Bulk material manufacture:

the potential impact of digitalisation and provenance systems on materi-als recirculation

Dr Martin Burgess
Professor Charlie Wilson
Environmental Change Institute, Oxford University

June 2023

Disclaimer

This report was written as part of the CircEUlar project under EC grant agreement 101056810. The information, documentation and figures available in this deliverable were written by the CircEUlar project consortium and do not necessarily reflect the views of the European Commission. The European Commission is not liable for any use that may be made of the information contained herein.

How to quote this document

Burgess, M., Wilson, C., (2023). Bulk material manufacture: the potential impact of digitalisation and provenance systems on materials recirculation. https://doi.org/10.5281/zenodo.8054783

Executive Summary

Reducing GHG emissions without reducing living standards implies recirculating materials rather than discarding or downcycling them: in particular, the emissions associated with the four major bulk materials (steel, cement, plastics and aluminium) are around two-thirds of the entire industrial emissions. This study examines, through a series of expert interviews, how digitalisation, both through provenance systems and analysis tools for sorting discarded materials, could improve circularity in Europe. It finds that whilst there is a large and sudden interest from construction companies and the automotive sector in using recycled materials due to self-imposed low-carbon targets, almost nothing digital is being developed for recirculating either steel or cement. The exception is Business Information Modelling which could assist building or material reuse in second lives, some 15-40 years into the future. For plastics, on-pack provenance systems could be implemented in the short-term, but this depends on cross-supply chain cooperation which is generally lacking. Only for aluminium is there the prospect of substantial near-term improvement, where the introduction of Laser Induced Breakdown Spectroscopy could greatly reduce the downcycling of wrought aluminium into cast grades, potentially eliminating a forecast surplus of cast aluminium by 2030.

Keywords

Digital sorting, Steel recycling, Aluminium Recycling, Plastics Recycling, Laser Induced Breakdown Spectroscopy

Contents

List of figures

List of tables

Bulk material manufacture:

the potential impact of digitalisation and provenance systems on materials recirculation

1. Introduction

The contribution of industrial emissions to global warming is significant, so reducing it is a significant opportunity. Direct industrial emissions are generally calculated to be around 24% of world totals, with a further 10% of the total emitted to generate electricity and heat for industrial purposes, illustrated in Figure 1. (IPCC, 2022).

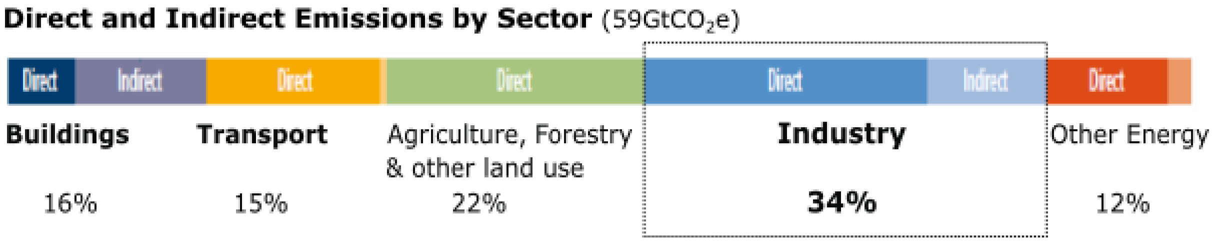

Figure 1: Global emissions broken down by end-use sector (Redrawn from (IPCC, 2022)).

Global industrial emissions are 20Gt CO2e (34% of 59Gt CO2e). In the EU four bulk materials (steel, cement, plastics and aluminium) account for around 66% of GHG emissions (including embodied carbon in imports). About half of emissions from the four materials are used in the mobility and buildings sectors (Material Economics, 2018).

The research starts from an assumption that the high-emitting industrial bulk material industries will be subject to the same data transformations affecting society more generally, and may have the potential to radically change the possibilities for narrowing, closing and slowing the usage of these materials. It looks at the potential for digitalisation (for example, using provenance systems) to increase European circularity of the materials in accordance with the principles of the Circular Economy (CE). This paper focuses on areas where the potential for an almost immediate impact of digitalisation appears greatest: recirculation post waste collection, through sorting and recycling or reuse. Longer term, the need for better, probably computer-assisted, design to lightweight material parts through stronger or better designed materials which can be readily recycled is vital, but this area is outside the scope of this study.

It is approached through the standard logic of Narrow, Slow and Close, where narrowing material usage loops implies using less material to achieve the same ends (increased material efficiency or dematerialisation). Slowing the circulation loop is brought about through longer lives (reuse, repair, repurpose, redesign) and Closing loops implies recycling or recovering the material at its end of life without downcycling (making an inferior product from the material because it has reduced properties) (Bocken et al., 2017).

1.1 Salient background on Steel, Cement, Plastics and Aluminium

1.1.1 Steel

European steel is produced in about 26 blast and basic oxygen furnaces and around 100 Electric Arc Furnaces, though the capacity of the blast furnaces is larger and they account for 56.4% of production in 2021 (Eurofer, 2022). Steel production accounts for 5% of total European GHG emissions (Material Economics, 2020), equal to about 25% of industrial emissions. European steel stocks have largely reached saturation levels: scrap arisings (115mtpa (Dworak & Fellner, 2021)) are increasing towards the level of new steel supplied (152mtpa in 2021 (Eurofer, 2022)). So scrap arisings are c.75% of production. However, the quality of the end-of-life scrap element ("old scrap") is poor: much is downcycled into reinforcing bar and mesh ("rebar") which is highly tolerant of contaminants and the remainder exported, also for rebar. While post-fabrication scrap of know composition ("new scrap") is all recycled, much of the new steel supplied in Europe is made from virgin iron ore and its derivatives, not old scrap. This mismatch of scrap quality with new demand means that the CE in steel is currently a mirage. Further ahead, a world surplus of highly contaminated and unusable scrap is forecast beyond 2040 (Dworak et al., 2022)..

1.1.2 Cement

CEMBUREAU, the European Cement Manufacturers Association, reports that 172Mtpa of cement is produced (CEMBUREAU, 2016), as are 7.9% of EU industrial emissions (EEA, 2017). Whilst CEMBUREAU claims that cement is 100% recyclable, it gives the two main reuses as aggregates in new concrete and aggregate in new roads and construction. This is not recycling: it is either downcycling or repurposing. CEMBUREAU does not suggest that recycling of reacted cement into more cement is possible: there is a real issue of non-circularity.

1.1.3 Plastics

The EU uses 49Mt of plastics each year: production of each ton causes about 2.5t of CO2 and there is another 2.7t of embedded carbon in each ton, which is released if the plastic is burnt in energy-from-waste plant at its end-of-life. Mechanical recycling at end-of-life produces less than 20% of the emissions coming from new plastics, although some degradation of the plastic occurs, leading to downcycling (Material Economics, 2018). Chemical recycling is under development for a wide variety of plastics, though many are at early stages, with potentially larger emissions savings than for mechanical recycling as the resulting monomers can be made into new virgin plastic without any degradation from the original properties: true circularity.

More than 40% of plastics are made into packaging and other single use products: these come through the supply chain as waste almost as soon as they are placed on the market. Accordingly, some 42Mtpa of plastics waste needs processing each year, much of which can be mechanically recycled in principle. However, only 10% of value is retained (Material Economics, 2020). There are many reasons for this: difficulties in separation of post-consumer plastics – value is only retained if the separation is into single polymer types; low collection rates, burning plastics in Energy-from-Waste plants, and degradation/conversion losses, as mentioned above.

1.1.4 Aluminium

Worldwide, about 100 Mt (million metric tons) of aluminium are currently produced per year, about 35% of which comes from post-consumer scrap and 40% from processing or fabrication scrap (Raabe et al., 2022). In Europe, about 10 Mt (million metric tons) of aluminium are currently produced per year, about 60% of which comes from scrap (both post-consumer scrap and processing or fabrication scrap) (Alucycle, 2022). Due to the very high electricity consumption when alumina is smelted in the production of aluminium, recycling takes only about 5% of the energy that it takes to create virgin aluminium (Material Economics, 2018). There are multiple grades of aluminium within each of two classes: wrought and cast. Wrought aluminium contains small specific percentages of alloying elements such as magnesium, zinc and manganese. Cast aluminium contains higher levels of silicon, and can tolerate higher levels of impurities than wrought. When wrought is recycled in Europe, fabrication scrap lots from a single factory are normally of known grade and kept separate for recycling directly back into a similar wrought grade. Mixed post-consumer scrap is shredded (wrought and cast together). This is either shipped to low-wage countries for hand sorting (wrought and cast shreds can be separated by skilled eye) or both are remelted together, downcycling the wrought into cast, because of its tolerance of impurities. Currently, there is considerable demand for cast aluminium internal combustion engine blocks, though this will decline over the next decade, potentially leaving an excess of cast aluminium between 2030 and 2050 (Løvik et al., 2014; Modaresi & Müller, 2012). Thus there is a demand for an automated method of separating wrought and cast shred to preserve the wrought and avoid downcycling.

1.1.5 Sectoral use

The building and mobility sectors are high consumers of steel, plastics and aluminium, with building using 33% of steel, 20% of plastics and 25% of aluminium, and vehicles using 20%, 10% and 20% respectively (all EU figures) (Material Economics, 2018). So end-of-life releases of these materials back into the economy is a very significant resource for reuse and recycling, for the Circular Economy and for GHG reduction compared to replacement with virgin materials.

Cement is used wholly in the construction sector (65% in buildings (ibid)), but the other three materials are used throughout the manufacturing economy, with hundreds of grades of each used across construction, automotive, household appliances and almost any other fabricated item. The variety of grades (or for plastics, completely different materials) causes complexity in material recovery, and without easy separation of grades ultimately causes inefficiency and losses in recycling.

1.2 Recycling and Downcycling

Current usage of all four of the materials is far from circular. Although recycling rates for steel (85%) and aluminium (78%) are respectable, most end-of-life steel is downcycled in Europe as is 80% of the recycled aluminium. Relatively little plastic is recycled (21%) and almost no cement (Allwood & Cullen, 2011; Material Economics, 2020). Many industrial initiatives focus on decarbonisation rather than circularity, for example fuelling cement production with alternative energy sources, which reduces the operational energy but ignores end-of-life recycling.

When manufacturing plastics, steel and aluminium from virgin materials specific grades are created from specific ingredients to give the finished material specific properties and create a high value product. For steel and aluminium, this involves alloying with more-or-less precise percentages of other metallic elements such as nickel, chrome and manganese. Current reprocessing of plastics, steel and aluminium suffer greatly from different high-value grades with specific compositions and properties being recycled together, creating a mixed product with unspecific and variable properties – dependent on the varying source material – of limited value (Burgess et al., 2021; Ohno et al., 2017; Stotz et al., 2017). This is referred to as ‘downcycling’ and indirectly causes the extraction of more resources to create additional high value materials with specific properties from virgin feedstocks. Additionally, when downcycling occurs in metals the valuable metal elements added to create the high-value properties are mostly lost into the downcycled product, causing more metal additives to be manufactured, mined or refined (Ohno et al., 2015). Downcycled mixed plastic has limited uses, for example in making fence posts, and so waste household plastics are usually burnt to recover the energy value (Malinauskaite et al., 2017; McKinsey & Co, 2018), regarded as a great waste of the embedded carbon compounds and causing more virgin material to be created and used.

The key to retaining the functional value of the material is separating materials by formulation before reprocessing to allow items with similar formulations to be recycled together, thus allowing the recycled material to have known properties and preserving it in its highest value state. Established separation and sorting processes based on density, colour, shape and manual separation are gradually improving but do not normally produce outputs of a high enough quality to recycle directly into high quality materials: the material is generally downcycled. This occurs as non-digital systems physically sorting proportionately more of one material than another into a certain channel are never 100%

accurate: depending on the parameters the machine is set to, either there are small proportions of the unwanted element in the sort, or there is a proportion of the wanted element left unsorted in the residue. Improved digital systems which could recognise items with certainty have the potential to improve this situation.

Figure 2 summaries the current position. Note that in all three cases the value losses far exceed the volume losses: the recycling is downcycling into lower quality materials.

	Original value of End-of-Life materials	Combined Price and Volume Losses	Recycling Rate by volume	Volume loss	Value loss
Steel	€63bn	€32bn	85%	15%	51%
Aluminium	€12bn	€ 5bn	78%	22%	42%
Plastics	€62bn	€55bn	21%	79%	89%
Reworking costs		(€14bn)			
	€137bn	€78bn	43%		

Source: Material Economics, 2020, Preserving Value of Materials in the EU, p6-8

Figure 2: A statement of the value destruction through recycling in Europe

1.3 Provenance Systems

Loosely defined, these are systems which enable a user to access data giving information about an item's origin, history, material content or any other matter which the originator may think is beneficial to the user. Users may be human or machine and may have passed security checks or may be members of the general public. Examples are company employees entering data on shipping movements, and a consumer scanning a QR code on a cosmetic product to check its history because the manufacturers have created the data for marketing purposes.

There are three principal types of provenance system. The first uses some sort of on-product code to access the data from a remote database. This could be as simple as the cosmetic example above, or more complex, such as an embedded molecule in handbag leather which can be read by a scanner and cross-checked against a secure database to prove authenticity (Security Matters Ltd, smx.tech). These databases may run on proprietary systems or on distributed ledger technology (DLT: also known as blockchain). The second type are 'chain-of-custody' databases which track the movement of products as they are created and moved through distribution channels: these are normally in place to discharge ESG responsibilities, for example the avoidance of so-called blood diamonds (tracr.com) or origin of bulk minerals such as cobalt (re-source.tech). Finally, the last type simply holds information securely, in a manner that enables updating, so that it is available to be interrogated by unknown users in the future. The exemplar of this is Building Information Modelling, where theoretically all information about the construction of a building is held for its subsequent users, to determine how best to refurbish it, or reuse components, typically when it reaches a second life (Zhao & Taib, 2022).

1.4 Digitalisation as an enabler of materials recirculation

In the context of this paper, digitalisation means the use of advanced information collection, storage and processing to further the aims of the CE. Provenance systems are just one instance of digitalisation in materials recirculation: others are data collection and analysis tools applied during waste sorting, and design tools used before the product is made. Digitalisation may or may not be applied to vast amounts of data, and occurs in multiple forms, such as (but not limited to):

- Provenance systems: remote access to data. Examples are given above, though in the context of recycling this could be envisaged as the ability to look up the precise alloy that a specific part, such as a car bonnet from a known model and year, was made from;
- Provenance systems: high-speed look-up systems in a Material Recycling Facility to read a code on an item as it moves along a conveyor belt and access a (probably local) database to better sort materials into purer streams which have higher value as they produce better quality recycled material (Burgess et al., 2021);
- Data collection and analysis: high-speed compositional analysis tools used in a Material Recycling Facility, to directly assess what an item is made from and sort it accordingly. These typically use X-rays or lasers (David & Kopac, 2015; Díaz-Romero et al., 2022);
- Data collection and analysis: process control through artificial intelligence (AI) with product identification (eg it's a can or a carton) but without sorting. Essentially this uses optical recognition and (in early incarnations) analyses the inputs and outputs of a Material Recycling Facility to optimise recoveries over a longer term by prompting management actions (Greyparrot.ai);
- Provenance systems and Data collection and analysis together: potential cross-matching of data to enable financial recoveries in the operation of Deposit Return Systems for bottles and in Extended Producer Responsibility. In some scenarios the bottle depositor could have an ID card which enabled the system to credit their bank account directly. Also, if each bottle had a unique serial number then other analysis linking time and place of purchase with time and place of return for marketing and fraud prevention purposes is also possible. In some theoretical Extended Producer Responsibility (EPR) scenarios, it is envisaged that producer taxes will be reduced by the proportion recycled. If proof of recycling is required on either an item-by-item or sampling basis then data collection and matching to the quantities placed on the market by each supplier will be necessary;
- Design tools: complex modelling of stresses in the design of parts with the twin aims of reducing material usage and eliminating bonding, welding or lamination of parts which prevent recycling (Suschem, 2020).

2. Research Design

2.1 Aims

The aim of the research is to understand the potential for new and emerging digital innovations and systems related to provenance and recirculation to significantly increase recycling rates or decrease downcycling rates in the period to 2050 for steel, cement, plastics and aluminium.

2.2 Research Questions

- How can chain-of-custody provenance data on material content increase recirculation rates of bulk materials?
- How can on-product provenance data on material content increase recirculation rates of bulk materials?
- How can improved data collection and analysis tools for examining materials during waste processing improve recirculation of bulk materials?

2.3 Approach, Scope and Boundaries

The study has originated as part of a pan-European project looking at future European emissions from a materials flow viewpoint, particularly focused on the application of materials projections to the areas of mobility and buildings. The research focuses on the impacts that digitalisation technologies may bring. Consequently, this study is also grounded in innovations in these areas, although most successful digital innovations can have applications across multiple domains.

GHG reduction strategies which do not utilise digitalisation as a prime enabler were noted but were not investigated in detail. Furthermore, the work was bounded by innovations already in commercial use, including those being piloted within a commercial environment. Hence, innovations still in laboratories with likely unknown commerciality or scalability, (for example (Ness et al., 2015; Stotz et al., 2017)) were not considered further.

3. Method

3.1 Analytical Framework

The transformative potential of digitally-enabled CE strategies being deployed by firms in relevant bulk material value chains was analysed along technical, market, firm, and regulatory dimensions. Furthermore, it suggested the prerequisite conditions necessary to enable widespread adoption of any new CE initiatives.

3.2 Data Collection and Analysis

This is detailed in Appendix 1. A Rapid Evidence Review was conducted to establish the key recycling themes for each of the four materials, using both academic and grey literature. These topics were used as a basis for expert interviews, interviewees being suggested from the literature and contacted by email or through LinkedIn. All interviews were recorded if possible.

.3 Details of the Interviewees

Sector	Steel	Aluminium	Plastics
Scrap handlers, traders and sorters	Scrap Buyer, pan-European Electric Arc Furnace steel producer (Interviewee 2)	Managing Director of an innovative pan-European aluminium waste sorting company (Interviewee 9)	Manager, Materials Recycling Facility and integrated plastics recycling company (Interviewee 15)
	Scrap Controller, worldwide integrated steel manufacturer (Interviewee 4)	Senior manager, recycling innovation, pan-European aluminium company (Interviewee 7)	
		Senior manager. aluminium scrap trading company (Interviewee 8)	
	Innovation Director, pan-European metal and plastic scrap processing and management company (Interviewee 12)		
	Innovation Manager, metal and plastic waste sorting and processing company, northern UK (Interviewee 14)		
Finished Metal Producers	Innovation Manager, pan-European Electric Arc Furnace steel producer (Interviewee 1)	Senior Manager, technical aluminium producer (Interviewee 13)	

	Two Technical Managers, worldwide integrated steel manufacturer (Interviewee 3)		
Academics and Consultants	Two steel consultants from a materials institute (Interviewee 5)	Highly experienced academic professor, specialising in aluminium industry (Interviewee 6)	Academic, researching business models in the plastics industry (Interviewee 16)
Sorting Machinery Manufacturer	Metal Manager, Northeast Europe, sorting machinery manufacturer (Interviewee 11)		
Artificial Intelligence	General Manager, AI information company focusing on waste sorting (Interviewee 10)		
Business Information Modelling	Building Consultant (Interviewee 17)		

4. Results

The sections below note all the main points made by the interviewees and attempts to place them in the context of themes mentioned by several interviewees. As such, they do cover points unrelated to provenance systems and digital technologies. Specific points are summarised at the end of each section. Each Interviewee is referred to by a number: on some occasions the number is replaced by the industry of the interviewee where not to do so might endanger their anonymity when read together with their other comments.

Results are based on interviews, and as such represent innovations close to commercialisation. Innovations discovered in literature which may have been discussed in interviews but which do not form interviewees views of the future are not included in results.

General Themes

This section covers themes which applied to most sectors: they can be grouped into two topics: the increase in demand for lower embodied-carbon products, and the importance of regulations in driving change.

The sudden interest in, and pressure from, the construction, automotive and packaging industries to reduce embodied carbon in their production over the last few years was remarked on by several interviewees (3,7,9,11,14): this is not being driven by legislation but apparently by these industries customers. "*What we're seeing is an absolutely dramatic change in the last couple of years in the number of people that are wanting to engage with us and the sort of people that want to engage with us and especially on steel and aluminium*" (Scrap recycling interviewee). "*OEMs trying to reduce the carbon footprint through the value chain*" is driving the business (Sorting machinery manufacturer). It's a "*really, really important driver*" (Interview 3) adding that the "*Institute of Structural Engineers…are kind of setting out an embodied carbon limit per metre squared of your building*" which sets a standard for the construction industry. As a result, many companies, both in production of materials and recycling of them, are starting to use the methodology and structure of Environmental Product Declarations as a standard measure of embodied carbon (Interviews 1,3,12,17). In particular, this highlights the benefits of reuse of existing construction materials compared to new (Interviewee 12).

In the context of refurbishing or replacing buildings, the pressure to reduce carbon footprints has led to a wider use of Building Information Modelling systems, where embodied and operational carbon can be compared for different options. Caution was advised against governments specifying targets here: refurbishment is highly contextualised dependent on the existing building and the clients' requirements, so placing mandatory targets on outcomes for refurbs is extremely difficult. Targets would have to be stratified dependent on the level of work envisaged. The more a building is refurbed, the more embodied carbon is added but the greater operational savings: demolishing and rebuilding adds greater carbon but will be better in some cases after a short payback period (Interview 17). The more knowledge an architect has of the detailed contents of a building structure, the more likelihood there is of being able to give those contents a second life.

There was a strong feeling across the interviews in all materials that regulations were crucial in driving change. Perhaps because of the context in which the interviews were requested and agreed to, the senior management interviewees were strongly pro-recycling, with one voicing the clear view that anything which creates demand for recycled materials is good (Interviewee 12) and another wanting "*mandatory recycled content in durable plastic items. Or in fact any, any item, any plastic, any metal, aluminium, mandatory recycled content*" (Interviewee 14).

The potential influence of government procurement policies was raised in two interviews, one in the context of specifying materials which would help the CE agenda, such as lower embodied carbon steel, and one because his experience was that where specific items were specified, such as UK steel content, these were not enforced years later when the materials were purchased by sub-contractors (Interviews 1 and 12).

A theme which emerged for both plastics and aluminium is the degree to which end users are historically anchored to precise specifications, readily obtainable by producing from virgin feedstock. If the end users are now wanting, or obliged to, use a proportion of recycled material then the specifications have to be widened, as the recyclate is made of mixed materials with different chemical compositions and is specified to be within a range of values and properties. Commonly, this will necessitate a whole new test programme for each component which adds inertia to the process. However, there was a common feeling that many, if not most, components were unnecessarily tightly specified through custom and practice (Interviewees 6, 9, 11, 12, 14).

With particular regard to steel, there was a view strongly expressed by two interviewees that regulations favoured downcycling steel in end-of-life vehicles, because they led to shredding of the vehicles and highly contaminated steel and aluminium (Interviewees 1 and 7). This theme of regulations favouring downcycling will be repeated for plastics also.

Other than the last point (end-of-life vehicles) all the above themes apply to Buildings, and apart from Building Information Modelling, they all apply to Mobility. So there is a large overlap of themes: perhaps a reflection that steel, aluminium and plastic are all incorporated in buildings and vehicles, and the recycling processes are somewhat independent of the source of the waste.

4.1 Steel

4.1.1 Economic - steel

A single clear theme emerged repeatedly: that a ready international market exists in steel scrap, irrespective of its quality or chemical content. *"Where's the drive for them to sort it [scrap] properly, if they can just ship it overseas and get it off their hands and get a decent price for it. Why put value into it by sorting it?"* (Interviewee 5). It was explained that EU scrap is ideal for making long products (reinforcing bar and mesh - 'rebar') for construction, which is principally taking place in the developing world, *"So there's this kind of overwhelming logic of export in scrap from the developed world to developing worlds"*… *"So you don't really need to spend a lot of money sorting that scrap"*. (Interviewee 3). This led to agreement that the steel industry was primarily focused on decarbonization rather than circularity (Interview 3).

Whilst this does not remove the price premium from higher quality, better sorted end-of-life scrap, it eliminates the motivation to do so in most participants minds. The study found no evidence whatsoever of any automated sorting of end-of-life steel scraps into different qualities.

On the other hand, post-fabrication scrap (also known as new scrap or factory scrap) was much in demand for recovery ("All the new production scrap is being chopped up already": Interviewee 12), which raises a concern about the expected decarbonisation of the European steel industry by moving from blast furnaces to EAFs. EAFs are currently charged with 100% scrap, much of it poor quality producing only rebar. To produce high quality steel from scrap requires high quality scrap. "It's clear in the UK that there's nowhere near the availability of very clean scrap that there is in America" (Interviewee 3). He referred to America's high manufacturing base and the UK's "hollowed out" one. These interviewees feel the situation is better in Europe, though they cite EAFs pulling scrap in from a wide area to get enough supply. This issue is covered in more detail in the technical section 4.1.3 below.

More positively, one of the participants had started a business in reused construction steels and other building materials. *"We're operating commercially. Yeah, we got several 1000 tonne projects happening"* and much demand as they can cope with (Interviewee 12). A better known online pan-European network was cited by another interviewee: *"There is a really great thing called Globe Chain, which I'm just starting to get more au fait with, it's really good because you can re-sell material and they can sell them on. Almost like a secondary materials market and in places like the Netherlands, as a Swedish we have business arms in Sweden and the Nordics, in places like Sweden and The Netherlands they've got a big market for materials that we really don't see in the UK*". (Interviewee 17).

One company had tried to work with provenance data on cars to determine which body panels could be profitably removed before shredding. While databases of some sort do exist, they are not in a consistent format and 'for the sort of people who work in scrappies that's a big barrier'. They did not think it would work at scale (Interviewee 14).

4.1.2 Steel Firm Characteristics

From comments made across interviews on all the materials it is clear that most supply chains are non-collaborative, when mutually cooperative supply chains is one of the known characteristics for a successful CE (Ellen MacArthur Foundation, 2013). There's a *"huge void"* between scrap collectors and steelmakers (Interviewee 11) and *"I was trying to close the gap between the carmaker and the scrap industry also bring some thought into what ultimately happened at end of life"* (Interviewee 13). This is clearly a hindrance to progress on circularity. In the case of steel, the overwhelming excess of poor-quality end-of-life steel scrap and consequent drive towards its export appears to overshadow any need for partnerships along the supply chain.

The need for new business models were mentioned by two interviewees. The first, in respect of the new reuse business mentioned by Interviewee 12 (above), noted that each part needed separate electronically stored data describing it– a video, test results, dimensions etc – which is in complete contrast to the normal bulk scrap business, and that this was a significant diversion. The second noted that there was no business model for steel as a service, or for design for disassembly, both of which he felt would be good developments (Interviewee 1). By 'steel as a service' he meant a process of take back of end-of-life steel from demolition and replacement with an equal weight of new steel rebar.

Decarbonisation of the steel industry (as opposed to making steel circular) tends to focus on the replacement of blast furnaces with Electric Arc Furnaces (EAFs). The sunk costs in coke ovens, sinter plant, blast furnaces and the like make this very difficult for European companies to contemplate (Interview 3).

4.1.3 Technical - steel

Steel quality is lowered by the copper content, with the best steel plate being around 0.1%, construction steels up to 0.2% and anything over 0.3% being usable only for rebar. Most end-of-life scrap in Europe is 0.25% copper or higher. Despite the prevailing economics of selling unsorted scrap overseas, two of the interviewees (approached separately by different routes) were collaborating on a project to produce high-quality shredded scrap. The logic runs along the following lines: (i) cars are shredded at end-of-life as this is by far the cheapest way of reducing them to usable material (ii) car body panels are some of the best steel there is, at about 0.1% -0.15% copper, but (ii) once they are shredded with the rest of the car, including copper electrical wiring and motors, the resulting shred is conventionally 0.3% to 0.6% copper, which is some of the most contaminated scrap available, and (iv) logically the copper is extrinsic to the steel – it's on the outside of the shred, not incorporated into the metal, so (v) it must be possible to find ways of removing it. The aim is to produce a high quality shred at 0.15% copper which would command a premium price (Interviewees 3 and 12). This is being attempted by undisclosed means, which could involve digitalisation in the form of laser sorting, but is as likely to be in clever automated separation techniques involving more traditional shaking and movement over grilles and suchlike.

Removing copper from scrap steel is a fundamental long term issue for the industry: once the copper has been melted into the steel it is economically impossible to get out again (Lu et al., 2022). While there is still huge growth in world stocks of steel, high copper scrap can be utilised in rebar. However, by 2040 to 2050 the demand for rebar will lower and on present projections there will be a growing excess of unusable high-copper steel (Dworak et al., 2022). Similarly, while industry, governmental and academic talk is of moving to lower-emitting EAFs which smelt scrap, there is not enough high-quality scrap to dilute the copper in the poor-quality scrap in order to make high quality steel. There is no home for high-copper steel: the EAFs will have be filled with iron ore derivatives ('ore based metallics') to make steel usable for non-rebar applications. To find only limited discussion of this issue, forecast to become an overwhelming problem, is noteworthy of itself. It appears to be too far away and too insoluble to be of current interest.

Currently the two routes for using high copper steel scrap are dilution with fresh iron ore (blast furnaces) and producing rebar (EAFs). Both processes appear to manage the blend for melt characteristics, buying scrap on size, density and thickness, and not chemical composition (Interviewees 2 and 4). Spot checks can be made *("they will either use the X-ray gun to check the actual chemical composition"*- Interview 2), but purchases are priced by eye: the buyers are very experienced and know the likely chemical composition of different scrap types, but ultimately pricing is by eye. Similarly, a 30,000t vessel sent full to Turkey is priced by eye (Interviewee 12). There is a need to develop a digitised test, which is being worked on, but the number of samples statistically required to achieve reasonable accuracy is large and creating a test is not easy (Interviewee 12)

4.1.4 Regulatory - steel

The points made above about regulations being key to drive change were relevant to steel (Interviewees 12 & 14).

The steel industry purchase scrap based on a set of grades set down by the industry body (Interviewee 2), based on size and the level of processing of the scrap – mixed sizes give an even melt and are predictive of energy usage (Interviewee 1): ultimately these are based on melt characteristics not chemical content. The trade standards are important in creating and maintaining a market: it is notably absent from the relatively newer waste plastics industry (Interviewee 14).

Interviewees were generally unclear about the impacts of a Carbon Border Adjustment Mechanism in Europe or the UK. A general lack of detail about how it would work is evident. One interviewee felt that it would come in to avoid the government having to give energy subsidies to UK steelmakers, which he thought was inevitable if the steel industry is to survive in the UK (Interviewee 3). However, it is clear that it is likely to make reusing and recycling steel in the EU relatively more attractive than today.

4.1.5 Steel summary

- In the context of the research, there were no digital innovations found (commercialised or not) to greatly impact GHG emissions or to increase recycling. No use of provenance systems, either databases or on-product marking, were discovered, and no sorting of scrap material by automated technology appears to exist;
- Some reuse of construction materials is happening in a niche manner. It is unclear how widespread this could become, but it can be postulated that regulation such as a Carbon Border Adjustment Mechanism can only make reuse more economically attractive;
- The existence of a simple route for selling poor-quality scrap all but eliminates the need and motivation to sort it into different qualities;
- Without sorting poor quality scrap most of it cannot be included into a CE strategy for steel in Europe;
- There is a project to sort shred by chemical composition, but it does not appear to be wholly digitally based;
- Regulations are regarded as crucial in driving change;
- Current regulations on end-of-life vehicles were felt to be perversely incentivising downcycling.

4.2 Cement

"There is no recycling route for cement" (Allwood & Cullen, 2011). Since 2011, there have been some trials with ground up and reused concrete from buildings (McKinsey & Co, 2023), though McKinsey paint a bleak picture of the cement industry reducing emissions significantly in the short term. An alternative binder in concrete is *"not anticipated in the near to mid-term"* (IPCC, 2022). Any initiatives are small and disparate and are not yet being scaled, if this is even possible (McKinsey & Co, 2020). Implicitly this eliminates the current possibilities of provenance systems or digitalisation being part of recircularization. Consequently, no interviews were arranged to pursue the digitalisation focus of the project.

There are a number of methods for substituting part of the clinker element (accounting for 90% of concrete emissions (McKinsey & Co, 2023)) with pozzolans, named after the Italian town of Pozzouli after a compound discovered there by the Romans. Pozzolans react chemically with calcium hydroxide, an unwanted by-product created as the clinker sets the concrete, to enhance binding and some also help dried concrete resist the ingress of chlorinated compounds which cause reinforcing steel to corrode, thus lengthening the life of reinforced concrete. The best known pozzolans are some types of ground blast furnace slag and pulverised fly ash from coal fired power stations, though both these sources are forecast to decrease in future years.

A third type of pozzolan is in use in the US but does not appear to have any traction in Europe: ground up bottle glass (sioneer.com; pozzotive.com, KLAW Industries; Vitro Minerals), which now have an ASTM Standard (ASTM C 1866/C1866M-20). This is in principle available in large quantities and can substitute 20%-40% of the clinker, is claimed to use about 5% of the energy compared to the clinker it replaces and would appear to be a possible abatement route.

The initiatives that there are centre on decarbonisation of the current processes and materials, not reuse or recycling in a circular economy.

4.3 Plastics

4.3.1 Economic - plastics

Economics vary with the particular plastics. Virtually all collected PET and HDPE bottles are recycled, and in the UK new capacity is being added steadily to increase the proportion recycled domestically (letsrecyle.com, 2023). However, as with steel, there is a ready international market in some types of unsorted plastics which (for some) reduces or eliminates incentives to sort more in the UK. For example, Interviewee 14 explained that plastic pots, tubs and trays (a common waste category referred to as PTT) can be separated at present, but it is not done because if the valuable PP (polypropylene) is extracted and sold, there is no market for the remainder which has to be disposed of at a cost, whereas the mix can be sold unsorted for export. This is a view not shared by all: at least one industry player is building plant to sort PTT (Biffa, 2020).

Export orientation is reinforced by the Packaging Recovery Note regime which favours exporting unsorted plastics and is widely regarded as manipulated (Interviewees 7 and 9, (Burgess et al., 2021)).

There are no standards that recycled plastics are produced to (Interviewee 14) though his company and others produced to consistent grades for their customers (Interviewees 12 and 14).

The usage of polymers will always be much higher than that recycled, partly because of the range of polymers used for different purposes. This causes many valuable materials to be used in relatively small quantities, making them difficult and uneconomic to extract in processes which can never separate used polymers with 100% precision. In addition, there are issues of legacy additives now banned, and yield losses, which further complicate sorting and reduce recycled volumes (Interviewee 12).

The UK Plastics Pact (and more recently, the EU Plastics Pact) pledges to eliminate PVC and PS (polystyrene) from packaging by 2025, which the supermarket chains can largely control by working with their suppliers to eliminate stocking of products which do not comply. However, in the wider sphere this is more difficult for economic reasons, for example on PS *"there are still customers holding on to it because it's millions to try and replace it"* (Interviewee 15), reflecting sunk costs in plant and the costs of new plant to process alternative materials.

4.3.2 Firm Characteristics - plastics

The comments made under the Steel section (4.1.2) about a non-collaborative supply chain apply here also. *"What stakeholders want doesn't fit in to one business model" (*Interviewee 16).

There is a definite focus on extracting more and better recyclate. *"I think people are really focusing now on this residue fraction to close, to try to close the loop. Purity is becoming even more important in the waste, where before it was mainly driven by production [volume]"* (Interview 11). Certainly, investments are being made in new plant, such as Biffa's £27.5m PET bottle recycling plant in Seaham, UK (Biffa, 2020).

4.3.3 Technical - plastics

There are technical developments underway in several areas. Separation of films from rigid plastics has long been a problem – it was clearly stated by one interviewee that there is no commercial solution yet (Interview 15) although another stated that there was a machine available to do it (Interviewee 11). Black plastic – which absorbs the Near Infra-Red spectrum used to sort most post-consumer plastics - continues to be an issue, though Mid Infra-Red is being targeted to address it: *"So it's very difficult technology and a very difficult material"* (Interviewee 11, also Interviewee 14).

Unimplemented provenance technologies exist for marking packaging plastics during manufacture or filling to enable cleaner separation in household waste Materials Processing Facilities (MRFs), although the supply chain would have to cooperate to enable this to happen, as in principle the financial benefits accrue to the entity able to separate the waste into purer streams whilst the costs of marking are borne by other upstream entities (Burgess et al., 2021). One solution, using machine-readable codes printed on the packaging and backed by some leading brands, is in semi-commercial trials (Holy Grail, 2023). Any solution would involve digital reading and analysis of the printed codes.

Artificial Intelligence (AI) is making an impact by analyzing the composition of materials on a recycling facility's conveyor belt in real time. By using a few of these camera-based devices, analysis of input/outputs and mass balances can be obtained, improving process control and profitability. One interviewee, whose company had already installed AI monitoring, expected it to become more important over time, for composition data only or for both data and sorting (Interviewee 15). Though another disagreed: *"In terms of game changing, kind of separation, I don't really see it having an impact"* (Interviewee 14). Optical sorting has already used for bottle identification and sorting for a number of years, though AI analysis of data has not yet been connected to sorting in any major sense. AI's use with a robotic arm to sort has been trialed, but this is too slow for Materials Recycling Facility use which would require investment in sorting from a conveyor running at 2-3m/s.

The Deposit Return System for drinks containers mandated in Scotland from 2024, depending on how it is formulated, may lead to advanced optical recognition with complex back-end functionality to recognize bottles and return deposits correctly, which could be an almost immediate application for AI (see 1.4 above). Further ahead, the advent of Extended Producer Responsibility (EPR), when taxes are paid by producers when product is placed on the market and (perhaps) refunded if and when the product is recycled, may not be possible without advanced optical recognition and AI to match data read from returned products to data held on product placed on the market with a high degree of accuracy. Interviewee 10 saw a direct line from EPR to enforcement through big data and AI.

Additionally, there are considerable existing investments in glycolysis, pyrolysis and other plants for chemically recycling polymers into smaller molecules which can then be fully recycled (revalyu.com; quantafuel.com; impact-recycling.com), the first two of which are building commercial scale facilities and the latter is a pilot plant. Historically, one of the main issues with developing chemical recycling plant has been the need for purity of inputs: and pure inputs have a cost of creation and can be mechanically recycled (Interviewee 14), so the cost-benefit window for chemical recycling was small. Logically, this problem must have been overcome to a necessary extent.

4.3.4 Regulatory - plastics

The importance of regulation was probably stressed in the plastics sector most strongly: it is notable that they have already experienced the introduction of the UK-only Plastics Packaging Tax (PPT) which levied a tax on plastics not having at least 30% recycled content.

Perhaps bizarrely the tax was implemented without there being a test for the level of recycled content in the marketed plastic: one is now being developed, Recon^2 (reconsquared.com), a University of Manchester spinout. This attaches a short chemical chain to the recycled polymer which fluoresces when radiated: the strength of the fluorescence can be digitally read and the concentration determined. At European level two provenance systems, RecyClass and PolyRec, are being used to provide a chain of custody and assurance that the offered product does indeed contain the recycled material which it claims (recyclass.eu; polyrec.eu). No interviewee referred to this topic, potentially implying that proof of the 30% level of recycled content was not an issue for the plastics industry at this point. This appears to be a likely interpretation, as regulators can hardly clamp down on proof if there are only two fledgling systems in Europe able to do so. It was reported in January 2023 that RecyClass had certificated 50 manufacturers in 2022, so its use is currently low (Recycling Magazine, 2023). The EU plans to implement a minimum recycled content in plastics by 2030.

Currently EPR covers WEEE, batteries and vehicles (EU & UK). The principles of EPR (originally an EU policy and taken on by the UK government before Brexit) are to be extended to plastic packaging in 2024 in the UK. There is no implementation date for EPR on plastics in the EU. In principle, EPR requires producers to pay for the destruction of their products at the end of their lives, and in theory the payments can be reduced if the materials in the product are recyclable (or in some versions, actually recycled).

It is not perfectly clear how EPR for plastics will work. UK Government post-consultation proposals (Defra, 2022) are that from 2024 fees will be paid by producers to a scheme administrator and then distributed to local authorities to compensate them for costs of collection. After a year modulated fees will be payable dependent on recyclability of the product. All products will have to be marked with a 'Recycle' logo or a 'Do not recycle' logo, though no intention to mark product any more specifically, such as with a QR code indicating the polymer content. Further, there is no recognition of a difference between 'recyclability' and 'recycled' either in total or on a producer-by-producer basis: maybe this is too advanced at this stage. Subsequently, retailers' organisations have lobbied the government, claiming that the proposals as drafted will not meet their aim of increasing investment in recycling (Financial Times, 2023). Also, without linking recycled items back to manufacturers there is no pressure to design for recycling.

Auditing of figures provided by recyclers is possible by sampling: the *"government in the UK … has been quite vocal as to how do we potentially use digital techniques to start really auditing and digitizing sampling and then understanding that better"* (Interviewee 10). AI/optical recognition suppliers will be well favoured. At present, *"legislation is crucial to all decisions that are made"* (Interviewee 15) and industry participants are waiting to see the detail of the final EPR legislation before making investments. For example, it is unclear whether there will be funding for investments in equipment (Interviewees 14 and 16): the proposals contain no additional incentives for recyclers to invest in the necessary capacity expansion over and above anything that they feel is viable at present. The uncertainty helps no-one: the point was made that if manufacturers had an idea of their potential liabilities then it would kickstart designing for recyclability (Interviewee 10).

4.3.5 Plastics Summary

- Two EU wide chain-of-custody provenance systems, RecyClass and PolyRec, to provide proof of the level of recycled content claims, are being developed. Once in the new plastic, the identity of the recycled material is lost: it will not, of itself, act as a provenance system to improve the volume of recycling.
- On-pack marking systems exist which could, subject to trialling and industry-wide agreement, be used to identify product at a MRF to enable better sorting and higher value recyclate. There is limited sign of industry-wide agreement.
- Sorting systems have not yet been impacted by the advanced data analytics and machine learning that AI offers when attached to optical recognitions systems. However, a combination of Deposit Recycling Schemes and Extended Producer Responsibility may further the impact of combined AI/optical recognition systems to improve process control, design for recyclability and recycling rates, though the specifics will only become clearer when the detail of the regulation is known.
- As bulk post-consumer plastics are of little intrinsic value, enhanced and detailed regulation is key to further recycling: it is expected by the industry but it is powerless to move before the detail is known. Digital technology will be fundamental to improved plastic sorting.
- A digital test for 30% recycled content is under development.
- There are no digitalisation initiative being imminently commercialised that will radically increase volumes of recycled plastics in the short term.

4.4 Aluminium

4.4.1 Economic - aluminium

Whilst most interviewees were aware of the profit to be made by meeting the demand for better separated waste fractions, this was not a universal view, viz: *"we're seeing now people want more and more cleaner fractions, so they have to add less and less primary to the secondary melt"* (Interviewee 11), and "*We've also looked at sorting the aluminium into different grades, so cast versus rolled aluminium. And it's all possible, but the market is not there for it. The market just wants all zorba"* (Interviewee 14). (Zorba is mixed shredded non-ferrous metals). However, one company is marketing 'green billet' which is 75% recycled, and so has a lower carbon footprint (Interview 8): the company must think that there is demand for it.

As with steel, a ready international market in zorba exists. Historically, UK zorba has probably gone abroad (Interviewee 11). It's also the case in Europe: for example, most zorba in Spain is sold to China (Interviewee 9). There is also a liquid market for post-fabrication (new) scrap: one interviewee explained how his company tried to match trades, buying and selling to avoid price fluctuations (Interviewee 8). So the market is thriving, which aids development and competition (it is more difficult for investors to make financial commitments which are predicated on pricing or supply from a few actors for reasons of monopoly and precarity).

4.4.2 Firm Characteristics - aluminium

Looking at Europe as an entirety, there is a capacity problem: Interviewee 9 suggested that the EU will state that it wants to keep scrap aluminium in Europe, but he did not believe that the capacity existed to make this possible.

The UK is limited by the lack of primary smelting capacity, limited to about 0.05Mtpa compared to a c.1.25Mtpa recycling market (Defra, 2021). Without the primary production *"the UK really… has no significant extrusion plants…. And it has no significant rolling mills"* (Interviewee 6). Sales of high-quality recovered material are *"98%"* abroad because smelters in the UK are not set up to take a product which can be mixed directly with virgin in primary smelting (Interviewee 9).

Investment in multi-machine sorting lines in Europe is very limited: one highly experienced professional named the only two companies he believed had them (Interviewee 6). *"One of the biggest challenges I see is getting local recyclers to invest in proper technology"* (Interviewee 11) and another pan-European recycler claimed that UK aluminium remelters do not understand how to make automated sorting work "*They buy one machine*" and put material through it multiple times: "*you can't sort in volume with one machine*" (Interviewee 9). This is not true throughout Europe: in regions where aluminium smelting has been preserved - Italy, Spain, Germany, parts of central Europe – it has been worthwhile for the local industry to invest in sorting machinery (Interviewee 11). The previously expressed UK view was also contradicted by one aluminium technology business, which knew of smaller companies investing in advanced laser machinery (Interviewee 13). So the picture is mixed, but it is clear that there is relatively little automated sorting currently, even if some smaller companies have the financial ability to purchase the equipment.

One forward-thinking company had already created a provenance system for their recycled material, showing which sources the original waste came from, because they thought customers would be requesting the data before long. But this appeared to be a one-off (Interview 9), although the inference that the purchase and sales invoicing systems can readily provide data to establish a provenance system is evidenced.

4.4.3 Technical - aluminium

Research was conducted knowing that high speed Laser Induced Breakdown Spectroscopy (LIBS) was a technology about to be marketed by two of the largest sorting machinery manufacturers, Tomra and Steinert. (Tomra were first to the market in June 2023 following the end of the research). A laser pulse fired at the material vaporises a tiny amount and this plasma is digitally analysed to identify it. Potentially this could transform aluminium recycling, allowing the wrought fraction to be separated from the cast fraction, and for the wrought fraction to be further separated into the individual series. This would not only create value to the sorters, but potentially would reduce, or even largely eliminate, downcycling of wrought aluminium. One interviewee company is already planning to build a European plant incorporating LIBS: another is building a post-consumer aluminium sorting line with a spot earmarked for a LIBS machine when it becomes available. Here is real evidenced belief that LIBS is the answer to aluminium sorting, and that the problem will be solved "*within five years*" (Interviewee 6), but not all are convinced that separation beyond broad wrought and cast grades is possible (Interviewee 13) or even that LIBS is any use at all *"So we also looked at LIBS. It's very early days for LIBS*" … "*For scrap, for true scrap, I think it's a long, long, long way off".* He did not think companies would be rushing to buy it (Interview 14).

Interviewee 6 also felt that LIBS would be combined with optical sorting and AI to replicate and improve on the visual sorting carried out in low wage economies who currently buy zorba ("It's been known for a long time that, you know, if you look at a pile of shred. You can look at it and you can pick out the bits that are casted. So the thing is to teach an intelligent system, ….to do what the human eye can do").

4.4.4 Regulatory - aluminium

EPR is expected to "*drive up the need for more recycled content, for sure*" (Interview 11), but he cautioned that "*A lot of companies here also I think are using post production scrap and promoting it as recycled content….. legislation has to also recognize this".* This is the distinction between new scrap, straight from factory offcuts (all currently recycled), and the much larger volume of post-consumer scrap which is dirtier and more difficult to clean, process and sort (most currently downcycled).

The comments on regulations from the aluminium interviewees differed qualitatively from most others, probably because aluminium is a profitable business using a valuable metal and there is an incentive to recycle it without underpinning regulation to force the issue. One of the few positive comments about regulations was made: that their business had been given a tailwind by the EU stance on supporting the CE (Interviewee 9).

Aluminium used for consumer packaging (most obviously drinks cans) qualifies for Packaging Recovery Note incentives and their comments about its failings are aligned with the plastic PRN problems noted in 4.3.1 above.

Permitting for new waste processing facilities were particularly mentioned by one of the aluminium processors, who regarded regulations as the most difficult challenge preventing expansion (Interview 9). This was echoed by another interviewee in a different field: "*reduce the burden of too much legislation in the wrong place for recyclers. Start helping them. Particularly in location …. to relocate to more state-of-the-art premises and locations*". He noted that changing environmental legislation is making things more difficult and pleaded for future regulations to be written with an understanding of the sector (Interview 11).

5. Impact: Analysis of the potential impact of LIBS on the forecast surplus of cast aluminium

Across all four bulk materials, this is the one digital initiative discussed with potential to make an almost immediate impact. It is analysed in four stages. Firstly, published forecasts for the global surplus are used to derive a forecast surplus in Europe. Secondly, a calculation is performed from literature sources to estimate how much wrought aluminium is currently downcycled into cast grades, and thirdly this wrought figure is adjusted downwards by losses in reprocessing before comparing the result to the forecast surplus. Finally, preconditions for a rollout of LIBS across Europe are summarised.

There are a number of modelling papers which forecast a global surplus of cast aluminium. Only one paper was discovered which estimates the global surplus using detailed series-by-series[1] level model of the different wrought grades, which suggests a global surplus of 5.4Mtpa by 2030 and 8.7Mt by 2040 (Van den Eynde et al., 2022). Earlier models suggest global surpluses 4.2Mtpa to 6.1Mtpa by 2030 (Hatayama et al., 2012; Modaresi et al., 2014; Modaresi & Müller, 2012). Based on total consumption, the European share of this would be about 14% (13.5Mtpa/95Mtpa (Material Economics, 2020) / (International Aluminium Institute, 2021), or 0.8Mtpa in 2030. A second paper provides a series-by-series analysis suggesting a surplus in Austria by 2030 without suggesting a specific figure (Buchner et al., 2017). Both Buchner and van den Eynde suggest proportions of wrought and cast in scrap arisings by use category, key numbers used in this analysis.

This potential surplus of cast aluminium could theoretically be alleviated to an extent by avoiding the downcycling of post-consumer wrought scrap into cast. Calculation of how much wrought aluminium scrap is currently downcycled, and how much of this could potentially be prevented by an implementation of LIBS, is given in Appendix 2, together with details of method and assumptions.

Two calculations based on the two different series modelling papers (Buchner and van den Eynde) suggest that between 1.5Mtpa and 1.9Mtpa of wrought is currently downcycled into cast, both significantly greater than the forecast surplus (0.8Mtpa). The difference in the two authors figures is due to differing assumptions about the wrought content of scrap arisings in the different use categories (buildings, automotive, etc). Neither gives any clear indication on the source of their figures, though the International Aluminium Association is heavily mentioned in both papers.

It is necessary to adjust any figure for wrought scrap downcycled by losses in reprocessing in order to compare it to the figure for the forecast surplus. Applying the following factors to adjust the potential recovery of 1.5Mt (using the lower figure of downcycled wrought calculated): 10% shredder losses (so 90% recovery) (Løvik et al., 2014), 90% sorting accuracy (ibid) and 8% remelting losses (Material Economics, 2020), a recovery factor of 74.5% is derived. This appears highly optimistic, especially for the early years of LIBS implementation. Accepting that 10% shredder losses is reasonable, a lower 80% sorting accuracy (ie 20% of wrought remains in the cast) and 15% remelting losses - [(Løvik et al., 2014) suggests that his modelled 90% recoveries may be beyond 'physical and thermodynamic limits'] would give a recovery factor of 61%. Applying 61% to 1.5Mtpa gives a recovery of about 0.9Mtpa, close to the derived European surplus of 0.8Mtpa. Clearly, using the higher figure for wrought arisings of 1.9Mtpa would give comfort that most wrought could be recycled.

It is therefore possible to conclude that the successful introduction of LIBS offers a realistic possibility of averting much or all of the forecast surplus of cast aluminium in 2030. However, there are a number of prerequisites for rolling out LIBS across Europe. Starting with the technical points, the equipment has to become widely available and to do what its proponents believe it will – to identify and sort wrought and cast aluminium series on a metre-wide conveyor belt running at 2-3 metres per

[1] There are hundreds of types of aluminium, split into the two major grades of aluminium, wrought and cast. Wrought is then broken into 7 series of sub-grades and cast into four series of sub-grades. Limited transferability between series during recycling means that a series level model is appropriate for forecasting surpluses and deficits.

second. At this point this remains an act of faith: LIBS has been in development for many years and proving it has been difficult (Interviewee 12) (Løvik et al., 2014). Secondly, it needs to sort to a high level of accuracy, say 90% (Løvik et al., 2014). Thirdly, there is skill required to set up and tune sorting equipment (Interviewee 12): if there is to be widespread rollout, this skill premium needs to be small, particularly since the input material will vary and the machine settings may need adjusting as the material changes. Fourthly, while there is much talk in the industry at present about the need to widen content specifications for materials input into industrial fabrication if recycled materials are to be incorporated (Interviewees 6, 9, 11, 12, 14), this needs to become a reality. The demand for low carbon content (recycled) material across industry (Interviewees (3,7,9,11,14), suggests that this may well occur. Fifthly, to an extent the volumes of scrap arising in the different series of wrought needs to approximately match the demand in those series, although some conversion of scrap between series is possible: this is beyond the scope of this report and analysis may be beyond the data currently available (Løvik et al., 2014). However, losses in reprocessing are caused by complexity: one must be careful in making simplifying assumptions.

Economically, a continuous and sufficient price premium for recycled wrought has to exist over unsorted grades destined for cast. In a world market where demand for engine blocks will probably not fall as fast as in Europe, this is not guaranteed. However, as a surplus of cast in the world comes closer, a real and permanent price premium for sorted recycled wrought is likely. The existence of a price premium for recycled high-quality aluminium (low carbon aluminium) (Interviewee 9) suggests that this is happening, and should a carbon border adjustment mechanism be introduced this can only help. Lastly, unless larger companies take over the market, results suggest that firm characteristics may slow adoption, as the perceived reluctance of smaller businesses to invest in advanced sorting machinery needs to be overcome, partly by the profits from doing so becoming clear. Regulation, through bans on the export of unsorted aluminium scrap would help, as Interviewee 9 thought the EU wished to do, while being aware that the capacity to sort the resulting volumes did not yet exist in the EU. It is this lack of sorting capacity that needs to be overcome in a LIBS implementation.

5.1 Aluminium Summary

- Of all the four bulk materials, aluminium is the only one where there is a realistic and near-term chance of digitalised technology transforming the reprocessing of post-consumer materials and potentially dramatically reducing downcycling.
- This is through the introduction of Laser Induced Breakdown Spectroscopy-based sorting equipment.
- There are plenty of doubters alongside some who will be early adopters.
- Longer-term, a combination of LIBS, optical sorting and AI – all digitally based – could make shipping unsorted non-ferrous metals to low wage countries for hand-sorting obsolete.
- The UK aluminium industry is missing primary smelter and large extruders, so it is highly likely that scrap will continue to be sold into the EU and further abroad, even if well sorted.

6. Discussion and Conclusions

Table 1 summarises the empirical research, covering potential impacts of provenance and digitalisation developments.

The table has a column for 'Other CE initiatives' which do not involve significant digitalisation or use of provenance systems. Additionally, there are a host of other decarbonisation initiatives in each material, such as use of previously reduced iron ore in blast furnaces and better energy efficiency in the cement making process, which are not part of the CE or of this research. Use of ground glass bottles as a pozzolan in cement manufacture is strictly a decarbonisation measure: it is included it only because it does not appear to be much known in Europe and it needs to be acknowledged.

Chain-of-custody provenance databases, as currently constituted, offer marketing information but will not offer any short-term improvement in emissions. Further ahead, continued investment into Building Information Modelling (BIM) (see 1.3 above) systems offers hope of increased circularity of not only key parts of the structure but also internal fittings such as office partitions. In that all buildings are designed in computer, BIM appears highly scalable across all building sectors relatively quickly. However, the benefits only impact at the time of second life, in 15-40 years time for commercial buildings and longer for domestic. Plastics in buildings (20% of new plastics usage (Plastics Europe, 2021)) are similarly impacted by BIM over similar timespans.

RecyClass and PolyRec, the pan-European chain-of-custody systems for certifying the proportion of recycled plastics with a final resin, may, by ensuring that false claims over recycled content levels are not made, make some impact in years to come, but is unlikely to contribute short-term.

For packaging plastics (40% of the total), use of marking systems (essentially on-pack provenance systems) – not necessarily of one single type across all plastics – is possible within a very few years should the supply chain be able to agree on one or more solutions. The economic imperatives of Deposit Return Systems (DRS) and EPR may provide the stimulus to bring this about, once the detail of the legislation is set.

For aluminium, digital technologies, in the form of Laser Induced Breakdown Spectroscopy (LIBS), could have huge impact on the ability to separate wrought and cast grades and so prevent downcycling of the wrought grades almost completely, depending on speed of adoption.

For plastics in the longer term, the integration of AI and optical recognition systems with current Near Infra Red and X-Ray Fluorescence detectors could bring significant increases in the identification and sorting of products, again possibly stimulated by the economic forces introduced with EPR. Such sorting systems are currently embryonic at best. Plastics recirculation is hindered by the range of materials used, notably for automotive plastics (9% of use), but recovery through shredding and separation will continue.

For steel, there are no short-term solutions enabled by either provenance systems or digitalisation, only longer-term impacts from BIM (facilitation of reuse, as noted above) together with an unproven expectation of some gains in material efficiency through better design.

Recirculation of cement in any meaningful way seems far off: there are some experiments in different countries, including in Europe, testing cement recycling but no large-scale plans for commercial exploitation.

Table 1: A summary of the research, showing potential for impacts of Provenance Systems and Digitalisation

	Provenance Systems	**Digitalisation**	**Other known CE initiatives for materials recirculation**
Steel	Short term None Long term BIM leads to re-use + refurb (Provenance databases)	Short term None Long term BIM leads to reuse + refurb (Provenance databases) Material efficiency thru better design (Data analysis)	Recovery & reuse of construction beams. Cleaning extrinsic residuals from shredded output to avoid downcycling.
	Short term	Short term	Partial cement substitution by pozzolans incl. ground blast

Cement	None Long term None	None Long term None	furnace slag, fly ash, ground bottle glass2
Plastics	Short term Possible for packaging: economic and collaborative barriers. Economic barriers may fall with EPR. (Provenance on-product marking) RecyClass certification scheme for % content (Provenance databases) Long term Possible for construction plastics with legislation. Will be helped by BIM. (Provenance databases)	Short term Digital recognition systems possible for packaging: economic and collaborative barriers. Economic barriers may fall with EPR3. (Provenance on-product marking) Long term BIM leads to reuse + recycling (Provenance databases) AI aligned with optical recognition to improve waste sorting and reduce non-recycling taxes under EPR (Provenance on-product marking + data analysis)	DRS, EPR, PPT extension. Potential ban on UK/EU plastic waste exports. Elimination of PVC & PS in packaging. Reduction of laminates in packaging. Investment in mechanical & chemical recycling plant. Commercial glycolysis of PET. Pyrolysis of thermosetting polymers.
Aluminium	Short term None Long term None	Short term Laser Induced Breakdown Spectroscopy (LIBS) to sort wrought waste from cast waste based on chemical signature. Potential to avoid large-scale downcycling of wrought into cast grades. Unproven at scale. *(Data analysis)* Long term AI aligned with optical recognition and LIBS to improve separation further. *(Data analysis)*	Companies developing separation of wrought alloys into different grades by other means than LIBS. Industry discussion about whether and how tight alloy specifications can be loosened to accommodate recycled material.

[2] Blast furnace slag and fly ash are diminishing in supply in Europe. No evidence found of recycled glass pozzolan substitution in Europe, though prevalent in USA. Increased use of pozzolans is strictly speaking a decarbonisation activity, not part of a move to the CE.
[3] Depends how the legislation is worded: if specific proof of item recycling is needed to reduce taxes then provenance marking/digital reading will be highly incentivised.

References

Allwood, J. M., & Cullen, J. M. (2011). *Sustainable materials: With both eyes open*. UIT Cambridge https://www.uselessgroup.org/publications/book/chapters

Alucycle. (2022). *Global Aluminium Cycle 2021*. Retrieved 15/3/23 from https://alucycle.international-aluminium.org/public-access/public-global-cycle/

Biffa. (2020, 29/1/20). *Biffa Opens £27.5m Plastic Recycling Plant in Seaham, County Durham and announces a new £7m facility*. Retrieved 2/2/23 from https://www.biffa.co.uk/media-centre/news/2020/biffa-opens-plastic-recycling-plant-in-seaham

Bocken, N. M. P., Ritala, P., & Huotari, P. (2017). The Circular Economy: Exploring the Introduction of the Concept Among S&P 500 Firms. *Journal of Industrial Ecology*, *21*(3), 487-490. https://EconPapers.repec.org/RePEc:bla:inecol:v:21:y:2017:i:3:p:487-490

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Bryman, A. (2016). *Social research methods*. Oxford University Press.

Buchner, H., Laner, D., Rechberger, H., & Fellner, J. (2017). Potential recycling constraints due to future supply and demand of wrought and cast Al scrap—A closed system perspective on Austria. *Resources, Conservation and Recycling*, *122*, 135-142.

Burgess, M., Holmes, H., Sharmina, M., & Shaver, M. P. (2021). The future of UK plastics recycling: One Bin to Rule Them All. *Resources, Conservation and Recycling*, *164*, 105191. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105191

CEMBUREAU. (2016). *Cement, Concrete & the Circular Economy*.

David, E., & Kopac, J. (2015). Use of separation and impurity removal methods to improve aluminium waste recycling process. *Materials Today: Proceedings*, *2*(10), 5071-5079.

Defra. (2021). *Domestic Scrap Steel Recycling – Economic, Environmental and Social Opportunities*. https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

Defra. (2022). *Extended Producer Responsibility for Packaging: Summary of consultation responses and Government response*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063589/epr-consultation-government-response.pdf

Díaz-Romero, D. J., Van den Eynde, S., Sterkens, W., Eckert, A., Zaplana, I., Goedemé, T., & Peeters, J. (2022). Real-time classification of aluminum metal scrap with laser-induced breakdown spectroscopy using deep and other machine learning approaches. *Spectrochimica Acta Part B: Atomic Spectroscopy*, *196*, 106519. https://doi.org/https://doi.org/10.1016/j.sab.2022.106519

Dworak, S., & Fellner, J. (2021). Steel scrap generation in the EU-28 since 1946 – Sources and composition. *Resources, Conservation and Recycling*, *173*, 105692. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105692

Dworak, S., Rechberger, H., & Fellner, J. (2022). How will tramp elements affect future steel recycling in Europe? – A dynamic material flow model for steel in the EU-28 for the period 1910 to 2050. *Resources, Conservation and Recycling*, *179*, 106072. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.106072

EEA. (2017). Retrieved 6/3/23 from https://transitionhighgate.org/the-paris-agreement/your-countrys-paris-pledges/the-eu/ quoting https://prtr.eea.europa.eu/#/pollutantreleases no longer available

Ellen MacArthur Foundation. (2013). *Towards the Circular Economy, Volume 2*.

Eurofer. (2022). *European steel in figures 2021 (EU27)*.

Financial Times. (2023). UK retailers to raise concerns over new recycling scheme with ministers. *Daniel Thomas and Jim Pickard*. https://www.ft.com/content/2400db6b-1e38-4a45-a42e-5d05b4e8250b

Flick, U. (2014). *An Introduction to Qualitative Research*. SAGE Publications Limited.

Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2012). Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. *Resources, Conservation and Recycling*, *66*, 8-14. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.06.006

Holy Grail. (2023, 3/22). *Holy Grail Intelligent Sorting*. Retrieved 11/1/23 from https://www.digitalwatermarks.eu/

International Aluminium Institute. (2021). *IAI Material Flow Update - 2021 update (2019 figures)*.

IPCC. (2022). Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In J. S. P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press. https://doi.org/doi: 10.1017/9781009157926.001

letsrecyle.com. (2023, 28 Feb). *Morrisons-owned soft plastics plant opens in Fife*. Retrieved 3/3/23 from https://www.letsrecycle.com/news/morrisons-owned-soft-plastics-plant-opens-in-fife/

Løvik, A. N., Modaresi, R., & Müller, D. B. (2014). Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. *Environmental Science & Technology*, *48*(8), 4257-4265. https://doi.org/10.1021/es405604g

Lu, X., Ohno, H., Takeda, O., Miki, T., Sasaki, Y., Zhu, H., & Nagasaka, T. (2022). Toward an efficient recycling system: Evaluating recyclability of end-of-life stainless steels by considering elements distribution during a remelting process. *Journal of Industrial Ecology*, *26*(5), 1701-1713.

Malinauskaite, J., Jouhara, H., Czajczyńska, D., Stanchev, P., Katsou, E., Rostkowski, P., Thorne, R. J., Colón, J., Ponsá, S., Al-Mansour, F., Anguilano, L., Krzyżyńska, R., López, I. C., A.Vlasopoulos, & Spencer, N. (2017). Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. *Energy*, *141*, 2013-2044. https://doi.org/https://doi.org/10.1016/j.energy.2017.11.128

Material Economics. (2018). *The Circular Economy: A powerful force for climate mitigation*.

Material Economics. (2020). *Preserving value in EU industrial materials - A value perspective on the use of steel, plastics, and aluminium.*

McKinsey & Co. (2018). *How plastics-waste recycling could transform the chemical industry*.

McKinsey & Co. (2020). *Laying the foundations for zero carbon cement*.

McKinsey & Co. (2023, 3/2/23). *Decarbonizing cement and concrete value chains: Takeaways from Davos*. Retrieved 14/2/23 from https://www.worldcement.com/special-reports/06022023/decarbonizing-cement-and-concrete-value-chains-takeaways-from-davos-part-1/

Meuser, M., & Nagel, U. (2009). The Expert Interview and Changes in Knowledge Production. In A. Bogner, Littig, B. & Menz, W. (Ed.), *Interviewing Experts*. Palgrave Macmillan.

Modaresi, R., Løvik, A. N., & Müller, D. B. (2014). Component- and Alloy-Specific Modeling for Evaluating Aluminum Recycling Strategies for Vehicles. *JOM*, *66*(11), 2262-2271. https://doi.org/10.1007/s11837-014-0900-8

Modaresi, R., & Müller, D. B. (2012). The Role of Automobiles for the Future of Aluminum Recycling. *Environmental Science & Technology*, *46*(16), 8587-8594. https://doi.org/10.1021/es300648w

Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology*, *18*(1), 143. https://doi.org/10.1186/s12874-018-0611-x

Ness, D., Swift, J., Ranasinghe, D. C., Xing, K., & Soebarto, V. (2015). Smart steel: new paradigms for the reuse of steel enabled by digital tracking and modelling. *Journal of Cleaner Production*, *98*, 292-303. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.08.055

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Fukushima, Y., & Nagasaka, T. (2017). Optimal Recycling of Steel Scrap and Alloying Elements: Input-Output based Linear Programming Method with Its Application to End-of-Life Vehicles in Japan. *Environmental Science & Technology*, *51*(22), 13086-13094. https://doi.org/10.1021/acs.est.7b04477

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., & Nagasaka, T. (2015). Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. *Resources, Conservation and Recycling*, *100*, 11-20. https://doi.org/https://doi.org/10.1016/j.resconrec.2015.04.001

Plastics Europe. (2021). *Plastics - the Facts 2021*. https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

Raabe, D., Ponge, D., Uggowitzer, P. J., Roscher, M., Paolantonio, M., Liu, C., Antrekowitsch, H., Kozeschnik, E., Seidmann, D., Gault, B., De Geuser, F., Deschamps, A., Hutchinson, C., Liu, C., Li, Z., Prangnell, P., Robson, J., Shanthraj, P., Vakili, S., . . . Pogatscher, S. (2022). Making sustainable aluminum by recycling scrap: The science of “dirty” alloys. *Progress in Materials Science*, *128*, 100947. https://doi.org/https://doi.org/10.1016/j.pmatsci.2022.100947

Recycling Magazine. (2023, 24/1/23). *RecyClass revises recycling guidelines & testing protocols*. Retrieved 21/3/23 from https://www.recycling-magazine.com/2023/01/24/recyclass-revises-recycling-guidelines-testing-protocols/

Stotz, P. M., Niero, M., Bey, N., & Paraskevas, D. (2017). Environmental screening of novel technologies to increase material circularity: A case study on aluminium cans. *Resources, Conservation and Recycling*, *127*, 96-106. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.07.013

Suschem. (2020). *European Technology Platform for Sustainable Chemistry: Sustainable Plastics Strategy*.

Trinczek, R. (1995). Experteninterviews mit Managern: Methodische und methodologische Hintergrunde. In C. Brinkmann, Deeke, A. & Volkel, B. (Ed.), *Experteninterviews in der Arbeitsmarktforshung, Diskussionsbeitrage zu methodischen Fragen und praktishen Erfahrungen.* IAB Nurnberg.

Van den Eynde, S., Bracquené, E., Diaz-Romero, D., Zaplana, I., Engelen, B., Duflou, J. R., & Peeters, J. R. (2022). Forecasting global aluminium flows to demonstrate the need for improved sorting and recycling methods. *Waste Management*, *137*, 231-240. https://doi.org/https://doi.org/10.1016/j.wasman.2021.11.019

Zhao, Y., & Taib, N. (2022). Cloud-based Building Information Modelling (Cloud-BIM): Systematic literature review and Bibliometric-qualitative Analysis. *Automation in Construction*, *142*, 104468. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104468

Appendix 1 – Data Collection and Analysis

This was done in two stages: a literature search followed by expert interviews.

A1.1 Literature search – overall method

- This did not seek to extract all available evidence to inform a further technical piece of work: rather, it sought to understand the key recycling concepts so that their practical adoption can be investigated. This was a Rapid Evidence Review (also called a Scoping Review or Targeted Review) rather than a Systematic Literature Review. It sought key recycling themes for each of the four materials (provenance, data collection and analysis) to assist the direction of unstructured interviews with academics and industrial partners: such partners are likely to be more aware of up-to-date industrial practice than published literature. (Munn et al., 2018)
- Additionally, the desire to select 'best practice' and 'state-of-the-art' literature requires selection of papers and articles, which is permissible in Scoping Reviews but not under a Systematic Review (Munn et al., 2018). 'State-of-the-art' is defined here as technologies under investigation in multiple universities or in commercial trials/implementation.

A1.1.2 Literature search - scope

- Grey literature – trade journals, trade press, industry bodies websites in addition to academic literature;
- Used all of Google Scholar, Google and Web of Science;
- Started with terms "Aluminium Recycling", "Steel Recycling", "Plastic Recycling" and "Cement Recycling" and snowball from references obtained from initial papers. Search using the names of specific processes as these become known;
- Focused on EU, but included worldwide;
- Focused on recent: within the last five years;
- Considered reuse as well as recycling, though *prima facie* this appears to be a minor area.

The literature search is necessary not only to establish the industrial background but also allow the interviewer to learn about the subject material in some detail: it is well established that interviewees respond more positively and effectively to well briefed interviewers (Trinczek, 1995).

A1.2 Expert interviews

The aim of these was to test and build on understandings gained from the literature and to build on these to find answers to the Research Questions. Experts are likely to be more aware of the most recent developments than the academic literature and more understanding of implementation realities of new technologies than grey literature. Results from the Rapid Evidence Review were used to construct a set of topics to guide the interviews. The interviews themselves were unstructured, using the guide to let the conversation flow whilst keeping it relevant (Meuser & Nagel, 2009).

The variation or consistency between experts is more important than the number of experts interviewed: a few cases, if triangulated with other sources, can be more informative than a larger number less deeply studied (Flick, 2014). Through the literature search potentially useful academics and industry figures were identified and then approached by email or via LinkedIn if possible. Those approached were a mixture of academics and industrial figures appearing – from their writings and/or publicity material - to have the appropriate insights to answer the issues arising from the literature. Pan-European businesses were deliberately selected if possible (8 of the 17 interviews). In addition, two interviewees were contacted having been participants in a previous project three years ago, one of whom was interviewed and the second suggested another member of their team would be more appropriate. One relevant transcript was included from another study using a different interviewer. There are known difficulties in recruiting the 'right' interviewees with the correct level of detailed knowledge (of both process and strategy, in this case) and they may be circumscribed by both time and confidentiality (Flick, 2014). Many will simply not respond to emailed requests: these will be followed up a second time, but if there is still no response then an alternative will be sought.. Interviewing was continued until no new themes emerge across the four materials, 2 categories and 3 research areas (provenance, marking and sorting), with at least three people spoken to in each section. The literature review of the cement industry turned up nothing whatsoever in the way of digitally-influenced innovation for materials recirculation which was remotely close to commercial implementation: the planned recruitment was cancelled.

Record the interviews, if possible.

A1.3 Themes for interviews with metal partners

This is the original set of themes and sub-questions for metal interviewees derived from the literature review. It was amended in the light of each interview and paying attention to the company's activities. Points in the right-hand column were largely included as aide-memoires if the theme was relevant to the interview.

It is angled towards recycling and digital systems rather than the CE more generally.

Theme	**Potential list of points to cover**
Background on steel and aluminium recycling acknowledged: it would be expected that they are fully up with this.	
Overarching open question: What do you think are the major current challenges associated with recycling steel/aluminium? How could your technology and expertise be brought to bear on the problem?	When sidelined into detail, possibly in the sections below, this may need to be returned to several times. Need to cover thoughts on sorting and its complexities with different alloys.
Amidst all the talk of the Circular Economy by governments, is recycling talked about in your business? If so, in what sense?	
Is recycling a significant theme in the 5 year plans of your business?	Try to determine if it's a major theme or merely a nice-to-have talking point. New technology?
Are there databases (for example, from car manufacturers) which detail the precise material content of materials? Are these available?	Try to understand what potential there is for a provenance system based on product look-ups of existing databases.
If the business is making products with recycled content, ask about their perceptions of its quality and applications. Ask about their customers and their potential customers perceptions of its quality and applications, and any limitations they perceive because of the expectations of	Establishing if they perceive there are business reasons for not increasing sales of products with recycled content.

their customers. Are their customers much concerned with EoL?	
Are there issues are with standardisation of materials in packaging, motor, building or other use classes?	Trying to understand whether manufacturers use different alloys indiscriminately, which adds to the recycling problem.
Do your company have specific suppliers of recycled material, or is it bought freely as an easily tradeable standardised commodity? Are there standards for recycled material or skips(?) of recyclate? How big an issue is changing raw material supply prices for recyclers? (eg used cars) How big an issue is changing output prices for recyclers? (eg PET prices)	Discover whether markets in the raw recyclate or recycled materials exist. Establish if they buy based on weight or on chemical content. Draw out how many value points there are and how many loss-making operations involved in creating the value (eg removal of contaminants)
Do waste regulations cause any issues?	
If there are one or two actions you would like to see the government take to facilitate [plastics, steel, aluminium] re-use and recycling, what would they be?	
Specific Issues: Aide Memoire if subjects are not covered by open questions above.	
Issues with recyclate quality	Sort quality Tramp elements Organic contamination Bonded materials Additives Toxic substances
How recyclate is sorted/identified. Use of better technology to sort	Barriers to this (eg cost, lack of time, lack of knowledge)
Issues with Recyclate markets	Who buys? UK, EU, China, other Far East? How many intermediaries? What is it used for? Blending, prime feedstock? How is value created currently? How should value be created? Ideas to improve?
If appropriate: What is removed from cars before shredding? Does this change as market prices for metals change? How much [plastics, steel, aluminium] is not recovered from the shreddings?	Issues and opportunities with car dismantling/shredding

What is the likely impact of Extended Producer Responsibility? (EPR)	Is it being discussed already? Is the impact of the proposals being seen already? How should the tax be assessed? Who should get some money or all the money? Experience of design for reuse? More investment in sorting technology? Are there likely risks because more money will be in the 'waste ecosystem'?
Local Authorities	Facilitator or inhibitor? Waste handling or transportation regulations an issue? Would regulatory changes help?

A1.3 Data Analysis

Each interview was recorded (if possible) and transcribed using the functionality of MS Teams. The interviews were replayed and the automatic transcripts corrected as necessary. The data was reviewed as collected to enhance the topic guide for later interviews.

17 people were interviewed in total, including a transcript of an interview performed by a colleague working on another study on building refurbishment. Given the relatively small numbers of people being interviewed in each area, mechanical analysis approaches (eg repeated word counts) are unlikely to produce valuable results. This similarly prevents the usefulness of grounded theory, and thematic analysis was used for analysis, although this is regarded as underdeveloped by some (Bryman, 2016) and in need of methodological support by others (Braun & Clarke, 2006). Under this approach, in past years it was usual to limit transcription to relevant passages (Meuser & Nagel, 2009). Modern transcription software reduces the overhead of transcription and the whole interviews were transcribed. The transcripts were the basis of analysis, in which relevant passages were summarised and compressed into themes, while keeping close to the terminology of the interviewee if possible. The first interview was analysed in detail to establish the likely themes (Flick, 2014). Themes or patterns relevant to the investigation were coded onto the summaries as discovered. They were compared for similarities to assess the adoption potential within industry, aiming to do this holistically with scientific, legal and financial viewpoints.

It was necessary to regularly check back to the transcripts to ensure that the meaning of the interviewee was maintained through the summarising and cross-tabulating procedure (Meuser & Nagel, 2009).

If themes do not involve digital systems, then the potential impacts were noted but the research of that theme was ended. Answers were qualified with likely problems, such as the possible need for new business models or the limitations on market penetration. If the aluminium industry, where digital technology is part of the solution, then potential impacts were quantified by assessing the EU market sizes relevant to the development. Several prerequisites were noted for the spread of the technology across the corporate sector.

Appendix 2 – Potential impact of LIBS on downcycling of post-consumer wrought aluminium scrap into cast grades.

As discussed in 4.4.5 above, the estimated size of the European surplus by 2030 is around 0.8Mtpa.

Method

The calculation is in two halves: firstly, to compute the probable weight of wrought aluminium currently downcycled, and secondly, to work out a realistic percentage of this that could be recovered based on the losses incurred at different stages of the recycling processes.

To produce a sensible estimate of the impact of sorting wrought and cast grades before they are recycled together and the wrought thus downcycled, it is necessary to look at the scrap arising from different uses and the likely proportions of wrought and cast in each of these uses. This starts with the global distribution of scrap arisings by category (building and construction, for example) from (Van den Eynde et al., 2022). Each use category is then downscaled proportionately by category to sum to the European total from the International Aluminium Institute (Alucycle, 2022). These scrap arising figures need to be further downscaled to the amounts collected in each use category. Where the percentage collections in Europe in a use category are known to be different from the global percentages, the European figures are used: these convert the scrap arisings to the scrap collections.

There are significantly differing estimates of the wrought and cast content in each category of post-consumer scrap in previous studies (Buchner et al., 2017; Van den Eynde et al., 2022), so two separate versions of the same calculation are then carried out to provide upper and lower boundaries for the amount of wrought collected in each category.

The working assumption then applied is that unless the wrought aluminium is identified and separated at this stage then it will be mixed with the cast and downcycled. So, for building materials, where aluminium is used in window profiles (window frames), some gutterings, fascias, pipework and grilles, it is likely that the majority of window profiles, which are known to be normally made of one of a few distinct aluminium alloys, will be kept separate and sent to a specialist recycler, whereas the rest will be merged into general aluminium scrap. In categories such as consumer durables the aluminium is unlikely to be identified or removed before shredding: no preservation of wrought is assumed.

So, applying this separation percentage to the categories allows derivation of a weight of wrought aluminium downcycled in Europe each year: depending on whether the Buchner or van den Eynde percentage of wrought by category is used, the total comes to 1.5 or 1.9Mtpa respectively.

Table A1 shows the derivation of the low-side figure of 1.5Mtpa: the high-side derivation is identical except that Column D is replaced by figures from van den Eynde which suggest a higher volume of wrought material across the Use Categories.

Distribution by category: van den Eynde et al (2022) ***Figures from supplementary data 2 & 5*** **Proportion of cast alloy in Use Category: Buchner et al (2017)**

Global				**Europe**								
				European end-of-Life old scrap arising is				5565 ktpa (c1)	5,810kt arising total less 245kt cans			
Old Scrap	**Collected**	**Not collected**	Collected %	End-of-Life *Distribution as global*	Collected % *Input*		Collected *Derived*	Cast alloy in Use category *from literature* Ref d	Wrought Alloy Collected	Proportion of wrought preserved		Wrought that is downcycled
				Column A	*Column B*	*Ref*	*Column C*	*Column D*	*E=C x (1-D)*	*Column F*	*Ref*	*Col G=E x (1-F)*
				'000tpa	%		'000tpa	%	'000tpa			'000tpa
Building & Construction use	3,457	593	85%	689	92%	a	634	10%	571	50%	i)	285
Automotive use	11,045	726	94%	2202	95%	a	2092	75%	523	20%	ii)	418
Aerospace use	182	46	80%	36	72%	b	26	0%	26	100%		0
Other transport use	2,296	461	83%	458	83%		380	75%	95	20%	ii)	76
Foil use	1,946	4,132	32%	388	42%	a	163	0%	163	100%	iii)	0
Machinery use	1,330	750	64%	265	56%	b	147	10%	133	0	iv)	133
Cable use	1,465	608	71%	292	63%	b	183	0%	183	100%	iv)	0
Other electrical use	1,643	579	74%	328	66%	b	215	10%	193	0	iv)	193
Consumer durables use	3,457	1,269	73%	689	65%	b	445	10%	401	0	v)	401
Other use	1,091	1,015	52%	217	44%	b	96	50%	48	0	iv)	48
Destructive use	0	4,067	0%	0			0		0			
	27,912	14,246	66%	5565	79%		4381 (c2)		2335			**1554**
							= 4,618kt-245kt cans					
							= 4,373kt					
Cans use (	4,073	1,692					Small discrepancy					

Column A takes the Global distribution from van den Eynde, keeps the same distribution, and reduces the total to the European arisings.

Column B adjusts the proportion collected by known European literature, in the major Use Categories, to achieve the total in Column C which also corresponds to IAI figures for 2021.

Column D applies the known % of cast aluminium to this distribution.

Columns E derives the weight of wrought alumnium collected

Column F uses known recycling methods to suggest a proportion of wrought aluminium that is preserved in its wrought state: the remainder being recycled with the cast and currently downcycled.

Column G applies the percentage in F to the weight of wrought collected to derive the weight of wrought currently downcycled.

Figure 3: Derivation of the low side figure of 1.5Mt for the amount of wrought scrap downcycled in Europe in 2021.

References

a) UK Aluminium Federation, UK Aluminium Industry Fact Sheet No.5
b) World averages, less 8%, to reach a balance with the totals from the IAI for amounts collected - small inconsistency in their figures.
c1) https://alucycle.international-aluminium.org/public-access/public-global-cycle/
c2) https://alucycle.international-aluminium.org/public-access/public-global-cycle/ Small reconciliation error of 8kt.
d) Buchner et al (2017)

i) Windows, guttering, fascia, pipes, grilles. Assume 50% preserved as wrought
ii) 20% from Buchner et al (2017); remainder assumed shredded
iii) If foil is collected, it will be recycled at MRFs. I have no evidence that it is downcyled: I'm assuming not
iv) No evidence of dismantling prior to shredding.
v) Other than fridges, these are generally shredded

For more information: http://circeular.org

And follow us on:

LinkedIn: **https://www.linkedin.com/company/circeular**

Twitter: ***https://twitter.com/circEUlar_model***

The CircEUlar project is funded by the European Union

This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI