would represent an underestimate.

Figure 5-5: Copper demand projections



5.4.4 Sustainability performance of copper

Produced through conventional metallurgical extraction, including from the by-product streams of other primary material production (e.g., nickel and iron), copper can carry high environmental loads, more heavily from upstream processes such as mining processing and fossil fuel consumption, in addition to extraction related demand for electricity (Copper Alliance, 2017). Copper has a GWP of 1.24 - 3.9 kgCO2e/ kg of copper (depending on level of secondary material integrated), which is heavily influenced by the energy consumption. With high energy consumption, in the range of 30 - 43.6 MJ/ kg of material, introducing energy efficiency and tackling energy-related emissions through electrification of production plant clean electricity is recommended as vital (Copper Alliance, 2023)

Electricity and natural gas is used in the melting processes and subsequent processing. Significant energy consumption, similar to the earlier materials, also creates a negative impact through formation of gaseous emissions the contribute to acid rain (acidification) and nutrification of land and water (terrestrial and aquatic eutrophication). With 100% virgin copper, direct extraction of copper ores contributes to the metal scarcity. However, use of significant amount of energy during the production phase is expected to reflect negatively as fossil resource depletion. Copper in the open environment also contributes to ecotoxicity and human toxicity by contaminating soil and water ecosystems (particularly those consumed by humans in areas with poor water and wastewater management systems.

Copper is 100% recyclable without any loss to its performance, however, the current recycled content is estimated to be at 35-40% (ASTM, 2022). Production scraps are often fully utilised towards primary copper production and therefore, there are any material waste generated. Significant demand for copper from substantial growth in EV uptake, in addition to a much more significant demand from the EV charging infrastructure and the overall energy sector decarbonisation is currently foreseen. This requires a considerable optimisation of the copper supply chain (from producers to consumers). Sound EoL management strategies that see collection, segregation by scrap quality and enable 100% circularisation of copper is a key requirement. According to Copper Alliance, strengthening resource efficiency and circularity aspects of copper production and consumption will be rewarding both in terms of mitigating the surge in market demand for copper, while directly reducing the environmental load associated with copper production. A qualitative overview of the sustainability credentials related to copper, as raw material, is provided in Table 5-10.

Table 5-10: Qualitative summary of key sustainability characteristics of primary material – Copper (99.7%)

Energy consumption	• 40% reduction in specific production energy demand since 2010 (Rotzer & Schmidt, 2020). • Still a high energy demand process (44MJ/ kg of material)
Material Consumption*	• Copper ores typically contain 0.4-0.6% copper, amongst other metallic fractions. • Current extracted material to ore ratio at 1:85 (International Copper Association , 2021)
Waste generation	• **Emissions to air:** Main emissions to air are GHGs resulting directly from the use of electricity. Trace elements of arsenic, copper and lead likely to pose air quality impacts around production plants, unless scrubbing systems are in place. • **Emissions to water**: Significant release of ammonia from the processing phase, release of trace elements of arsenic, copper and lead which could provide to be toxic to ecosystems and humans, unless treated through appropriate wastewater treatment facilities.
Potential for circularity	• 100% recyclable; Current copper supply containing 35-40% recycled content. Production scraps 100% recycled. • Closed loop recycling of automotive scraps yet to be demonstrated
**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*	

5.5 GLASS

5.5.1 Material production methods and volumes

The conventional production of flat glass, which is mainly used in the automotive sector, involves drawing all the raw materials into a batch house (Glass on Web, 2022). Typical raw materials used in flat glass production include 62% silica sand, 16% soda ash and around 16% of dolomite and limestone. (British Glass , 2023). The batch is then fed into the furnace, melting raw materials at 1,700° C. Majority of glass production plants in the UK utilise natural gas, which is responsible for 65% of the total production-related emissions. The molten glass is then homogenised and refined to remove gas bubbles. The molten glass is the formed in tin baths to produce flat glass. Once formed, the glass is then coated. This is followed by annealing, which involves re-heating of the formed glass at 400-600°C and slow cooling to relieve internal stress and improve durability, prior to shipping to consumers (British Glass, 2021), (Saint-Gobain, 2023). Nevertheless, automotive-grade glass, which include tempered and laminated glass, require further processing. Tempered glass is commonly used for backlights and windows, while laminated glass is used for windshields and sunroofs.

Tempered glass refers to float (annealed) glass that is strengthened through a unique toughening process, such as instant cooling. This makes the glass 4-5 times physically and thermally stronger, compared to normal glass. This process makes automotive glass shatter-proof to a great extent.

On the other hand, laminated glass consists of layers of two or more sheets of glass, with an interlayer of polyvinyl butyral (PVB) for safety purposes. This design renders laminated glass even more shatter-proof upon impact or collision improving the safety performance of the relevant component. Glass fibre is also used in many car parts like body panels and hoods, but it will not be discussed in this section, categorising it as a composite.

In the UK, 3.5 million tonnes of glass was produced in 2019 (British Glass, 2021). In Europe, 15% of glass was consumed by the automotive and transport sectors (Glass for Europe, 2023). Although the exact glass production volume from the UK automotive industry is not identified, a few flat glass manufacturers are producing automotive products like Pilkington UK Ltd and Charles Pugh (Glass) Ltd. Both are leading players in the market globally, producing automotive final products such as windshields and side windows.

As glass can be recycled infinitely at the same quality, understanding the glass recycling process would be important. In the case of laminated glass, the PVB interlayer must be identified and removed, prior to glass recycling. Once removed, the glass component is separated from other materials. and remelted to produce either automotive-grade glass or other products. Up to 300kg of CO_2 can be saved by remelting a tonne of glass (British Glass, 2023). However, flat glass in the automotive sector has barriers to being recycled due to potential ineffective sorting or contamination of the batch by residual PVB. Currently, most of the glass cullet from ELVs end up being open loop recycled (in other products such as container bottles).

5.5.2 Emerging innovations in material production and consumption

Glass production emits 0.511 tonnes of CO_2 per tonne of glass produced. In the UK, 1.5 million tonnes of CO_2 emissions from the glass industry were reported in 2019 (British Glass, 2021). Of these emissions, energy consumption accounts for 75 to 85% of GHG emissions, while the rest are attributed to material use. The glass sector has strived to reduce its environmental impact significantly, almost halving the overall energy consumed to produce glass, since 2010 (Griffin, et al., 2021). In the short term, some of the most effective ways of reducing the overall production-related impacts are switching to renewable energy and using recycled glass cullets in primary glass production (Griffin, et al., 2021) (SEKISUI Chemical Co. , 2023). From a policy perspective, end-of-life vehicle regulation ensures producers are responsible for the waste disposal of the vehicles (DEFRA and OPSS, 2021)

In the long term, switching from current gas-fired furnaces to electric furnaces, hybrid furnace using both electricity and gas energy, and hydrogen furnaces are considered. There are large-scale plans for replacing natural gas with hydrogen in the EU and the UK, like 5 projects aiming to achieve 100% hydrogen-based operation (British Glass, 2021).

With consumers increasingly preferring sunroofs and moonroofs in their vehicles, there is an increasing demand for automotive glass (Neiger & Homer, 2022). (SEKISUI Chemical Co. , 2023). Currently used heated glass saves energy, by removing snow or ice on the windows without the help of heaters. Another trend that is observed in the application of glass is smart glass in automobiles. Smart glass, also known as switchable glass, is a type with features including controlling window transparency in response to temperature. Such features help to save energy, by reducing the need to control temperature using air-conditioning (Mordor Intelligence , 2023) (Rykov, 2019). Similarly, there are infrared glass products that filter out infrared waves, preventing cars from overheating (Dean's Autoglass, 2021).

Case Study 7: Automotive glass in the NSG group

NSG Group, one of the world's largest suppliers of automotive glass, are offering a range of aforementioned innovative products. (NSG Group, 2024) *They enable CO_2 emission reduction, an extension of EV battery range and improve vehicle comfort at the same time by controlling the amount of light transmission. This allows optimisation of cabin temperature and thus reduces energy consumption and emissions relevant to temperature control.*

Their products like infrared reflective solar control coatings, heated windshields, Variable Transmission Glass Coatings (Sundym™ Select), and low emissivity coatings (Energy Advantage™) are oriented towards the control of heat transfer and the amount of ultraviolet and infrared light. (Pilkington , 2024)

They are also leading innovation in other trends. For instance, they are developing the world's first head-up display (HUD) windshields with augmented reality. (NSG Group, 2021) *They are also advancing safety measures through the implementation of Advanced Driver Assistance Systems (ADAS) equipped with cameras and sensor-integrated windshields, contributing to accident prevention.*

Case Study 8: Corning Gorilla Glass for Automotive

Gorilla glass from Corning is an emerging lightweight variant that is one-third lighter and two times tougher than conventional soda-lime glass Corning , 2023)*. It is normally installed on personal devices like smartphones or tablets. For automobiles, it can be used for parts such as windows, sunroof, dashboard and touchscreen* (Ulanoff, 2017)*. As mentioned, this emerging technology is just making a commercial entry into vehicles such as Mercedes Benz who have adopted the gorilla glass for dashboard and touchscreen.* Neiger & Homer, 2022)*.*

Alternative innovations to glass, such as plastic windshields, either made of acrylic or polycarbonate are also being explored. Acrylic windshields offer high-quality clarity and are both lightweight and cost-effective. However, they may be prone to surface damage with limited repair capabilities and recyclability. Alternatively, polycarbonate-based windshields could provide high impact resistance but render challenges similar to that of acrylic windshields. In terms of consumption, laminated glass and tempered glass are dominating the market and it is unlikely to be shifted to others candidate at least in the short-term (Polymer Shapes , 2023) (Glass Fixit, 2023).

5.5.3 Current and future use

Glass is primarily used in vehicle windscreens, side and rear windows, and some internal applications such as dashboards. Glass demand in vehicles is proportional to the surface area of glass on the vehicle exterior, which is low for vans (rear side windows replaced with contained storage), slightly higher for cars (including rear side windows), higher again for lorries with larger windscreens, and much larger for buses and coaches that have observation windows for all onboard passengers. For vans and rigid lorries, glass comprises only 0.6% of the total weight. Similarly, articulated lorries have glass as 0.3% of their total weight. A slightly higher share is estimated in cars (2.5%) and buses (4.6%). There are no significant differences estimated between ICEVs and BEVs, since window area doesn't need to change given a different powertrain, although there may be small differences in glazing techniques to facilitate for better thermal management (Glass for Europe, 2018), which will be particularly important in BEVs to prolong the life of the battery. In addition, Polestar (a premium electric vehicle manufacturer) has recently introduced two models that do away with the rear window and replace this with a camera-based rear view mirror instead (InsideEVs, 2023). However, the main reason for this is cited as it facilitates a bigger/full-length glass roof whilst maintaining a sleek and aerodynamic design, a trend that is also popular of other premium EVs, including Tesla. However, should the camera-based technology prove viable/popular, it is possible this might be introduced also in other models without glass roofs.

Glass demand per vehicle is not currently estimated to significantly change in the future, although there is some potential for replacement in some cases by polymer composites to reduce mass. However, as the unladen mass of vehicles is reduced, glass will comprise a slightly higher share of vehicle weight. In 2050, it is estimated that glass ranges between 0.8-5.8% of the total vehicle weight, depending on the vehicle type (Table 5-11).

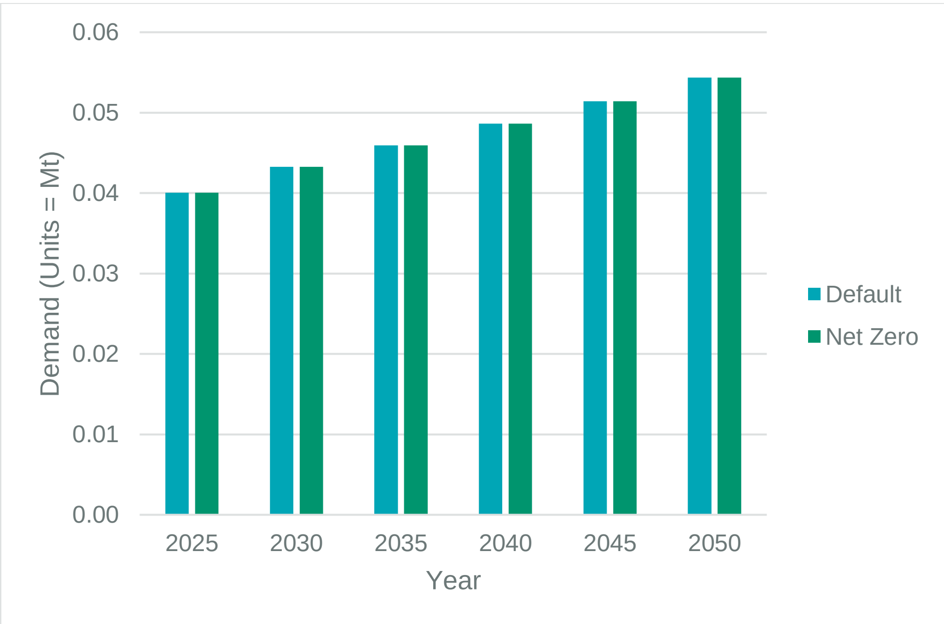
Table 5-11: Estimated current and future use of glass in UK vehicles in the Default scenario, differentiated between ICEVs and BEVs (Units = kg/vehicle)

Vehicle	2025	2030	2035	2040	2045	2050
ICEV						
Car (Lower medium)	37	37	37	37	37	37
Van (N1 Class III)	14	14	14	14	14	14
Rigid Lorry (12t GVW)	45	45	45	45	45	45
Artic Lorry (40t GVW)	56	56	56	56	56	56
Bus (12m SD)	577	577	577	577	577	577
BEV						
Car (Lower medium)	37	37	37	37	37	37
Van (N1 Class III)	14	14	14	14	14	14
Rigid Lorry (12t GVW)	45	45	45	45	45	45
Artic Lorry (40t GVW)	56	56	56	56	56	56
Bus (12m SD)	577	577	577	577	577	577

Source: Ricardo's own estimates, based on previous analyses (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020)

Figure 5-6 below shows that aggregate demand for glass across all vehicles produced the UK is estimated to increase slightly, largely reflecting our assumptions on the increasing number of vehicles being produced. It is possible that emerging innovations such as smart glass, recycled automotive-grade glass or lightweight candidates such as Gorilla glass or plastic windshields could disrupt the traditional glass manufacturing sector, but these are yet to be adopted in large numbers and therefore are not reflected in our demand projections.

Figure 5-6: Glass demand projections



5.5.4 Sustainability performance of glass

Glass is conventionally produced through energy intensive melting and forming of key components such as silica, soda ash, lime, dolomite with recycled glass cullet (mainly production scrap, and less than 1% post-consumer scrap). Glass, as a material carries a GWP of 1.4 $kgCO_2e$/ kg, however, Environment Product Declaration (EPDs) of automotive glass demonstrates GWP impacts in the range of 1.7-3.3 kgCO2e/ kg (depending on the nature of the glass components e.g. float glass, laminated glass) (EPD International, 2023)

(EPD International, 2022). GWP of glass produced in the UK was 2.2 million tCO2e in 2010 (Griffin, et al., 2021). Glass production globally is energy intensive consuming 13-30 MJ, primarily towards melting and refining of molten glass and this accounts for 70% of the energy consumed. UK glass sector, however, has improved energy efficiency of glass production significantly, through glass furnace optimisations and investment into waste heat recovery, reducing glass's overall energy intensity (5.3 MJ/ kg of material) since 2010 (British Glass, 2021). Recovered waste heat is utilised to pre-heat raw materials thus reducing reliance on the energy grid and other energy sources required for the processing steps. This is expected to positively influence, to some extent, on the acidification and eutrophication impact. However, the use of high impact materials such as soda ash and lime are anticipated to exacerbate these impacts (Glass for Europe, 2023).

In the case of glass component in windshields, owing to the presence of plastics, windshields from ELVs fall under both glass and plastic recycling. Recycling of windshields involved specialist management of the EoL route where crushes windshields are sieved to separate glass fraction from plastics. Crushed glass is turned further into cullet which can ideally be close-loop recycled towards new windshield production (Windscreen Company Group, 2023). However, any residual contamination of the glass cullet (from the PVB (polyvinyl butyrate) interlayer) or elements running though the layers in heated glass, could render the product cullet unusable as automotive grade glass and therefore reused in other product systems (such as container glass or other products). A pilot study by Audi, in collaboration with Saint Gobain, examines the impact of reclaiming recycled glass and has achieved a recycled content of 30-50%, in their prototype automotive grade glass. This innovative circular design was found to reduce overall GHG emissions of prototype windscreens by roughly 30% (Jesse Crosse, 2022). A qualitative overview of the sustainability credentials related to glass, as raw material, is provided in Table 5-12.

Table 5-12: Qualitative summary of key sustainability characteristics of primary material – Glass

Energy consumption	• 50% reduction in specific production energy demand since 2010 (Griffin, et al., 2021) • Glass sector in general is continuously seeking ways of improving energy efficiency
Material Consumption*	• 10% conversion of raw materials to glass achieved, leading to negligible amounts of waste being produced (Sekurit, 2023)
Waste generation	• **Emissions to air:** Main emissions to air are GHGs resulting directly from the use of electricity and other energy sources (NG). Trace elements of fluorides, lead and nickel are contemporarily treated before release into the open environment • **Emissions to water**: Ammonia from production of high impact materials (like sodium carbonate) used in glass production and waste water from processing site, may contain pollutants such as Nickel (II) and Zinc (II)
Potential for circularity	• 100% recyclable; Currently recycled content of 30-50% achieved through pilot study (Jesse Crosse, 2022) • Production scraps 100% recycled (PE International, 2011).

**Ratio of raw material/ ore to final product (excluding scrap generated), plus the amount of process materials needed to produce foundation material*

6 KEY CROSS-CUTTING TRENDS

From the review of the collected published literature and the material-level deep dive, a number of overarching trends emerged and appeared to touch upon the three key strategies that will build and strengthen the demand for materials in the medium and long-term periods. These include:

- Impact of vehicle lightweighting on foundation material demand trends
- Impact of renewable electricity on the sustainability profiles of foundation materials
- Need for supply chain circularisation as a means of introducing supply chain resilience, in addition to improving the sustainability profile of the foundation materials.

6.1 VEHICLE LIGHTWEIGHTING

Particularly relevant for ICE vehicles, where most of their lifecycle emissions are emitted through the combustion of fuel during the use phase (Ricardo, 2020), one of the ways to reduce these emissions is to reduce the weight of the vehicle, which lowers the energy requirement to propel the vehicle forwards and leads to less fuel combustion (Czerwinski, 2021). This typically involves the replacement of denser materials (historically, conventional iron and steel) with less dense materials that have comparable tensile strength, maintain functionality and safety, but crucially reduce the weight of the vehicle. These materials include high strength steels, light alloys (aluminium, magnesium, titanium) in varying composition, and an array of composites (glass-, carbon-, and natural fibre-reinforced polymers) (Taub, et al., 2019) (Zhang and Xu, 2022), with each material finding use in different parts of the vehicle depending on vehicle specifications such as type, segment etc. Mass reduction can also be achieved through design improvements and also through the secondary weight reduction that is possible for lighter designs (e.g. through down-sized components like brakes) (Ricardo, 2015a) (Ricardo, 2015b).

Key materials contributing to the expected change in the composition of material demand in the UK automotive manufacturing sector are as follows:

- **High Strength Steel**: a range of higher strength steels (HSS, AHSS, UHSS) have been developed and have been used for inner reinforcement and key structural components in the body-in-white (BIW) structure.
- **Light alloys**: Aluminium has emerged as a viable alternative to iron and steel in automotive manufacturing, finding commercial uses in smaller components and in the chassis and bonnet structural components. Other light alloys have also found more limited use (Magnesium, Titanium).
- **Composites**: in recent years, lightweight polymers and composites have been developed as an alternative to metallic materials, including carbon- and glass- fibre reinforced polymers (CFRP, GFRP) and natural fibre composites (NFC). These can deliver comparable or even better weight-savings compared to light alloys, and hence significantly lower use-phase impacts, but given their greater embodied energy (Monteiro, et al., 2022) and lower availability on the market, have not been as widely adopted in vehicles to date. In addition, there are challenges for recycling polymer composite materials.
- Other materials include **thin wall ductile cast iron (TWDCI)**, a lightweighting fabrication technology which can achieve weight reduction compared to cast iron while maintaining its strength.

Table 6-1 below shows a selection of applications for lightweight vehicle models in recent years. Applications differ due to the material requirements of different automotive components: for example, stronger parts are needed for structural parts (both inner and outer), while less dense/lightweight materials have been used in anti-intrusion barriers such as bumpers and impact beams.

Table 6-1: Recent applications of a selection of shortlisted lightweight materials in automotive manufacturing

Lightweight material	Application	Vehicle Model
Aluminium	Chassis	Audi A8
	Monocoque	Jaguar XE
	Body	Mercedes AMG GT
	Body panel	Ford F-150
	Bonnet	Toyota GT86
	Bumper	Mazda MX-5
	Battery case, sealing component	Nissan Leaf
	Frame and heat exchangers	Tesla Model S
(A)HSS	Inner reinforcement	Jaguar XF, Dodge Caliber, Ford Fusion, Porsche Cayenne, Volvo XC90
	Body-in-white (BIW) structure	GM Cadillac ATS, GM Chevrolet Sonic
Composites	Monocoque	BMW i3, i8
	Seatback, door panel, lining	Audi A2, A4, A6, A8 BMW 3, 5, and 7 series
	Floor tray, B-pillar, boot liner	Ford Mondeo CD 162
	Insulation, rear storage shelf	Rover 2000
	Body panel, spoiler, seat	Lotus Eco Elise
	Door panel	Fiat Punto, Brava
	Front and rear door panels	Peugeot 406
	Door panel, seatback, boot-lid finish panel, boot liner	Volkswagen Golf A4
	Cargo area	Honda Pilot, Mitsubishi Space star, GM Cadillac Deville
	Interior door panelling	Citroen C5

Source: Adapted from (Zhang and Xu, 2022)

Lightweighting is anticipated to remain important for ICEVs to improve energy efficiency and reduce emissions. It is well established that replacing conventional materials (steel and iron) with lighter alternatives decreases the vehicle life cycle energy use and GHG emissions for ICEVs (Luk, et al., 2018). The debate on the most sustainable of these lightweight materials for use in ICEVs is ongoing. A recent review of LCA studies on the lightweight materials has suggested that (A)HSS is the most preferable lightweight material when evaluated on a lifecycle emissions basis given its lower production phase emissions and improved recyclability, however other studies claim that aluminium more than makes up for these factors through savings in use-phase emissions (Sun, et al., 2019). Lightweight material selection is also highly influenced by the EoL stage, and the outcomes reported in published literature also depends on the specific assumptions and cases considered in these studies. Depending on the EoL scenario and also other assumptions, the preferable lightweight material may change. Results showed that improvements in material recovery and recycling technologies of aluminium, magnesium and composites could promote an offset of their production impact (through avoided burdens). Given that, **lightweight materials with high embodied energy (e.g. CFRP/GFRP) were generally found to be more advantageous for longer driving distance vehicles (e.g. trucks) and are recommended for further investigation, through the incorporation of recycled materials in their production process.** In this way, lightweight material selection should be related with feasible disassembly, material recovery, and recycling strategies for future EoL (Monteiro, et al., 2022).

BEVs operating on renewable electricity (or energy mixes) can highly reduce use stage LCE when compared to ICEVs. Thus, the embodied energy of alternative lightweight solutions for electric vehicles should always be considered to avoid shifting of burdens across a vehicle's life cycle stages. This is also because an increase in embodied impact may not be offset by mass-induced energy savings at use stage (Monteiro, et al., 2022)**.** Furthermore, carmakers are now designing EVs from scratch rather than converting ICE models, which increases the driving range. Cars such as the Nissan Leaf and Tesla Model 3 are less aluminium-intensive than previous models (Green Car Congress, 2018). For heavy duty electric vehicles using extremely heavy batteries, lightweighting is still required in parallel with energy density improvements for the battery (Automotive World, 2022). A 10% reduction in weight can lead to increased fuel efficiency of 6-8% in trucks. For these vehicles, the main consideration is therefore weight savings per unit cost. Aluminium alloys for wheels can create up to 60% weight saving versus conventional iron or steel materials. However, aluminium often costs 1.3-2x more than conventional steel or iron parts, whereas AHSS and glass fibre-reinforced composites cost between 1-1.5x more (Taub, et al., 2019), making the latter often more attractive to heavy duty vehicle manufacturers.

Innovation from OEMs may be anticipated to increase focus on BEV production, and in particular is expected to to balance three factors: (1) the cost of the battery (i.e. with lightweighting reducing the size of the battery required to meet range objectives); (2) the costs of lightweighting efforts and materials; and (3) the vehicle's CO_2 footprint, which includes production and EoL emissions (Automotive World, 2022)**.** Hence, innovative lightweighting materials such as aluminium and synthetic composites that deliver sustainability benefits now may be replaced in the future in favour of green low-level lightweight materials such as green steel and (A)HSS.

6.2 SUPPLY CHAIN CIRCULARISATION

Sustainability has been an element that appears to cut across any of the above mentioned strategies and is one of the highly-cited criteria for consideration with any automotive materials. The significant environmental load associated with automotive materials has been reported exhaustively (ALFED, 2021) (ArcelorMittal, 2020) (BPF, 2023) (Copper Alliance, 2017) and, besides, improving the environmental profile of these materials, material recovery strategies, particularly in the order of recovery/ reuse and recycling, right from the material design stage, is recommended as a priority.

With clear evidence on the significant environmental profile of automotive materials discussed in section 5, the irrevocable need to build and improve material efficiency is emerging as a key take away when considering innovative materials, both in terms of composition, design and end-use. To reduce the overall material demand by the automotive sector, either through cutting-edge casting/ moulding technologies or through material recovery strategies (recover, reuse and recycle) cuts across as the overarching sustainability requirement for emerging automotive materials.

Most studies indicate 100% recyclability of all foundation materials covered in this study, except plastics, polymers and composites (Section 5.3). However, the current technical (recycling methods) and demand-driven (loss of desired functionality while recycling) limitations associated with recycled materials leads to restrictions in their close-loop utilisation. While open-loop consumption is beneficial in terms of retaining the materials as a part of the general consumption loop, cumulative demand for foundation materials will persist, if the challenges pertaining to closed-loop consumption are not addressed sufficiently in the current time frame. Therefore, identifying the challenges related to closed-loop consumption of these secondary foundation materials must ideally take priority.

From the review of the collected literature, some of the key factors that often lead to time-consuming debates between emerging promising materials, from the standpoint of circularity include the following:

- From supply chain perspective, lack of guidance or dedicated business models for setting up reliable supply chains for secondary materials.
- Material supply chain from foundation material production to ELV scrap processing, acting in silos as opposed to the combined research and development effort needed to enable material circularity.
- From policy perspective, lack of policy-driven pressure or subsidies incentivising secondary material integration and to bolster closed-loop material recovery targets from ELVs, as opposed to the current generic recovery targets.
- From a technical perspective, a potential lack of consideration of material functionality from a life cycle perspective, particularly emerging material alloy compositions designed for dismantling, high-quality segregation and material recovery through EoL routes.
- Current lack of dedicated extended producer responsibility (EPRs) that accounts for establishing specialist EoL management infrastructure for ELV (end-of-life vehicle) - scrap segregation and processing, prior to recycling.

6.3 USE OF RENEWABLE ELECTRICITY IN THE SUPPLY CHAIN

Mining, refinement, and downstream production of foundation materials into vehicle components used in the automotive sector requires large energy inputs, either as thermal energy (conventionally from fossil fuels) or electricity. Therefore, in order to reduce the lifecycle emissions from foundation materials, it is integral to address the direct emissions from on-site combustion of fossil fuels and indirect emissions from the energy sources used to generate imported electricity. Increasing the use of renewable material production has large potential to reduce the total lifecycle emissions of automotive materials, creating a more sustainable automotive material supply chain without the need for re-design of vehicle components or development of new innovative materials.

Green hydrogen, generated through electrolysis, has emerged as a key element for future low carbon production of foundation materials to the automotive sector, including for steel (*please see section 5.1.2.3*), aluminium (*please see section 5.2.2*) and copper (*please see section 5.4.2*). In particular, demand for hydrogen for primary steel production via. the DRI-EAF route is expected to grow from around 8 MtH_2 per year in 2030 to 62 MtH_2 per year by 2050 (IEA, 2019). However, the environmental impact of green hydrogen is heavily dependent on the energy sources used to generate the electricity powering the electrolysis process. Using an electrolyser with the global grid electricity mix in 2021 would produce 23.5 $kgCO_2e$ per kg of H_2, compared to close to zero emissions from using solar PV or onshore wind (IEA, 2023c). Therefore, continued and rapid decarbonisation of the electricity grid, alongside transparency on the carbon intensity of electricity used in hydrogen production, is required to ensure that direct emissions from on-site fossil fuel combustion in furnaces aren't outsourced to off-site green hydrogen production facilities as indirect emissions. The UK government aims to expand hydrogen transport and storage infrastructure to satisfy 10GW hydrogen production capacity by 2030 (DESNEZ, 2023).

Furthermore, electrification of production stages can deliver deep emission reductions in the supply chain. 60% of aluminium production emissions are indirect emissions from the consumed electricity used in the primary aluminium smelter and other stages (*please see section 5.2.2*). The use of the electric arc furnace (EAF) in both the DRI-EAF primary production process for steel and in the secondary scrap-EAF route allows significant electrification of steel production. However, in order for electrified infrastructure to deliver on their significant supply chain decarbonisation potential, the electricity supplied requires a substantial increase in renewable energy share. The UK government has set a target for the UK to fully decarbonise grid electricity by 2035, as a part of the government's Net Zero strategy (UK Government, 2020). The UK's National Grid Electricity System Operator has assumed that electricity capacity will increase in line with increasing electricity demand, from about 100GW capacity today to around 200GW in 2035 (Green Alliance, 2023).

Furthermore, many of the activities, such as transport and logistical activities and EoL handling, to process the raw materials into vehicle components have the potential to be fully electrified and powered using renewable electricity. The net zero roadmap for copper production introduced by the International Copper Alliance (ICA, 2023) includes the use of electrified vehicles and machinery to extract and transport the mined copper ore for processing. Coupled with decarbonised electricity supply, equipment electrification is expected to contribute to around 30% reductions in scope 1 and 2 emissions by 2030, and 70-80% reduction in emissions by 2040.

Hence, the impact of renewable electricity in decarbonising the automotive supply chain will be dependent on the extent to which the manufacturers implement infrastructure electrification and electrified equipment. Additionally, the availability of green hydrogen from renewable electricity sources will have a further, indirect emission impact.

7 DISCUSSION

There are some key trends that have emerged from the review of published literature. These findings have informed a series of potential questions that can be posed to stakeholders in the UK automotive industry (see Table 7-1). This list of questions is non-exhaustive and is only intended as a preliminary starting point for further consultation with these stakeholders, aiming to refine these key findings into tangible recommendations for research in UK foundation industries that meet the needs of the automotive sector.

Key finding 1: manufacturers continue to explore mass reduction in vehicles (although there is a trend for cars at least to larger vehicles which is still driving an increase in average mass), and therefore lighter materials, in order to deliver use-phase emissions savings.

There is an incentive to reduce mass from ICEVs, and for BEVs to comply with CO_2 regulations to reduce energy usage during the use phase (reducing CO_2 for ICEVs and allowing for smaller batteries for BEVs). The UK has historically been effective at early-stage funding for developing new materials but struggles with commercialisation. Viable candidate materials have already been developed from a functional perspective (aluminium, fibre-reinforced composites) and are being implemented in new vehicles (see Section 6.1). Achieving scale is critical to reaching a material cost which creates incentives for manufacturers to consider integration into mass-produced vehicles. We expect to investigate/ discuss with stakeholders about materials that they anticipate having the need to be prioritised for innovation and integration in the short-to medium term, as a part of the stakeholder engagement events planned in the following stages of this project. In particular, we will explore the role which innovative plastics and polymers such as carbon fibre and bio-based plastics are expected to play in future vehicle designs.

Key finding 2: manufacturers are actively seeking closed loop supply chains to reduce the sustainability impacts of automotive materials and preserves scarce resources.

Although recovering and recycling of foundation materials from EoL vehicles has clear sustainability benefits, current technologies, performance barriers of the outputs and the overall economic feasibility limit the deployment of recycled materials in the automotive sector. Efforts to increase circularity of automotive materials, particularly aluminium and steel, are being pursued by several OEMs in the UK and Europe, including JLR and Volvo for aluminium (*please see section 5.2.2*) and BMW for steel *(please see section 5.1.2*). Cost- and energy-efficient carbon fibre recycling, which is also a high-impact materials maybe crucial in the long-term owing to their anticipated demand for further lightweighting strategies in the long-term. Therefore, efforts into building and strengthening the UK as a ‘circularity hub’, by encouraging policy development, setting targets, incentives and support for OEMs and partners to close the loop for automotive scrap may be crucial. This support should, for a start, focus on materials with high realised recyclable potential, but low recycled content in the UK, such as steel, glass and copper.

Key finding 3: manufacturers are increasingly favouring materials from suppliers using low or zero carbon energy.

As BEV sales begin to outweigh ICEV sales, also reducing production emissions will become more important for the overall sustainability of vehicles. The production of foundation materials is energy intensive and requires stable energy supply that can cater to competing demands from other sectors and the growing UK fleet of EVs in the medium and long-term. Ensuring the production of foundation materials has access to a sufficiently diversified and scalable renewable energy sources, supplemented by appropriate energy storage solutions should, therefore, be a priority. This is particularly relevant with the roll-out of carbon border adjustment mechanisms (CBAM) in the EU, that will increasingly penalise the import of high-carbon foundation materials (e.g., steel and aluminium). It is therefore, recommended that further support is provided to support production facilities gain access to fully renewable energy and accelerate decarbonisation beyond grid-level improvements over a longer time horizon. This could be achieved through supporting domestic energy production facilities or a secure supply chain for green hydrogen, which is emerging as a critical alternative to fossil fuels for the low-carbon production of almost all foundation materials.

Key finding 4: manufacturers are ultimately concerned about the end user (customers) expectations and may not adopt material innovations beyond a certain degree without incentives.

Whilst policy and market trends have a large impact on material demand in vehicles, a thread running through all of the above findings is that OEMs will be primarily concerned with the comparable profitability and customer’s perception of their vehicle’s market price. Regulatory policies seldom keep pace with innovation in material design or vehicle design in the automotive sector and this leads to emerging technologies being reserved for when relevant policies are proposed or enter into force. Demand-led innovation needs to be affordable from the OEMs’ perspective, and by extension, any ‘passover’ costs to consumers cannot exceed any additional tangible benefits like running costs, engine performance, durability, reliability or comfort. Consumer considerations and relative profitability remain key knowledge gaps that are not explored extensively in the literature. These aspects will be further explored during the interviews scheduled to take place as part of Task 3 of this project.

The questions arising from these key findings are reported in Table 7-1 below.

Table 7-1: Key findings and knowledge gaps from the literature review, informing further questions for UK stakeholder consultation.

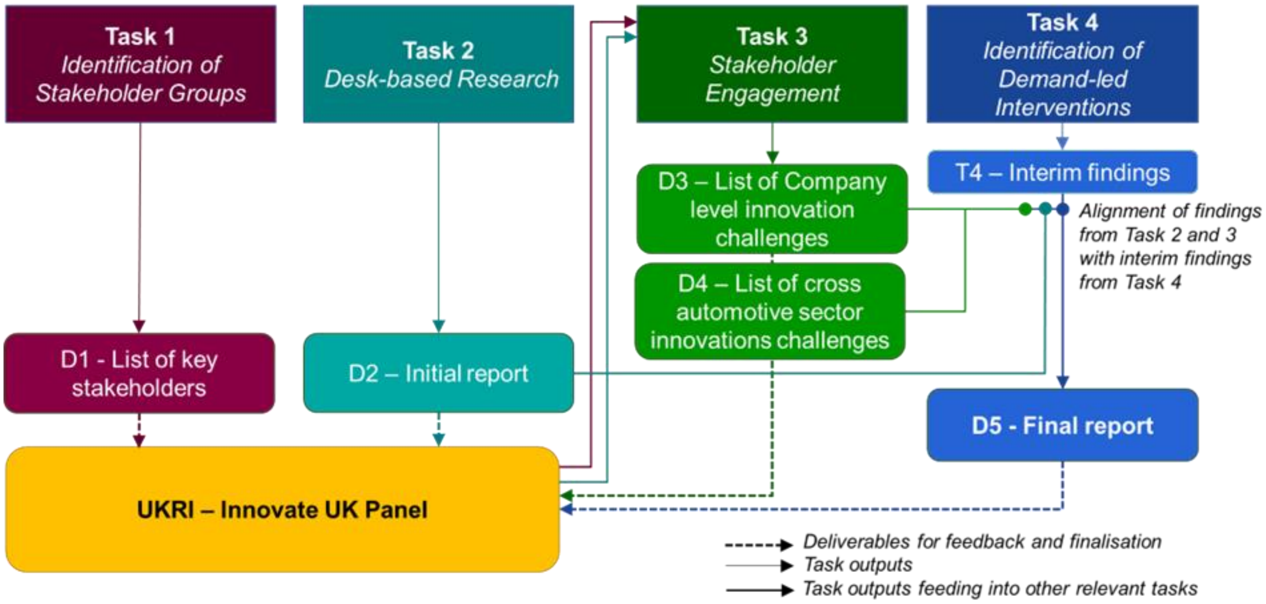
Key finding	Knowledge gaps	Preliminary innovation challenges identified	Potential questions for UK stakeholders
Automotive OEMs are incentivised to **reduce vehicle mass**, with lighter materials part of this picture, to deliver use-phase energy savings. (However, there is also a trend to larger cars counter-acting this).	• The lightweight materials currently preferred from the sustainability / cost / function trade-off	1. Availability and stable supply of lightweight, low carbon, low-cost materials 2. Current lack of affordable specialist treatment methods to convert light weight alloys into their 100% pure base metals	3. Does the UK have comparative advantage in the production of any lightweight materials in particular? 4. How might innovations like aluminium mega-casting affect the industry? 5. Will current innovations in carbon fibre and bio-plastic production and recycling help in their wider adoption?
Foundation material and automotive OEMs are actively seeking **closed loop supply chains** to reduce the embodied carbon of automotive materials and preserves scarce resources.	• In-depth insights into the technical and economic barriers to recycling automotive scrap. • Performance trade-offs from the integration of higher recycled content into vehicle construction • Extent to which cost and energy efficient CFRP recycling would promote uptake of recycled material	• Availability and stable supply of lightweight, low carbon, low-cost materials • Lack of dedicated specialist dismantling and sorting processes in the end-of-life vehicle management plants and the limited economic feasibility of this process • Current lack of affordable specialist treatment methods to convert separated light weight alloys into their 100% pure base metals	1. Which of your supply chains is currently the least circularised? 2. What is the greatest barrier to increasing the recycled content of materials in vehicle production? 3. Where could government support help to bridge the identified barrier(s)? 4. Which materials need to be prioritised towards research efforts for closing the loop? 5. What level of technological readiness is available for each of the foundation materials EoL handling?
Automotive OEMs are increasingly favouring materials from foundation material manufacturers and suppliers **using low or zero carbon energy**.	• Key barriers to renewable energy adoption by foundation industries • Effect of competing demand for renewable energy from other	• Significant reliance on grid electricity (which is slowly but steadily decarbonising), due to the challenges associated with retrofitting production plants with zero carbon energy generation technologies. • Increasing demand for EPDs and GHG profile, from automotive OEMs, for materials	1. Where in the energy supply chain would government intervention, such as through a wider national policy, help the most? 2. To what extent would renewable energy certificates or guarantees of origin influence your supplier decision?

Key finding	Knowledge gaps	Preliminary innovation challenges identified	Potential questions for UK stakeholders
	industrial sectors affect the demand from foundation industries	to support their carbon footprint declaration for their final product. • Lack of pull-factors such as incentives or wider policies for FI producers to switch to low or zero carbon electricity. • Complexities-related to the use of renewable energy certificates (RECs) or Guarantees of Origin (GOO), particular with the entry of CBAM into regulation, need to be investigated, from a foundation materials producer perspective	3. What foreseeable trade-offs do you identify in materials produced employing renewable energy, particularly, in terms of supply stability, material costs, besides the established sustainability benefits
Automotive OEMs are ultimately concerned about the **end vehicle consumers**	• Relative profitability of different innovative materials • Impact of material choice on consumers • Extent to which consumers will pay for more sustainable vehicles	• High-cost differential related to the use of low-carbon or zero carbon electricity and relevant innovative raw materials (e.g., secondary resources, bio-based resources) • Lack of innovative sustainability-driven business practices such as "access-based" business models between material producers and automotive OEMs.	4. To what extent would a change in automotive design from using [insert material] to [insert material] affect the consumer's experience of: a. Vehicle purchase cost b. Running cost c. Comfort d. Engine durability 5. Are there any consumer considerations impacting your choice of automotive materials? 6. What are your thoughts around the concept of "material-as-a-service" where the material producers may become involved in the EoL management of the ELV?

8 NEXT STEPS

The findings gathered from this literature review and quantitative assessment will feed into the planned stakeholder consultation, Task 3 of this study, as per the workplan shown in Figure 8-1. The material shortlist created in Section 3.1.2 has been used to hone interview questions towards specific material types and further draw out industry insights and innovation challenges. At point of submission of this report the stakeholder interviews are still ongoing. Vice-versa, stakeholder interviews will act as a means of verifying the findings in this deliverable in terms of industry trends, innovations and expected future material demand. The quantitative analysis on current material uses and future projections in the automotive sector, as well as being used as underlying inputs into the interview questions, will form the basis of discussion points for the planned industry roundtable (also planned as part of Task 3) which is due to take place in early February 2024. The key findings alongside the key questions for stakeholders presented in Table 7-1 serve as an excellent starting point for thematic discussions during the industry roundtable and should stimulate further insight from industry from both a demand and supply of foundation industry material perspectives. Findings from the interviews and roundtables will be presented in D5 - Final Report for this study presented to Innovate UK in March 2024.

Figure 8-1: Project workplan



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APPENDICES

A1.1 JUSTIFICATION FOR THE ALLOCATION OF PARTIAL SCORES UNDER THE MCDA-DRIVEN MATERIAL SHORTLISTING

- **Iron and Steel**: The rationale for the steel scoring '0.5' under the "automotive relevance" criteria have been provided as an example under step 3 of the shortlisting process. An established domestic infrastructure and a strong supply chain covering production, use and recycling of materials was found to contribute positively leading to a partial score of '0.75'. Current improvements and plans to expand sustainable manufacturing practices through renewable energy integration was also found to positively influence the overall sustainability credentials of the foundation material, in addition to the anticipated future demand from OEMs at least in the medium -term period. There is also further potential for the use of advanced high-strength steels and optimised designs to reduce the overall vehicle mass and amount of material used in vehicles. This led to the allocation of a positive score of '0.75'. From a sustainability perspective, in addition to anticipated efforts to reduce the production-related impacts, the current demonstrated recycling efficiency of iron and steel are at 99% and 85%, respectively. The current recycled content oof iron and steel are also at 98% and 25% respectively. However, there is little information on how much of these materials are close-loop recycled for the foundation material to truly demonstrate its suitability for considerations as a part of emerging innovations and sustainability performance in the medium and long-term. Therefore, iron and steel, under the sustainability criteria have been found to score just over '0.5'. Considering the weights allocated for all criteria are equal ('1'), the iron and steel drew an overall final score of '3.7' out of '5'.
- **Aluminium**: Contributing significantly (10-45%, by weight, depending on vehicle type) towards the construction of both LGVs and coaches, aluminium alloys are being increasingly explored for lightweighting strategies in cars and vans, even as an alternative to AHSS (steel) in some cases (Tata Steel, 2017). Due to the identified demand for aluminium (based off our initial analysis in section 4) and its current contributions to the vehicle construction, aluminium was allocated a partial score of '0.75'. While there is no bauxite mining in the UK, aluminium is produced in the UK through a mature post-consumer scrap processing supply chain, showcasing UK's strong domestic production capacity. This also provides a supportive infrastructure providing opportunities to investigate and integrate innovation, as a means of optimising the supply chain and this has led to the allocation of a partial score of '0.75'. Aluminium is in the centre of significant innovation with design considerations being explored for heavily for lightweighting and material-efficient vehicle construction, leading to a partial score allocation of '0.75'. Compared to AHSS steel, aluminium carries a relatively high environmental impact per kg, and therefore, 'green' manufacturing of aluminium is being explored as a more energy and carbon efficient production route . However, currently demonstrated high recycling efficiency and recycled content of 75% provides a strongly positive place for consideration in the shortlist of materials (at a partial score close to '1'). The overall evaluation of the material's performance led to aluminium drawing a final score of 3.6 out of '5', being the second most relevant material to be included for a deep dive.
- **Plastics, polymers and composites**: Making up 4-22%, by weight (depending on vehicle type) of road vehicles through roughly 30,000 parts and components, automotive plastics (in varying polymer compositions) are predominantly made of polypropylene (28%), polyurethane (15%), PVC (16%), and polyamides (7.6%), in addition to polystyrene, polycarbonates and other polymeric candidates. While the overall demand trends for these materials is decreasing, the noted reduction is rather gradual as these materials appear to be highly relevant for lightweighting strategies and material efficiency efforts towards future vehicle construction. This has led to an allocation of partial score of '0.75' under "automotive contribution". With the demand for plastics and polymers to somewhat persist over the medium and long-term in the UK automotive sector (based off our initial analysis in section 4) , innovative compositions, bio-based fibres (in composite production), innovative moulding methods and material recovery innovations are being currently explored. Yet the use of 100% plastic and polymer components is expected to be gradually phased out leading to a partial score of just '0.5' under the "innovation potential" criteria. However, their limitations in terms of sustainability characteristics are a major challenge (being predominantly produced from oil-based products, with major challenges in their recyclability and achieving high recycled content for automotive application, plastics and composites bring in a both the significant challenges but also opportunities for innovation in terms of developing innovative compositions and vehicle component designs that support ease of dismantling and efficient

sorting. This has led to the allocation of a partial score of just over '0.5' under the sustainability criteria. UK has strong domestic capabilities for plastics; however, this has been for application predominantly in other sectors than automotive plastics. This highlights the need for a dedicated supply chain and the current limitations on the opportunities to influence innovations and optimisation strategies to existing supply chains yielding a low score of '0.25'. The overall final score drawn by plastics and composites, following an evaluation of its performance under the different criteria is '2.7' out of '5'.

- **Copper**: Making up roughly 5-7% of ICEVs currently as alloys and in electric motors, the anticipated contribution of copper in future powertrains such as EVs is expected to be much higher. While ICEVs have 20-30kg of copper content, BEVs contain roughly 80 kg and PHEVs contain roughly half of that of BEVs. Demand for copper (based off our initial analysis in section 4) has been forecasted to significant increase (almost double that of current demand) with increase in EV uptake of the short- and medium-term periods, leading to a partial score allocation of '0.75'. With limited to no emerging alternatives to copper, research efforts into introducing material efficiency such as use of secondary copper or thinning of wires for cables are being explored. This also provides an opportunity for further explorations from the angle of material design and innovative manufacturing techniques and this led to the allocation of a partial score of '0.75' under the "innovation potential" criteria. Currently, UK has not domestic production or processing capacity for copper since most of copper is being imported from Chile and other countries, leading to a partial score of '0.25' under "domestic production" and "domestic influence" criteria. From a sustainability perspective, copper does carry a high environmental profile, contributing to nearly 1-9% of the overall vehicle's (ICEV) GHG footprint. This is anticipated to be much higher for EVs. Nevertheless, copper has been demonstrated to be recycled at 45-53% and carry a recycled content of 30%. With a scope for copper recyclability at 100%, there is room for innovation to enable such targets, leading to the reduction of the overall environmental impact of materials, and subsequently the vehicles where these materials are used. This has led to the allocation of a partial score of '0.75'. The overall final score drawn by copper, following the evaluation of all these impacts was '2.7' out of '5'
- **Glass**: Contributing roughly 3-5% of vehicles (depending on vehicle type), focus in glass is increasingly gaining momentum requiring significant strategies to develop, much more durable lightweight versions. The demand profile for glass (based off our initial analysis in section 4) showcases that material demand is expected to remain constant over the medium and long-term period through innovative applications such as smart glass, heated glass and other emerging technologies. There is also an increasing trend among consumers for sunroofs and moonroofs to allow sunlight and improve air fresh air circulation in the vehicles. This led to the allocation of a partial score of '0.75', under the "automotive contribution" and '0.5' under the "innovation potential" criteria. From a sustainability standpoint, glass only contributes to 0.6-0.8% of ICEVs, with much higher contributions anticipated with the need for higher glass content, as discussed earlier in relation to customer expectations. Glass is also currently recycled at a rate of 75%, with 100% recycled content. However, the current recycled content of automotive-grade glass is unknown, and this is planned for investigation as a part of the deep dive. Glass, under the "sustainability characteristics" criteria, has therefore scored just over '0.5'. In terms of domestic production, UK has a somewhat strong production capacity catering to applications to a wider industrial sector with only minor capacity operating towards the production of automotive-grade glass production. As a result, a partial score of '0.5' and '0.25' has been allocated towards, "domestic production capacity" and "influence on supply chain" criteria. The overall score acquired by the glass, upon evaluation of its performance under the various criteria is '2.7' out of 5.

A more detailed analysis of the selected foundation materials has been provided under section 5.

A1.2 MATERIAL DEMAND QUANTIFICATION

A1.2.1 Methodology

In order to create high-level estimates for material demand in the UK automotive sector, a modelling exercise was undertaken. The approach to this modelling exercise is outlined in Equation 1 and explained beneath.

Equation 1: Estimation of UK automotive material demand for a given year

$$Demand[kg]_{mt} = \sum_{v=1}^{V} \left(VehicleMaterialMass[kg]_{vmpt} \times VehicleProduction[\#]_{vpt} \right)$$

Where:

- $VehicleMaterialMass$ is the expected mass of a material in a typical vehicle (units = kilograms)
- $VehicleProduction$ is the expected number of vehicles produced in the UK in a given year (units = # of vehicles)
- m=material type
- t=year
- v=vehicle type
- V=total number of vehicle types
- p=powertrain type

A1.2.2 Key data and assumptions

This section lays out the key data sources and assumptions used in this modelling work.

Representative vehicle types in the UK fleet ***(v)***

To account for the fact that different vehicle types use different types of quantities of materials, and that the material composition of a BEV may be different to an ICEV, the UK automotive fleet is categorised into a number of representative vehicle types. Table A-1 below presents the vehicle types considered most representative of the UK fleet.

Table A-1: Vehicle types considered as representative

Category	Vehicle type	Powertrain
Low duty vehicles (LDV)	Car (Lower medium)	• Petrol (ICEV-G) • Battery Electric (BEV)
	Van (N1 Class III)	• Diesel (ICEV-D) • Battery Electric (BEV)
Heavy duty vehicles (HDV)	Rigid Lorry (12t GVW Box)	• Diesel (ICEV-D) • Battery Electric (BEV)
	Articulated Lorry (40t GVW Box)	• Diesel (ICEV-D) • Battery Electric (BEV)
	Bus / Coach (12m SD)	• Diesel (ICEV-D) • Battery Electric (BEV)
Motorcycles (L-category)	N/A*	

** Motorcycles were not included in this analysis since current UK production of motorcycles is limited, and hence material demand from this sector is not expected to be significant.*

Mass of material in a given vehicle type ($\boldsymbol{VehicleMaterialMass_{vmpt}}$)

Data on the material composition per vehicle over time is from a vehicle Lifecycle Assessment Model developed by Ricardo for DG CLIMA, which was created to estimate the total lifecycle impacts of all vehicle types in the EU for policy analysis purposes (Ricardo, 2020). The material mass estimated depends on the vehicle type, powertrain, and year. Table A-1 above shows the representative vehicle classes for the UK that are selected for the projection.

The LCA model forecasts the materials required to produce vehicles by vehicle types and year, with different assumptions on innovation or policy requirements. As mentioned in Section 4, two scenarios reflecting different sensitivities and uncertainties over time are applied for this project.

- **Default scenario**: a baseline scenario including all currently planned/ implemented EU and national policies. This represents a scenario with more limited innovation in automotive material design.
- **Net Zero scenario**: a long-term strategy to reach a climate-neutral Europe by 2050[15]. This scenario implies more significant innovation in material design, driven by compliance with a more ambitious net zero agenda.

UK vehicle production ($\boldsymbol{ExpectedVehicleProduction_{vt}}$)

For **LDV production**, projections for the UK were taken from SMMT estimates (SMMT, 2023), which extend to 2028. LDV production beyond 2028 was assumed to grow in line with the expected GDP growth of the UK, taken from the OECD Real GDP long-term forecast (SMMT, 2023).

For **HDV production**, the most recent SMMT estimates on the total production of commercial vehicles was used as the baseline 2023 value. Commercial vehicles were split into representative vehicle types (rigid lorry, articulated lorry, bus/coach) using recent vehicle registry data from 2022 published by the SMMT (SMMT, 2023). HDV projections beyond 2023 was assumed to grow in line with the expected GDP growth of the UK, taken from the OECD Real GDP long-term forecast (OECD, 2023).

Table A-2: Estimated vehicle production in the UK split by vehicle type

Year	Vehicles produced per year, by vehicle type				
	Car	Van	Rigid Lorry	Artic Lorry	Bus
2025	791,700	143,500	56,563	51,550	5,337
2030	873,407	127,793	60,365	55,015	5,696
2035	928,666	135,878	64,184	58,495	6,056
2040	983,611	143,918	67,982	61,956	6,415
2045	1,040,346	152,219	71,903	65,530	6,785
2050	1,099,745	160,910	76,008	69,271	7,172

Source: own estimate based on (SMMT, 2023)

Powertrain split: the production estimates and forecasts above do not dissociate by powertrain. As such, government targets and recent projections were used to split total vehicle production into broad 'ICEV' and 'BEV' categories. Many other types of powertrain exist (full hybrid, plug-in hybrid, etc), but according to the Lifecycle Assessment Model, these do not differ significantly in material composition from ICEVs and BEVs and therefore the additional accuracy of including these powertrains was not warranted for this high-level exercise. The BEV share of LDV production is assumed to follow the UK mandate for Zero Emission Vehicles (ZEV) sales (Department for Transport, 2023). Amongst HDVs, these are expected to be fully electric by 2040 (Department for Transport, 2021), but before 2040 the trajectory for electrification is unclear. Consequently, estimates are taken from the recent projections provided by the UK Department for Transport to Ricardo for use in policy analysis.[16]

[15] This scenario would be consistent with the EU meeting the Paris Agreement objective of keeping global temperature increase to a maximum of 1.5 ºC.

[16] For confidentiality reasons, these are not reported here.

Table A-3: Vehicle electrification assumptions

Vehicle type	2025	2030	2035	2040	2045	2050
Car	28%	80%	100%	100%	100%	100%
Van	16%	70%	100%	100%	100%	100%
Rigid Lorry	3%	29%	91%	100%	100%	100%
Artic Lorry	1%	25%	63%	100%	100%	100%
Bus	30%	65%	100%	100%	100%	100%

Sources: (Department for Transport, 2021) & (Department for Transport, 2023)

Caveats and discussion

Since the calculations utilized existing model and secondary data, the following factors should be considered.

Firstly, the vehicle LCA model used for material weight compositions has not been derived specifically for the purposes of this project and is based on a European policy context. The model is suitable for generic comparisons of vehicles, but the input data on energy consumption, mass, power, emissions and others are based on the model's generic vehicle types, which was not updated for a UK context. UK and EU policies are often aligned, but not perfectly. For this reason, it is important to interpret the results by focusing on the trends rather than the accuracy of the absolute values.

Secondly, representative vehicle types were chosen to resemble the UK fleet and assumed static, but total material demand varies significantly for vehicles of different sizes, especially when it comes to heavy duty vehicles. For instance, this approach assumes that all rigid lorries are 12t GVW Box lorries (given they are the most prevalent in the UK fleet), but rigid lorries can be up to 40t unladen. Similarly, the lower medium segment is the most common car in the UK fleet, but consumer trends are tending towards larger vehicles over time – if most cars were large SUVs towards 2050, our projections would represent an underestimate. Similarly to the first caveat, this approach is a simplification intended to represent trends rather than estimate absolute demand estimates at a high level of detail.

Thirdly, vehicle production is not a perfect indicator of material demand for UK producers. UK automotive manufacturers can choose to produce using local foundation materials, or alternatively by importing materials from abroad. They may choose to import based on availability and the competitive cost of materials sourced outside of the UK, amongst other strategic factors. However, given the options available for scaling to the UK automotive sector level (vehicle production data, or vehicle registration data), the former was assessed as a better proxy for demand from UK foundation industries. All things being equal (cost, sustainability performance etc.), it is more likely that an automotive manufacturer will use local materials rather than imported materials for logistical reasons. Registered vehicles include those that are imported from abroad, which for similar reasons are more likely to use materials local to the origin of production. Therefore, vehicle registration data may capture a higher proportion of material demand from other countries of production, and therefore vehicle production data was chosen as a better proxy.

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